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Potential predators and parasitoids for conservation biological control in smallholder bean farming tropical ecosystem

Mkenda, Prisila Andrea

POTENTIAL PREDATORS AND PARASITOIDS FOR CONSERVATION BIOLOGICAL CONTROL IN SMALLHOLDER BEAN FARMING TROPICAL ECOSYSTEM

Prisila Andrea Mkenda

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ABSTRACT

Conservation biological control (CBC) is an attempt to protect the already existing natural enemies (predators, parasitoids or pathogens) of insect pests within the agricultural systems by manipulating the environment and farming practices to provide the required resources for their survival. This study assessed the major arthropod predators and parasitoids of common bean (*Phaseolus vulgaris*) insect pests in smallholder bean farming tropical ecosystem and their contribution in pest management, in three elevation zones during 2016 and 2017. The farmers' knowledge about natural enemies, insect pest and pesticide use was investigated followed by field surveys and experiments to determine the contribution of major predators and parasitoids to pest management in smallholder bean fields. The importance of field margin vegetation to the population of predators and parasitoids was also examined. The study identified a severe lack of knowledge about natural enemies among the smallholder farmers. However, the field survey revealed the existence of a rich community of natural enemies, where a total of 5003 natural enemies were identified out of 13 961 insects collected. The natural enemy abundance differed along the elevation gradient where the high zone was leading with 50.3%, while mid and low zones had 31.7% and 18% respectively. Majority of the natural enemies were sampled along the margin vegetation compared with the bean fields for low (61.1% in margin vs 38.9% in field) and mid (52.1% in margin vs 47.9% in field) zones, but in the high zone they were more abundant within the bean fields (44.6% in margin vs 55.4% field). A dye experiment to monitor their movement revealed high levels of spatial flux (71%) between the two locations. Aphids (*Aphis fabae*) mortality rates measured by predation and parasitism of sentinel aphids did not significantly differ between the field edges and field centre in all the three elevation zones, indicating the centre of the fields still receive comparable pest control service as the field edge. Parasitoid wasps were the most abundant natural enemy while *A. fabae* were the most damaging insect pests in the smallholder bean fields. Molecular identification of *A. fabae* parasitoids revealed 85% primary parasitoids (*Aphidius colemani*) and two species of secondary parasitoids (*Pachyneuron* sp., 7% and *Charipinae* sp., 1%) which may have significant effects in biological pest control. The study revealed the potential predators and parasitoids important for pest control within the smallholder bean fields which can be enhanced through CBC.

DECLARATION

I, Prisila Andrea Mkenda, do hereby declare to the Senate of the Nelson Mandela African Institution of Science and Technology that this thesis is entirely my own original work and that it has neither been submitted nor being concurrently submitted for degree award in any other institution.

10th April, 2020

Prisila A. Mkenda | Date

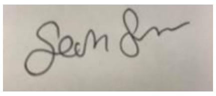
Name and signature of the candidate

The above declaration is confirmed

10th April, 2020

Prof. Patrick A Ndakidemi | Date

Name and signature of supervisor 1



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CERTIFICATION

This is to certify that the accompanying thesis titled "Potential Predators and Parasitoids for Conservation Biological Control in Smallholder Bean Farming Tropical Ecosystem" is written by Prisila A. Mkenda under the supervision of Prof. Patrick A. Ndakidemi, Prof. Geoff M. Gurr and Prof. Philip C. Stevenson at the Nelson Mandela African Institution of Science and Technology. The undersigned certify that they have read and hereby recommend the thesis to the NM-AIST Senate for award of the degree of Doctor of Philosophy in Life Sciences of the Nelson Mandela African Institution of Science and Technology.

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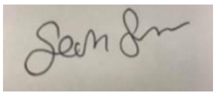
Name and signature of supervisor 1



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Prof. Geoff M. Gurr — Date

Name and signature of supervisor 2

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Prof. Philip C. Stevenson — Date

Name and signature of supervisor 3

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DEDICATION

This thesis is dedicated to my husband, Rev. Daniel Mlaki, and our twins Eliya and Elisha and our daughter Elizabeth, for their determination to make me excel in my studies even when times were hard. I pray that the Lord may reward them abundantly for their tireless endurance and support.

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LIST OF ABBREVIATIONS AND SYMBOLS

CBC	Conservation biological control
NGOs	Non-governmental Organizations
IGRs	Insect growth regulators
IPM	Integrated pest management
Masl	Meters above the sea level
IVR	Interactive voice response
UV	Ultraviolet
TPRI	Tropical Pesticide Research Institute
SARI	Selian Agricultural Research Institute
TACRI	Tanzania Coffee Research Institute
UK	United Kingdom
DNA	Dioxyribonucleic acid
PCR	Polymerace chain reaction
NCBI	National Center for Biotechnology Information database
glm	generalized linear model
K-W	Kruskal-Wallis
df	Degree of freedom
ANOVA	Analysis of variance
LSD	Least Significance Difference
SE	Standard error
VETA	Vocational educational and training authority
SEVIA	Seeds of Expertise for the Vegetable Sector of Africa
TAHA	Tanzania Horticultural Association
L	Low zone
M	Mid zone
H	High zone
ENS	Effective number of species
H`	Shannon Weiner diversity
NE	Natural enemy
IP	Insect pest
FRN	Farmer research networks
FFS	Farmers field schools

CHAPTER ONE

INTRODUCTION

1.1 Background of the Problem

Ecosystems provide numerous services to humans including regulating services, supporting services, provisioning services and cultural services (Liu *et al*., 2010). Agricultural ecosystems are both provider and consumer of ecosystem services. They provide services such as food, bioenergy, forage and pharmaceuticals by relying on ecosystem services such as biological pest control (Inclan *et al*., 2015), pollination (Bartomeus *et al*., 2014), maintenance of soil structure and fertility, nutrient cycling and hydrological cycles (Liu *et al*., 2010; Swinton *et al*., 2007). These agricultural ecosystems vary depending on the climate of the area, topography, cropping systems and overall management of the agricultural lands (Marshall, 2004). As a result, the abundance and diversity of both flora and fauna in ecosystems may differ leading to different levels of ecosystem services.

Conservation biological control (CBC) is one of the ecosystem services provided to agriculture through habitat manipulation to enhance the survival and activity of the natural enemies within agro ecosystems (Eilenberg *et al*., 2001). Habitat manipulation involves integration or management of the features (natural and semi natural habitats) on or close to the crop land (Gurr *et al*., 2016; Ribeiro & Gontijo, 2017), or at the landscape level (Begg *et al*., 2016; Schellhorn *et al*., 2008). However, manipulation within the crop habitat like planting of flower strips or use of cover-crop pose some challenges as these approaches interfere with the normal farming practices and may lead to competition with the crops and difficulties during harvesting especially if mechanized. Currently, much attention is given to the features that are already present around the crop lands which can be managed or preserved for provision of alternative food resources and habitats or refuge sites during disturbance (Heimoana *et al*., 2017). Landscape structure and composition together with non-crop vegetation plants along the field margin contribute significantly to the abundance and diversity of the natural enemies within the crop land (Alomar *et al*., 2002; Gardiner *et al*., 2009; Macfadyen *et al*., 2015; Thies *et al*., 2005; Tscharntke *et al*., 2005; Veres *et al*., 2013). This is due to the fact that, natural and semi natural habitats are less disturbed in comparison to crop land, thus they act as reservoirs and source of natural enemies to recolonize the crop area after disturbance. A study by González *et al*. (2016) found the natural enemies were predominantly moving from the native forest to the crop compared with other insect groups and the movement decreased during crop senescence, showing a greater contribution of native vegetation to natural enemies than herbivores. Most of predators and parasitoids require a variety of resources than the crop can provide, thus diversification of the agricultural land is important for their survival. The natural and semi natural habitats such as field margin vegetation have been reported as important structures in enhancing the natural enemy population (Bianchi *et al*., 2006; Gurr *et al.*, 2003; Landis *et al*., 2000; Marshall, 2004; Ramsden *et al*., 2014).

Agricultural intensification associated with simplification of agricultural land through monoculture cropping system with increased chemical inputs as well as conversion of natural and semi natural habitat to arable farms is becoming dominant (Jonsson *et al*., 2012; Meehan *et al*., 2011; Robinson & Sutherland, 2002). All these agricultural practices are associated with decreased biodiversity of wild plants and animals as well as decline in natural pest control due to increased chemical inputs that kill natural enemies of insect pests (Jonsson *et al*., 2012). Consequently, there has been increased pest infestations with new pest outbreaks especially in most African countries as a result of lack of natural pest control and increased pesticide resistance. Understanding the importance of biodiversity in agriculture and the effects of different agricultural management practices can help farmers better promote beneficial ecosystem services. According to Farooq (2007) and Yaseen *et al*. (2016), access to agricultural knowledge and information by rural farmers is the central element for improved production systems.

This study investigated the feasibility of conservation biological control in bean farming ecosystems of smallholder farmers in three agro ecological zones of Moshi rural district in Northern Tanzania through: (a) assessment of farmers' knowledge about natural enemies, insect pests, pesticide use and ways used to access agricultural information; (b) field survey on the abundance and diversity of natural enemies and insect pests of common beans within the smallholder farms; and (c) field experiments to assess the influence of margin vegetation to the natural enemy population and their movement to the field crop for biological control activity.

1.2 Statement of the Problem

Insect pests have been one of the major limitations in crop production. A total global potential loss due to various pests are about 50% to 80%, where 34% is due to animal pests and pathogens (Oerke, 2006), despite the widespread use of chemical pesticides which has increased from 15 to 20 times in the past 40 years (Martin *et al*., 2013). The use of synthetic pesticides have been a challenge since most of them are not selective and sometimes they are applied at inappropriate rates which is harmful to the environment and its associated organisms (Rahman & Prodhan, 2007). Emergence of new pests together with secondary pest outbreak is the impact of lack of natural pest control as a result of environmental damage by toxic chemicals. Conservation biological control is one of the integrated pest management techniques that relies on native natural enemies, well adapted to local agricultural ecosystems. It provides effective and economically viable pest control and leads to residue-free crop products with high market value. Habitat manipulation for conservation biological control have other several ecosystem benefits like enhancement of pollinators (Altieri, 1999; Delattre *et al*., 2010; Rands & Whitney, 2010; Ricou *et al*., 2014), increased survival of rare and endangered species (Kuiper *et al*., 2013; Wiggers *et al*., 2016; Wuczyński *et al*., 2014) and enhancement of soil macrofauna important for organic matter decomposition and nutrient cycling (Crittenden *et al*., 2015; Roarty & Schmidt, 2013). Therefore, successful control of pests by naturally occurring biological agents is of key economic and ecological importance (Naranjo *et al*., 2015; Sharma *et al*., 2013; Varennes *et al*., 2015).

Much information on the importance of non-crop vegetation to natural enemy populations, biological control activity and other ecosystem services is reported in Europe (Balzan, *et al*., 2016; Fusser *et al*, 2016; Sorribas *et al*., 2016), but there is limited information from Africa and other tropical countries and this is an important information gap addressed in the present study. Related to this, whilst the manipulation of cropping systems by planting strips of flowering plants along the field margin or within the field crop (Ribeiro & Gontijo, 2017; Tschumi *et al*., 2016b) or by the use of cover crops (Bryant *et al*., 2014) is well known to enhance beneficial insects in developed country cropping systems, there is limited information relevant to small holder tropical farming systems. In addition, farmers' awareness about conservation biological control in bean farming ecosystems was not well known. Accordingly, this study was carried out to characterise the pest and natural enemy assemblages and biological control activities through a participatory research study in the smallholder bean farming ecosystems in northern Tanzania. Farmers' awareness about natural pest control was assessed and training was done to raise their knowledge towards adoption of conservation biological control measures.

1.3 Rationale of the Study

Conservation biological control is well practiced in many developed nations (Fusser *et al.*, 2016; Sorribas *et al*., 2016), but with poor application in many developing countries of Africa including Tanzania (Wyckhuys *et al.*, 2013), despite its well known biodiversity and associated tropical climatic conditions. Agricultural sustainability in Africa requires the production practices that are less dependent to external inputs (Kremen & Miles, 2012). There exist a huge potential of promoting natural pest control through conservation biological control for sustainable agriculture and pest management in Tanzania and Africa in general.

1.4 Objectives

1.4.1 General Objective

To examine the major predators and parasitoids of common bean (*P. vulgaris*) insect pests within the smallholder bean farming tropical ecosystems and their contribution in pest management.

1.4.2 Specific Objectives

i) To investigate farmers' knowledge about natural enemies, insect pests and pesticide use and ways used to access agricultural information

ii) To determine the abundance and diversity of the natural enemies and insect pests within the bean farming systems in three elevation zones

iii) To quantify the movement and biological control activity of the natural enemies within the bean fields and along the field margin vegetation in each elevation zone

iv) To determine the percent vegetation cover and diversity of field margin plants in the three elevation zones

v) To identify the most preferred margin plants by the natural enemies around the bean fields in the three elevation zones

1.5 Hypothesis

i) H1: Farmers are knowledgeable about natural enemies, insect pests and pesticide use and have access to agricultural information

Ho: Farmers are not knowledgeable about natural enemies, insect pests and pesticide use and have no access to agricultural information

ii) H1: There are abundant and diverse natural enemies and insect pests within the smallholder bean farming systems and vary across the three elevation zones

Ho: There is no abundant and diverse natural enemies and insect pests within the smallholder bean farming systems and no variation across the three elevation zones

iii) H1: Natural enemies move from the field margin vegetation to the bean field for biological control activity and varies across the three elevation zones

Ho: Natural enemies do not move from the field margin vegetation to the bean field for biological control activity in the three elevation zones

iv) H1: The smallholder bean fields are surrounded by many and diverse margin plants and varies across the three elevation zones

Ho: The smallholder bean fields are not surrounded by many and diverse margin plants and no variation across the three elevation zones

v) H1: Some field margin plants are more preferred by the natural enemies in the three elevation zones

Ho: Some field margin plants are not preferred by the natural enemies in the three elevation zones

1.6 Significance of the Study

The study identified the major limitation towards the adoption of conservation biological control among the smallholder farmers to be lack of knowledge associated with poor information dissemination to the farmers. The training and participation of the farmers in the field during the study transformed the farmers' knowledge and farming practices towards more sustainable pest management techniques that enhance farm biodiversity for biological pest control. The study also came up with a profile of natural enemies and insect pests that exist within the smallholder bean farming systems, together with important field margin plants that are highly visited by the natural enemies suggesting possible conservation measures to enhance the natural enemy population. The identification of *Aphidius colemani* as the primary parasitoid of bean aphids in the smallholder bean farming systems, along with two species of secondary parasitoids (*Pachyneuron* sp. and *Charipinae* sp.) gives useful information for future conservation biological control programs that will enhance the survival and fecundity of *A. colemani* without benefiting hyperparasitoids and pest species.The published findings of this study will show the way towards the adoption of conservation biological control measures in other parts of the country and Africa in general where this technique have been given less attention despite the several challenges existing with the current practices of pest control among smallholder farmers.

1.7 Delineation of the Study

The study was conducted in low, mid and high elevation zones of Moshi rural district, Northern Tanzania. A total of 24 smallholder bean fields, 8 fields per zone, and a total of 300 smallholder farmers, 100 farmers in each zone were included in the study.

CHAPTER TWO

LITERATURE REVIEW

2.1 Meaning and Types of Biological Control

Biological control is a component of integrated pest management that refers to the reduction of a pest population by natural enemies, a process also known as natural pest control. Natural enemies in pest management refer to predators, parasitoids or pathogens that suppress pest population by feeding, parasitizing or by causing a disease (Aquilino *et al*., 2005; Martin *et al*., 2013).

Predator is a group of natural enemies that are generally characterized as free living, mobile, larger body size than their insect prey, and capable of consuming several prey throughout their life cycle (Getanjaly *et al*., 2015; Jones, 2005). Arthropods are the most important predators in pest management. Some of the predators deposit their eggs near their prey so that when they hatch the immature ones can immediately find their prey and begin feeding (Macfadyen *et al*., 2015). They prey on different life stages of pest including insect eggs, larvae stages and adults. Some common predator groups include beetles (example lady beetles, rove beetles and carabid beetles), bugs (example assassin bugs, damsel bugs, mirid bugs, pirate bugs, stink bugs and ambush bugs), flies (example long legged flies, hover flies and robber flies), lacewings, ants and spiders (Getanjaly *et al*., 2015; James *et al*., 2018).

Parasitoids are usually members of the order Hymenoptera (wasps) and few belong to the order Diptera. Several studies have reported that, more than 80% of the known hymenoptera species are parasitoids (James *et al*., 2018; Sampaio *et al*., 2009). Chalcid wasps, encyrtid wasps, ichneumonids and braconid wasps are some of the commonly studied parasitoid waps (Getanjaly *et al*., 2015; Inclan *et al*., 2015; Landis *et al*., 2000). Parasitoids are considered important bio-control agents for a range of pest species around the world (Costamagna & Landis, 2004; De Conti *et al*., 2008; Lee *et al*., 2001; Schmidt *et al*., 2003; Sigsgaard, 2002). The free-living adult parasitoids search for a host in different environments especially in agricultural systems where they are more abundant and parasitize different life stages of their host depending on the parasitoid species. The parasitoids lay a single egg or several eggs on or within their hosts (Lee *et al*., 2001). The immature parasitoid(s) depend on their host for growth and development through feeding and later the host is killed, where it emerge as free-living adult parasitoid (Getanjaly *et al*., 2015). The adult parasitoids are free living and sometimes may be predators. Many parasitoids are limited to one or few closely related host species because they must be adapted to the life cycle, physiology and defenses of their hosts (Lajeunesse & Forbes, 2002). In comparison to predators, parasitoids are considered more effective due to the fact that they are host specific, increase with increasing density of the host, can complete their life cycle within a single host and able to synchronize with the host (Murdoch *et al*., 1985). Their impact is easier to quantify since they can be reared on a host in the laboratory to record how the species emerges, hence direct estimates of parasitism rates in the field are not difficult to obtain.

Pathogens are also important biocontrol agents and their value in insect pest management has long being recognized (Rombach *et al*., 1987). Insect pests like other living organisms, are susceptible to diseases caused by pathogens. Pathogens as natural enemies include entomopathogenic fungi, bacteria and viruses that can infect and kill the insect pests (Baverstock *et al*., 2008; Baverstock *et al*., 2012; Singh *et al*., 2017). Insect pathogens can be applied in the environment through augmentation, which involves inundative or inoculative releases, formulation of bio-pesticides and by natural development in the environment (Ramanujam *et al*., 2014). Advantages of using entomopathogenic organisms as biological control agents is that they have negligible effects to non-target organisms and easily produced in mass (Singh *et al*., 2017).

2.1.1 Classical Biological Control

This is a process where new natural enemies are introduced to an area for establishing a permanent population (Charlet *et al*., 2002). It involves an extensive research into the biology of the pest and the potential natural enemy as well as the possible unintended consequences before introducing the natural enemy to the area (Cock *et al*., 2010). The natural enemies are released after careful studies of the pests' life cycle in a site where they are abundant so as to allow complete establishment of the natural enemies. This process is very complex and time consuming, but once it is established it is long lasting. The need for importing the natural enemies occurs when a pest is accidentally introduced into an area and its natural enemies are left behind. Therefore, an attempt is made to locate these enemies and introduce them to re-establish the control that often existed in the native range of the pest. In Africa, classical biological control has been useful in the control of mites in cassava (Herren *et al*., 1987; Herren & Neuenschwander, 1991; Korang-Amoakoh *et al*., 1987; Megevand *et al*., 1987;

Onzo *et al*., 2005; Zannou *et al*., 2005; Zeddies *et al*., 2001), with very limited application in other crops including leguminous crops.

2.1.2 Augmentative Biological Control

Augmentative biological control is an attempt to reduce pests' population to non-economic levels by temporarily increasing number of the natural enemies in an area through periodic releases (Collier & van Steenwyk, 2004; Crowder, 2007). It is a direct manipulation of insects which involves rearing predators, parasitoids or pathogens at a commercial scale and releasing them to the crop where the host pests are present, particularly in glasshouse environments, where it can be more effective (Van Lenteren, 2000; Van Lenteren, 2012). In some countries, the natural enemies are reared artificially and then released into the field in a more effective way and economical (Levie *et al*., 2000; Van Lenteren & Bueno, 2003). However, in most developing countries including those in Africa, it is less practical in outdoor field crops and unlikely affordable in small holder farming systems.

There are two types of augmentative biological control; the inundative and the seasonal inoculative release method (Orr, 2009; Van Lanteren, 2000). Inundative release method is where the natural enemies are collected and reared into large number, then released for immediate control of the pest by the released natural enemies and not their offspring (Van Lenteren, 2000). This is mostly applicable in situations where viable breeding population of the natural enemies is not possible or where rapid control is required and in situations where only single pest generation occurs. On the other hand, seasonal inoculative biological control involves collection and rearing of the natural enemies and releasing them periodically in situations where several pest generations occur for immediate pest control and throughout the season especially in greenhouses (Bale *et al.*, 2008; Cock *et al.*, 2010). Augmentative biological control has been very successful in many places (Van Lanteren, 2000, Van Lanteren & Bueno, 2003), though in some areas it has been a challenge due to the movement of the released natural enemies away from the target area as a result of low pest densities or high level of competition (Wajnberg *et al.*, 2008). It is usually a commercial activity which involves mass production and large area release of the natural enemies (Van Lanteren, 2012), thus rarely applied among the small scale farming systems in Africa.

2.1.3 Conservation Biological Control

Conservation biological control is an attempt to protect the natural enemies that are already present in an area by manipulating the environment or the farming practices so as to provide the required resources for them to survive and build up populations to levels where they can manage the pest and prevent them from causing economic damage to crops (Gurr *et al*., 2000; Gurr & Wratten, 1999; Wyckhuys *et al*., 2013). Agricultural intensification and broad-spectrum use of pesticides have resulted to a decrease in the diversity of natural enemy populations and an increase in the likelihood of pest outbreaks (Heitala-Koivu *et al*., 2004; Landis *et al*., 2000). Apart from direct toxicity effect of the synthetic pesticides, they may also pose subtle effects on the physiology of the natural enemies (Cullen *et al.*, 2008; Jonsson *et al.*, 2008). To conserve the natural enemies, simple strategies such as reducing frequency of synthetic pesticides and carefully targeting pesticide use when necessary based on reasonable economic injury levels are recommended (Gurr & Wratten, 1999; Landis *et al*., 2000; Van Driesche *et al*., 2008; Wyckhuys *et al*., 2013).

Conservation biological control can be achieved by manipulating the landscape through provision of flowering resources and source habitats for natural enemies (Gurr *et al*., 2016; Landis *et al*., 2000; Sigsgaard *et al.*, 2013). In Africa, the manipulation of natural enemies through conservation biological control is very promising due to favourable climatic conditions with diverse biodiversity (Sampaio *et al.,* 2009). It is also the most readily available biological control practice to farmers and less expensive as it just involves the manipulation of the environment and the farming practices to attract the natural enemies. It is self-perpetuating, unless it is disturbed by introduction of some chemicals or any other environmental disturbance like fire. Conservation biological control can be economically worthwhile, although, unfortunately, only few studies have been conducted with the specific goal of assessing its economic benefit in crop protection (Cullen *et al*., 2008). Despite the high tropical diversity of Africa, application of conservation biological control is very limited (Wyckhuys *et al*., 2013) especially for leguminous crops. There is therefore a need to assess how conservation biological control can be employed in African agricultural systems due to its richness in terms of biodiversity.

2.2 Potentials of Conservation Biological Control in Pest Management in Africa

There exist a huge potential of promoting conservation biological control for sustainable agriculture and pest management in Africa, as the continent is known worldwide in terms of its biodiversity which forms the base of its natural wealth (Newmark, 2002). Africa harbours about one quarter of the world's 4 700 mammalian species, 40 000 – 60 000 plant species and about 100 000 known species of insects, spiders and other beneficial insects (Duruigbo *et al*., 2013). Sub Saharan Africa specifically is a home of more than 1/5 of the worlds' plant and animal diversity (Duruigbo *et al*., 2013). However, this biodiversity has not been sufficiently integrated into broader sectors, such as agriculture, fisheries and economy leading to low development in those sectors (Sunderland, 2011). Furthermore, trade-offs between food production, biodiversity conservation, ecosystem services, and human well-being in agricultural landscapes is not yet addressed (Martinet & Barraquand, 2012). As a result, insect pests continue to be among major problems in crop production leading to poor quality and low crop yields in Africa (Delate *et al.*, 2008; Mwang'ombe *et al*., 2007; Shannag & Ababneh, 2007). Thus, with proper understanding, sustainable use of the agricultural biodiversity present will particularly be beneficial to small-scale farmers who usually have poor access to external inputs due to financial and infrastructural constraints (Belmain *et al*., 2013). Management practices that use complex, ecologically based approaches are, therefore, encouraged. There is need to identify innovative and acceptable ways of integrating biodiversity conservation such as use of natural enemies in food production systems in Africa.

There are several reasons why conservation biological control of pests should be promoted in crop production in Africa. Development of pesticide resistance by numerous pest species have been one of the major reasons apart from increasing concern of the effects of chemicals to the environment, non-target organisms and human health (Chidawanyika *et al*., 2012). Pesticide residue is another cross cutting issue among different consumers and generally in the market chains (Van Lenteren, 2012). There is an increased awareness of the effects of pesticides in food production among consumers. Less risk is associated with the foods produced through biological pest control compared with those which synthetic pesticides were applied (McNeil *et al*., 2010). Permanence, safety, and economy are the three major factors to consider in pest management strategy (Chaplin-Kramer *et al*., 2011; Eilers & Klein, 2009; Pimentel, 2005). Conservation biological control has several advantages of being safe, self-sustaining, cost effective and eco-friendly compared with most other pest management techniques (Chaplin-Kramer *et al*., 2011; Eilers & Klein, 2009). Due to these benefits, many countries especially in Europe have started using pest management approaches that cut down cost of farming, one of which is application of biological control methods (Brouder & Gomez-Macpherson, 2014; Kassam *et al*., 2014; Pretty & Bharucha, 2015). There is, therefore, a need to explore on the feasibility of the conservation biological control for sustainable pest management among smallholder farming systems in Africa.

2.3 Farmers' Knowledge About Conservation Biological Control

Conservation biological control is knowledge intense and farmers need to be well informed about the underlying principles and approaches to support natural pest regulation for sustainable food production. Insufficient knowledge among the farmers is correlated with the farmers' level of education and limited access to agricultural information is one of the main factors contributing to continuing reliance on pesticides (Olajide, 2011). Kariathi *et al*. (2016) and Ngowi *et al*. (2007) reported that many farming communities in northern Tanzania are not aware of the hazards associated with chemical pesticides while their excessive use is largely due to poor training and knowledge of alternatives. Most farmers cannot read so are unable to follow instructions on application rates or heed safety warnings on pesticide labels (Ntow *et al*., 2006; Williamson *et al*., 2008). This results to increased insecticide resistance and greater pest numbers associated with low numbers of arthropod natural enemies. In response to insecticide resistance, some farmers mix several pesticides together at increased concentrations exacerbating their negative effects (Ngowi *et al*., 2007; Wilson & Tisdell, 2001). These agricultural practices are impacting ecosystem services including natural pest control as well as creating health problems to humans and other non-target organisms.

Access to agricultural knowledge and information by rural farmers is the central element for improved production systems (Farooq, 2007; Yaseen *et al*., 2016). The relevance of agricultural information source to smallholder farmers usually depends on its accessibility, efficiency and effectiveness in disseminating updated information. Education and facilities available to the farmers may also facilitate information accessibility. According to Casmir *et al*. (2012), farmers' access to agricultural information such as weather, good farming practices, pest management techniques and market information can help them in making informed decisions and hence improving their crop and animal production. Information plays an important role in decision making throughout human life (Edejer, 2000). In agriculture, information access is a powerful tool to increase farmers' awareness towards different agricultural developments and challenges and, in taking appropriate action for their livelihood (Ballantyne, 2005; Sarker & Itohara, 2009; Siyao, 2012). Timely and accurate information accessibility is capable of increasing efficiency as late or expired information will never affect performance.

Pest and disease control together with production/farming methods are among the most demanded type of information by most of the farmers regardless of the farming type (Angello *et al*., 2016; Elly & Silayo, 2013; Lwoga *et al*., 2011; Msoffe & Ngulube, 2016; Mtega *et al*., 2016; Ronald *et al*., 2014). Good farming practices can result to high quality produce at large quantities and with good market information, farmers' income could raise tremendously (LeeEden & Kalusopa, 2005). It is obvious that farmers could have a better livelihood if they could access the needed agricultural information. The farmers are therefore, not only groping in the dark but also destructing the environment with the associated biodiversity (Moyo *et al*., 2006; Prakash *et al*., 2008). There are many technological information and innovations continuously happening in agriculture sector but many farmers are still relying on older technologies which are poor and not environmentally friendly as a result of poor knowledge and information. Many efforts have been directed to agriculture sector including advanced scientific researches on various agricultural issues by the government and NGOs (Yaseen, 2016) but this may not bear fruit unless the farmers are directly involved in the research or through effective dissemination of the results. Adomi *et al*. (2003) reported that most of the African countries have no efforts of disseminating agricultural knowledge and information to the rural areas where majority of the farmers are located. Farmers are not aware of much of the agricultural information that is available in research institutions, universities, public offices and libraries due to weak linkages between knowledge creating organs, agricultural extension officers and consumers of the knowledge (Lwoga *et al*., 2011). Much attention should therefore, be directed to the ways of enhancing the knowledge of the farmers through trainings and active participation of the farmers in various research conducted in their areas in order to improve their knowledge and information towards adoption of conservation biological control. This will lead to reduced cost of production among the farmers while protecting the environment for the benefits of current and future generations.

2.4 Natural Enemy and Insect Pest Population in Agricultural Systems, Across Elevation Gradient

Organisms exhibit habitat specialization that lies between two extremes, highly disturbed habitats like crop land and less disturbed or natural habitats (Baldissera *et al*., 2004). The organisms that are mostly restricted to the natural habitats and never come to the crop land are referred to as stenotypic species, whereas those mostly found in crop land are known as cultural species (Duelli & Obrist, 2003). Most of beneficial insects including the natural enemies of crop pests are between the two extremes, meaning they require both types of habitats at varying degrees (Bianchi *et al*., 2006; Landis *et al*., 2000). Most insect pests of crops are more specialized to certain crops as their host plants, thus restricted to the crop land.

Landscape ecology including the elevation gradient and local management of agricultural lands are major determinants of biodiversity patterns in agricultural landscapes, especially those related with biological pest control (Landis *et al*., 2000; Martin *et al*., 2013). Landscape in terms of the amount of natural or non-crop habitat surrounding the farm and land use intensity, are known to be the driving force of natural enemy dynamics in agricultural ecosystems (Landis *et al*., 2000; Landis & Marino, 1999; Martin *et al*., 2013; Woltz *et al*., 2012) and may vary along elevation gradient due to differences in temperature and humidity. A study on the effect of temperatre and humidity to the survival of insects by Jaworski and Hilszczanski (2013) reported that, increase in temperature to an optimum level stimulates the activities of insects with more dispersal across the landscape. Temperature may also have indirect influence on the environment where it affects plant formations and plant phenology.

Increasing vegetation diversity within crops is predicted to enhance the survival of natural enemies in agricultural systems; consequently pest outbreaks tend to be less common in polycultures (many crops) than in monocultures (Bianchi *et al*., 2006). Polycultures promote the activities of natural enemies through provision of various resources such as alternative food resource, breeding sites, shelters and overwintering sites within the field (Kremen & Miles, 2012). Therefore, intercropping can be a good method to increase beneficial insect diversity within agro ecosystems compared with mono cropping. Depending on the size of the natural enemies, increasing vegetation diversity can be the best way to enhance natural enemies (Gurr *et al*., 2016). This is because not all entomophagous species are sufficiently mobile to travel outside the field to search for food resources. For example, most larval stages of many natural enemies are relatively immobile, thus food resources should be within the field so as to promote their activity. The best way of conserving natural enemies and stabilizing their populations is to meet their ecological requirements within or near the cropping environment (Landis *et al*., 2000).

Reduced dependence to external inputs such as pesticides, chemical fertilizers, herbicides and fungicides leads to favourable environment to beneficial insects including the natural enemies (Arbuckle & Roesch-McNally, 2015; Chatterjee, 2013; Kaspar *et al*., 2001; Pimentel *et al*., 2005; Singer *et al*., 2007). It has been reported that, most of the applied synthetic insecticides affect the natural enemies of insect pests at a greater extent than their respective hosts due to the fact that the insect pests may develop detoxification mechanisms that originate from the plants in their feeding process (Gill & Garg, 2014). The synthetic pesticides affect the beneficial insects in both direct and indirect ways. The direct effects lead to death of the organisms (Bacci *et al*., 2007; Martinou *et al*., 2014; Thomson *et al*., 2001), while indirect effects include reduced mobility and ability to capture prey (Fernandes *et al*., 2010), reduced oviposition (Umoru *et al*., 1996), reduced growth and development (Radjabi, 1995) together with reduced fecundity (Delpuech *et al*., 1998). Therefore, there is a need to consider other pest management options that are environmental friendly with little or no effect to non-target organisms. Organic agriculture is important in promoting and maintaining the beneficial insects since it involves the augmentation of ecological processes that aim at increasing agricultural production sustainably, with no harmful effect to the environment and non-target organisms (Kremen *et al*., 2012; Pimentel *et al*., 2005). Habitat manipulation and management of the features on or close to the crop land (Gurr *et al*., 2016; Ribeiro & Gontijo, 2017), or at the landscape level (Schellhorn *et al*., 2008) may enhance the population of natural enemies for biological pest control. Some of those practices are outlined in Table 1.

Table 1: Habitat manipulation and management practices for enhancing natural enemy population

Natural enemies requirement	Practices	References
Food resources such as pollen, nectar, honeydew, artificial food	Planting annual flower strips in field crops and field margins	Gurr *et al*. (2016); Tschumi *et al*. (2016b)
	Planting perennial flowering plants	Blaauw and Isaacs (2015); Tschumi *et al*. (2016a)
	Intercropping with flowering plants	Bickerton and Hamilton (2012); Brennan (2016); Ribeiro and Gontijo (2017)
	Artificial foods and honey dew	Wäckers *et al*. (2008); Wade *et al*. (2008)
Alternate host, shelter, overwintering sites	Maintaining field margin or interplanting	Chaplin-Kramer and Kremen (2012); Manandhar and Wright (2016); Williams and Martinson (2000)
	Staggering harvesting or refuge crop stripes	Hossain *et al*. (2002)
	Creation of refuges plants (beetle bank))	Collins *et al*. (2003); MacLeod *et al*. (2004)
	Banker plants	Frank (2010); Xiao *et al*. (2012)
Less toxic environment	Organic farming/ integrated pest management, insect growth regulator (IGRs), use of semiochemicals	Crowder *et al*. (2010); Naranjo and Ellsworth (2009); Pickett *et al*. (2006)
Microhabitats with optimal conditions	Mulching and cover crops	Bryant *et al*. (2014); Schmidt *et al*. (2004); Schmidt *et al*. (2007)

On the other hand, monoculture may lead to increased pest problems as the pests can accumulate in the area each season as long as their host plants are available (Benton *et al*., 2003). This is because continuous growing of a single crop in a certain area provides a narrower range of habitat to beneficial insects while harbouring more pests, leading to an increased need for chemical pesticides. According to Kremen and Miles (2012), monoculture systems have been found to be more susceptible to insect pest infestation and plant viruses than polycultures. In addition, the misuse and/or overuse of synthetic pesticides have resulted to development of pesticide resistance which consequently increases pest population with new pest outbreak (Bass *et al*., 2014; Silva *et al*., 2012). Therefore, pest management practices that use complex, ecologically based approaches with reduced use of external inputs are more encouraged.

2.5 Influence of Field Margin Vegetation to Natural Enemy Population and Biological Control

In most farmland, field margin vegetation may represent the key semi-natural habitat available to enhance biodiversity. Field margins can promote more diverse natural enemy taxa when there is also reduced pesticide use, tillage and enhanced crop cover compared with a conventionally managed crop (Vickery *et al*., 2009). Ramsden *et al.* (2014) reported on the potential of field margins for food provisioning, overwintering sites and hosts to various predators and parasitoids for enhanced biological control services in agro-ecosystems. Several studies have reported on the importance of field margin management in arable fields for the provision of foraging habitats, nesting sites, food resources and shelter for both invertebrates and vertebrates (Bianchi *et al*., 2006; Gurr *et al*., 2003; Landis *et al*., 2000; Marshall, 2004). These benefits can be particularly important after disturbances caused by agricultural practices like tillage, pesticide application and harvesting (Lee *et al*., 2001). Understanding the various benefits of field margin and non-crop vegetation in agriculture and environment is particularly important for proper management. Intention of integrating agronomic and biodiversity objectives may widely be achieved through field margin establishment and management.

Several studies have reported on the importance of increased diversity of field margin plants to the populations of different natural enemy groups and pest control (Atakan, 2010; Pluess *et al*., 2010; Rouabah *et al*., 2015; Torretta & Poggio, 2013; Werling & Gratton, 2008). Strips and borders of non-crop vegetation were found to increase the abundance and diversity of spider communities and other natural enemies (Amaral *et al*., 2016; Ditner *et al*., 2013; Gurr *et al*., 2016; Pluess *et al*., 2010). Field margin plants such as trees and shrubs are considered as ecological refuge sites, for increased population of predatory insects (Burgio *et al*., 2004). It was found that field margins with several plant species at local and landscape level are effective in managing pests compared with simplified field margins (Bischoff *et al*., 2016).

Field margins with sufficient flowering plants act as reservoirs of beneficial insects to recolonize the crop field as observed in hoverflies and tachinids (Inclán *et al*., 2016; Sutherland *et al*., 2001). They are also regarded as hotspots for other beneficial insects including ground beetles as an indicator species, since they are very sensitive to environmental changes (Yu & Liu, 2006). Crop cover at the field margin was also found to be the major factor that influenced the activities of non-crop ground beetle as compared with the effects of temperature and rainfall (Eyre *et al*., 2016). Attractiveness of the flowers and presence of nectar are reported to be the major factors that enhance the parasitoid population in the field margin plants (Bianchi & Wäckers, 2008). Whiteflies are an example of one taxon found to be effectively controlled by parasitoids, populations of which were enhanced as a result of the floral nectar of non-crop vegetation around bean fields (Hernandez *et al*., 2013).

Generally, non-crop habitats within arable lands significantly influence the abundance and diversity of natural enemies. Even a very small area of non-crop habitat have a significant effect to the natural enemy population (Knapp & Řezáč, 2015; Pluess *et al*., 2010; Jung *et al*., 2008). Contradictory findings of a much weaker influence of non-crop vegetation on spider populations are reported by D'Alberto *et al*. (2012), where other factors like crop characteristics (annual vs perennial) and regional differences appeared to play a larger role. Arthropod populations in field annual crops are highly dependent on the surrounding non-crop vegetation because of the periodic disturbances that occur within the field crop unlike the perennial plants where there are fewer disturbances. Another study by Noordijk *et al*. (2010) reported on the influence of the field margin age to invertebrate population where predators were found to decrease with increase in the age of the field margin as a result of decrease in quality of margin vegetation. Generally, many natural enemies are enhanced by timely availability of three key resources: prey as a food resource, floral resources as additional food, shelter habitats and overwintering sites in case of disturbances (Ramsden *et al*., 2014). Some invertebrates move from the field margin to the field crop during the growing season when there is abundant food resources and later back to the margin when the resources are scarce or due to agronomic disturbances (Girard *et al*., 2011). This highlights the importance of margin vegetation as alternative shelter and food resource to natural enemy population and biological control activity around crop land.

2.6 Agronomic and Management Factors Influencing Field Margin Plant Composition

Farming activities adjacent to the field margins such as application of herbicides (Boutin *et al*., 2004; Riemens *et al.*, 2009), pesticides and fertilizers (Schmitz *et al*., 2013; Schmitz *et al*., 2014b) can be considered potential disturbances and may adversely affect the margin flora structure and composition. The effect of fertilizers and herbicides significantly affected the occurrence and frequency of several light feeder plant species that require less nitrogen and other nutrients leading to low diversity while few heavy feeders (plant species with high demand of nitrogen and other nutrients) were favoured by the applied fertilizer (Schmitz *et al*., 2014a). Though agrochemical inputs are typically applied in the crop, their effect can be observed in the field margin as a result of direct overspray or spray drift due to their close proximity to the field (Firbank *et al*., 2008). The effects of pesticide drift or overspray are more pronounced in narrow field margins, particularly those less than 3m wide (Hahn *et al*., 2014). It is recommended that agrochemical inputs should be selectively applied or restricted completely in order to increase the diversity of both flora and fauna along the field margins for conservation biological control.

Field margin establishment such as fencing, application of sown flower mixtures or natural regeneration by rotavation (Fritch *et al*., 2011; Huallacháin *et al*., 2014) and their structural connectivity (Fridley *et al*., 2009; Kang *et al*., 2013) determine their vegetation structure and plant diversity. Field margins established through sowing seed mixtures led to the highest diversity of flora and fauna, especially in highly intensified land (Fritch *et al*., 2011). Generally, uncropped margin types were found to be more capable of supporting high plant diversity and abundance compared with cropped field margins, due to the effect of competition from the crop (Walker *et al*., 2007). Subsequent management such as cutting (De Cauwer *et al*., 2008), grazing or mowing (Coulson *et al*., 2001; Fritch *et al*., 2011), coppicing, trimming and pollarding (Deckers *et al*., 2004) and other techniques including agrochemical input applications (Schmitz *et al*., 2014a) have been found to influence the floral species composition as a result of disturbances or changes to the soil nutrient content. As field margins may consist of a human-selected floral composition, they can also be affected by weed invasion; this will alter the vegetation structure and composition and was found to be influenced by the establishment and management practices employed (Bokenstrand *et al*., 2004; De Cauwer *et al*., 2008; Reberg-Horton *et al*., 2011; West *et al*., 1997). In addition to management practices, the vegetation structure and composition at the field margin depend on the ecological and biogeographical context of the area, as well as their historical seedbanks. Field margins have more seedbanks and hence are more species rich compared with the field centre (Jose-Maria & Sans, 2011). Therefore, species richness of a particular field margin depends on the seedbank which also determines the past management practices.

2.7 Failure of Field Margin Vegetation to Enhance Biological Pest Control

There are some reported cases (Table 2) where field margin vegetation fails to enhance biological pest control.

Table 2: Factors accounting for ineffective pest regulation of field margin vegetation

Influencing factors	**Explanation**	**Example of species studied**	**Reference**
Lack of effective natural enemy in the area	Invasive pest species may arrive in an area without their biological control agents, unless they are introduced in the area where they can be enhanced by the vegetation diversity	Migratory locust, *Locusta migratoria*	Lomer *et al*. (2001)
Intraguild predation	Predation of the biological control agents by other natural enemies lead to more pest outbreak regardless of the vegetation diversity in the area	Insectivorous birds and wasps	Martin *et al*. (2013)
Natural enemy dispersal ability	Field margin vegetation are good in harbouring the natural enemies, but poor dispersal of the natural enemies may lead to ineffective pest control within the crop land	Carabid beetles	Fischer *et al*. (2013)
Margins with non-crop hosts	Host plants (susceptible plants) at the field margins may provide habitat to insect pests and act as a source of pests in the field	*Drosophila suzukii* and *Stictococcus vayssierei*	Arnó *et al*. (2016); Kenis *et al*. (2016) and Tindo *et al*. (2009)
Planting of susceptible crop variety	Planting of susceptible crop varieties with little or no crop diversification may lead to high pest infestation regardless of the presence of margin vegetation	Pegion pea (*Cajanus cajan*) genotypes and maize	Dasbak *et al*. (2012); Poveda *et al*. (2008)
Field margin with substitutional resource	Depends on the degree to which the alternative resource is complementary or substitutional for the prey. This may limit pest control in the field	Adult lacewing and aphids	Robinson *et al*. (2002)
Improved margin (sown species-rich margin	Improved (undisturbed) field margin may provide favourable habitats for survival and reproduction of some pests	Slugs	Eggenschwiler *et al*. (2013)
The quality of field margin plants	The quality of plant resource mediates positive or negative effects to pest suppression within the crop land	Big-eyed bug (*Geocoris punctipes*) and pea aphids	Eubanks and Denno (2000)

Therefore, the relative importance of field margin vegetation and other non-crop features around agricultural lands may vary dramatically due to several factors as outlined in Table 2. It is further reported by Karp *et al*. (2018) that there are inconsistent responses of natural enemies and insect pests to the surrounding landscape composition, hence the need to understand when habitat management represent the win-win situation.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study Sites

The study sites were located across three agricultural zones in the Kilimanjaro region of northern Tanzania within the Moshi rural district (Illustration 1). The three zones were classified based on the elevation in order to understand the effect of elevation to the abundance and diversity of the insects and for wider application in the tropical areas where zonation do exists (Bussmann, 2006; Seo *et al*., 2008). The three elevation zones also differed in terms of land use management and farming practices (Soini, 2005), which may consequently influence the abundance, diversity and biological control activity of the natural enemies. The low zone was between 800 to 1000 m asl, the mid zone was between 1000 to 1500 m asl and the high zone was between 1500 to 1800 m asl. The maximum and minimum temperature from the data collected using climate loggers for the low zone was 13.5 °C and 46.5 °C, mid zone was 12.5 °C and 46.5 °C and high zone was 7.5 °C and 37.5 °C, respectively. The maximum temperatures include the temperature when the loggers were exposed to sun as they were left in the field throughout the year. The high zone receives more rainfall compared with the mid and low zones, and as a result, there is only one bean cropping season during the short rains (July to October) in the high zone unlike in the low and mid zones where farmers can have two bean cropping seasons during short (July to October) and long rains (March to June). In the high zone, the study site comprised Mbahe village (3.23 ^{o}S, 37.50 ^{o}E) which is located in the Marangu Mangharibi ward. The mid zone involved farmers from Mieresini village (3.33 ^{o}S, 37.53 ^{o}E) whereas the low zone involved Kilimo Makuyuni village (3.40 ^{o}S, 37.55 ^{o}E) farmers. The major crops cultivated in the selected villages are maize and beans in small scale subsistence farming systems. All the sites were smallholder farmers' common bean (*Phaseolus vulgaris*) fields and the assessments were done under their normal farming practices but without pesticide application.

In addition to the field sites, on station predation experiment and rearing of aphid parasitoids was conducted in the green house at Nelson Mandela Africa Institution of Science and Technology, Arusha, Tanzania

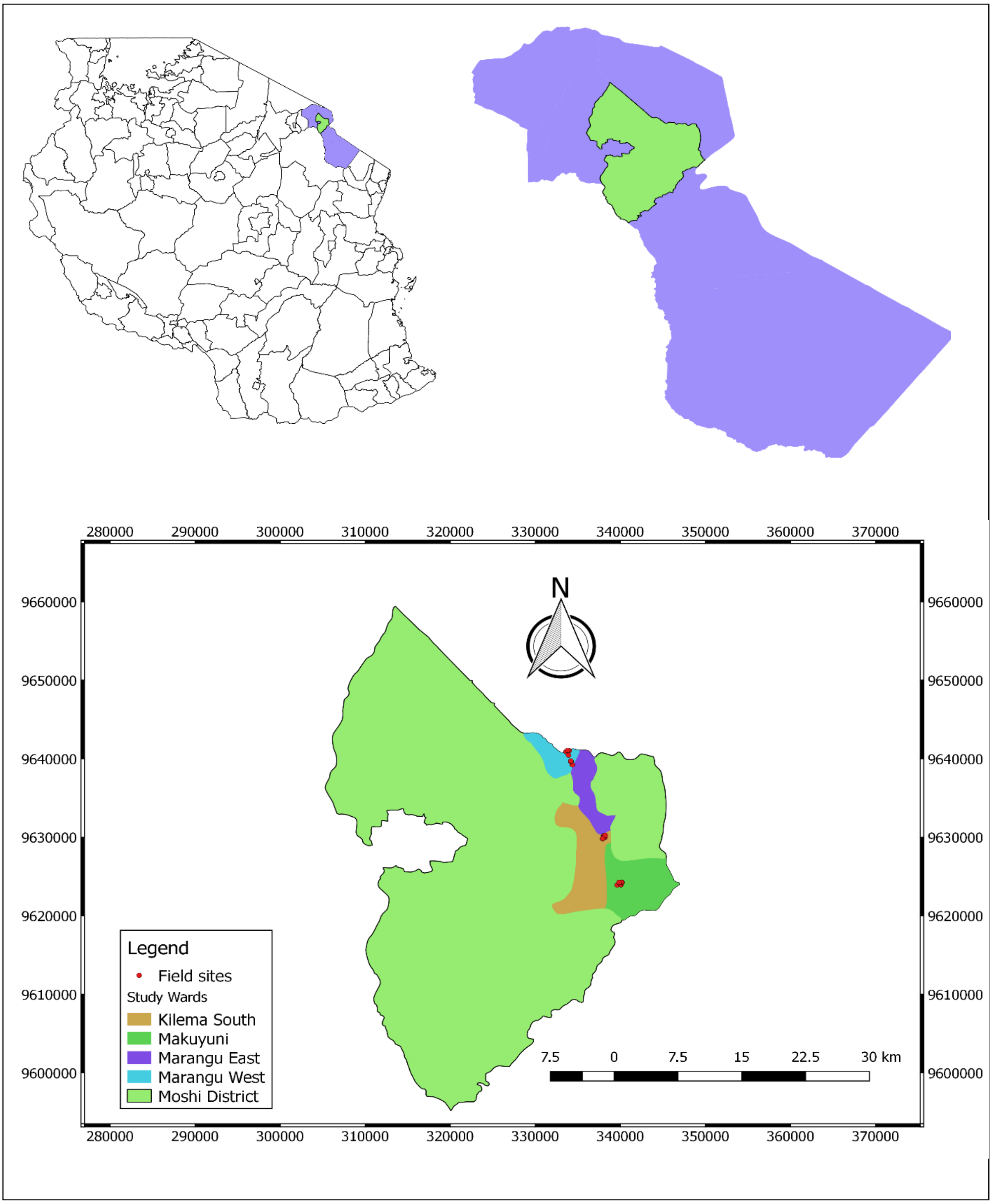

Illustration 1: A map of Moshi rural district in Kilimanjaro region, Tanzania showing the study sites located in the three elevation zones

3.2 Sampling Design

Farmers growing beans (*P. vilgaris*) in the three zones were identified with the help of agricultural extension officers and a cluster sampling was performed to identify 100 participating farmers in each zone.

Field survey and experiments involved eight bean fields in each zone, one major site (involved intensive data collection) and seven minor sites (involved less intensive data collection). The sampling design was purposeful based on the field size and the presense of field margin vegetation. Surveys involved assessment of the natural enemy and insect pest abundances along the field margin and within the focal bean field together with margin vegetation composition in all sites of each zone. The distribution of the natural enemies and insect pests at different distances within the bean field was determined for major sites. Field experiments on biological control involved five of the eight sites in each zone and the fluorescent dye experiment to monitor the movement of insects was done on three of the sites in each zone in order to allow for effective and timely sampling of the insects.

3.3 Social Survey Data Collection

The instruments used for data collection were questionnaires and the Interactive voice response (IVR) previously known as Voto mobile platform (https://go.votomobile.org/). Farmers were interviewed using structured questionnaires with both closed- and open-ended questions. The researcher made use of enumerators who were trained for two days at NM-AIST on data collection techniques followed by a pilot study at Nambala village inorder to assess their capability as well as the validity of the questionnaires.

Farmers' knowledge about natural enemies and insect pests was assessed by provision of pictures of an adult individual insect of the following functional groups; Hoverfly (Diptera: Syrphidae – using *Episyrphus* sp), Lady beetle (Coleoptera: Coccinellidae – using lunate ladybird *Cheilomenes lunata*) and Long legged fly (Diptera: Dolichopodidae – using *Condylostylus* sp.) as natural enemies and Aphids (Hemiptera: Aphididae – using *Aphis* sp.), Blister beetle (Coleoptera: Meloidae – using *Mylabris phalerata*), and caterpillar (Lepidoptera: Crambidae - using *Maruca vitrata*) as insect pests, presented as A4 printouts of high resolution photographs, accompanied by a silhouette image indicating actual size. Farmers were asked to state whether they have seen such insects in their fields, the name of the insects (in their local language), and their importance in agriculture.

The IVR system involved recording the questions in the local language of the region (Kiswahili) and uploading the recordings in to the system. Pre-trials and training for the IVR system was done through farmer meetings in all zones where farmers were directed on how the voice-response system worked. A sample of 135 (45%) farmers who attended the meeting were involved in the actual IVR survey. The survey comprised a subset of questions that were carried out during the face to face interview which focused on insects (both beneficial and pests) observed in their field, pest control technique employed and information accessibility. The farmers proposed a day and time at which the calls would be made automatically every week throughout the bean cropping season (July to September, 2016). Farmers were asked to inspect their fields every week before the calling day in order to be able to respond to the questions, especially about insect abundance. The farmers' responses were recorded directly into the IVR mobile system as they were talking through the phones or by pressing buttons on phone keypads as instructed. The recorded information was then translated into English language before analysis.

Pre training survey suggested a need to train the farmers on the major insect species that occurred in bean fields and their agricultural relevance. Several insect species (pictures and live insects) including those which were shown during the pre-training survey were used in the training. The training aimed at increasing the farmers' knowledge and awareness about natural enemies, insect pests and pesticide use, as well as about good farming practices that will enhance the survival of beneficial insects while reducing the insect pests in their farms. Four months after the training, farmers were assessed on their knowledge change about insect identification using the same insect species that were shown during the baseline survey. They were also assessed on their interest to different types of pesticides.

3.4 Natural Enemies and Insect Pests Data Collection

Sampling for insect abundance and diversity was done using clusters of three coloured pan traps (blue/white/yellow UV paint). Ten traps were used in major sites, five traps equidistant along a 50 m transect in the field margin and the other five equidistant along a 50 m transect perpendicular to the field margin into the bean crop. For the minor sites, only two traps were used, one at the centre of the field margin and another within the bean field. Each pan contained 300 ml of water with a drop of detergent to reduce surface tension and prevent trapped insects from escaping. The abundance and diversity of insects was surveyed four times per season for major sites (seedling, flowering, podding and post-harvest stages) and three times per season for minor sites (flowering, podding and post-harvest stages). Trapped insects were collected two times, after 24 and 48 hours for major sites and after 24 hours for minor sites, by keeping them in labelled vials containing 70% ethanol for identification. The natural enemies and insect pests were sorted and identified to family or species level after each stage (seedling, flowering, podding and post harvest) of data collection at Tropical Pesticide Research Institute (TPRI), Arusha.

3.5 Fluorescent Dye Experiment to Monitor the Movement of the Natural Enemies and Insect Pests from the Margin Plants to the Bean Field

Fluorescent dye spray was used to monitor the movement of insect pests and natural enemies from non-crop vegetation to the bean crop on three sites in each zone, making a total of nine sites. The sites contained native and non-native plants naturally growing along the field margins. The yellow fluorescent pigment was purchased from Spray Shop, Adelaide, Australia (www.sprayshop.com.au). It was prepared as per manufacturer's instruction with 1 L of pigment diluted in 100 L of water. The dye was applied using clean backpack sprayer of 12 L capacity, manufactured by Taizhou Kaifeng Plastic and Steel Co. Ltd China. Spraying was done on to the non-crop vegetation along the field margins of 3 m wide and 50 m long when beans were at 50% flowering. The spraying time was 10 am $\pm$ 1 hr. Sampling of the insects was done after 24 hours using sweep nets for three consecutive days along a 2 m wide and 50m long transect lines. Sampling time was 10 minutes per transect. Samples were collected in the bean field at 0 m, 10 m, 20 m, and 40 m from the field margin as previously described by Perović *et al*. (2010), except in high zone where it ended at 20 m only because of the smaller size of the bean fields. The collected insects were immediately kept in separate tubes containing cotton wool with ethanol to make the insects inactive and reduce the chances of contaminating each other. They were then kept in a fridge at 4 °C for later identification. Sampled insects were inspected for traces of fluorescent dye under UV light in a dark room. The insects were considered marked if a drop pattern of the dye was observed on any part of the body reflecting the original application but the insects with small scattered flecks were considered contaminated during sampling and thus were disregarded.

3.6 On station Predation Experiment

Predation rates by adult lady beetle (Coleoptera: Coccinelidae: *Cheilomenes lunata*) was determined using potted bean plant infested with aphids (*Aphis fabae*) as a sentinel host.

Lady beetle was chosen because it is the most abundant predator in the field. A single adult *C. lunata* was assigned to each of the four potted bean plant with different aphid density (25, 50, 100 and 200) of mixed instar nymphs placed in cages for 48 hours. Each aphid density was replicated five times. Aphids were counted after 2, 4, 8, 12, 24 and 48 hours in each treatment and the number of aphids remained at each time interval was recorded.

3.7 Field Predation Experiment

Field predation was assessed using 45 potted bean plants, each infested with 60 ± 10 *A. fabae* as sentinel hosts. On station predation experiment was used as a base in the assessment of field predation. The potted bean plants were placed into 5 bean fields in each zone, one at the field centre, one near the field margin and one control (caged to prevent entry of natural enemies) placed randomly within the bean field making a total of 3 potted plants per field and 15 potted plants per zone. This resulted in exposure of the sentinel plants to the natural enemies present in each part of the field. The sentinel aphids were exposed for two days during the bean flowering period. Assessment of predation rate was done by counting the number of aphids before and after 2 days' exposure. The removal of aphids in the caged sentinels was used to partition mortality caused by factors other than predation.

3.8 Field Parasitism Experiment

Parasitism levels were assessed using a different set of potted bean plants to those in 2.4, again infested with 60 ± 10 aphids, which were reared in green house inside cages to prevent them from experiencing any parasitism before field exposure. This was followed by controlled field exposure under caged and open conditions in same fields used for the predation experiment. A total of 20 potted bean plants were exposed in each zone, in five bean fields, four potted bean plant per field where two plants (caged and uncaged) were placed near the field margin and other two at the field centre for 2 days. The cages were made of a coarse mesh (1 mm) which allowed the entry of parasitoids while preventing the entry of predators. After field exposure, the potted bean plants were all placed in individual cages measuring 30 x 30 x 60 cm (L x W x H) size with a fine mesh which were placed in the green house. Parasitoids emerged after 12 to 14 days and were collected using an aspirator and preserved in 98% ethanol for later identification.

3.9 Identification of Aphid Parasitoids

Identification of the parasitoids was done at Tropical Pesticide Research Institute (TPRI) Arusha, Tanzania based on morphological features where the identification was 90% possible to genus level. Further identification at molecular level was done at Greenwich University laboratory, UK where the identification was done to species level. DNA was extracted using the non-destructive method as described by Mitrović and Tomanović (2018), followed by chelex method. Amplification of a partial fragment of the mitochondrial cytochrome oxidase 1 gene was performed using either the LepF1 and C_ANTMRID primers, or the MLepF1 and LepR1 primers when amplification with the first primer pair was unsuccessful (Table 3). The 20 µl PCR reaction mix contained 10 µl RedTaq ReadyMix (Sigma), 7 µl sterile molecular-grade water, 1 µl forward primer, 1 µl reverse primer and 1 µl DNA. PCR conditions are described in Table 3 and the reaction was performed in a 2720 Thermal Cycler (Applied Biosystems). PCR products were visualized using electrophoresis on 1.2% agarose gels in 0.5 x TBE buffer stained with GelRed (Biotium). PCR products were purified using a GeneJET PCR Purification Kit following manufacturer's instructions and sequenced by GATC Biotech using the forward primer (5 µM) for each gene. The sequences obtained were trimmed to give 'mini-barcodes' of 285 bp when amplified with LepF1/C_ANTMRID primers and 192 bp when amplified with MLepF1/LepR1 primers for phylogenetic analysis. These were compared to sequences in the National Center for Biotechnology Information database (Sayers *et al*., 2019) using the Basic local alignment search tool (Altshhul *et al*., 1990).

Table 3: Primers used for sequencing of parasitoid wasps

Primer	Sequence (5'-3')	PCR conditions	Reference
C_ANTMRID (cocktail primer)	RonIIdeg_R-GGRGGRTARAYAGTTCATCCWGTWCC AMR1deg_R- CAWCCWGTWCCKRMNCCWKCAT	2 min 94 °C, 5 cycles (40s 94 °C, 40s 45 °C, 1 min 72 °C), 36 cycles (40s 94 °C, 40s 51 °C, 1 min 72 °C), 5 min 72 °C	Smith *et al.* (2015)
LepF1	ATTCAACCAATCATAAAGATATTGG		
MLepF1	GCTTTCCCACGAATAAATAATA	1 min 94 °C, 5 cycles (30s 94 °C, 40s 45 °C, 1 min 72 °C), 35 cycles (30s 94 °C, 40s 51 °C, 1 min 72 °C), 5 min 72 °C	Smith *et al.* (2008)
LepR1	TAAACTTCTGGATGTCCAAAAAATCA		

3.10 Field Margin Plants Composition Assessment

Vegetation assessment involved a transect approach surveying plant species in 1m x 1m quadrats (Illustration 2) along the field margin. The transects were 50 m long for major sites and at each 10 m, two quadrats of 1m x 1m were measured, one before the 10 m mark, and one after, making a total of 10 quadrats per margin. In the minor sites, two quadrats at the centre of the field margin were measured. The plant species present in each quadrat were identified and the % coverage was recorded. A walk along margin transect was also done to record any plant species missed in quadrats. The plant species which were difficult to identify in the field were collected for herbarium preparation and thereafter they were sent to TPRI and Royal Botanic Gardens, Kew, for identification.

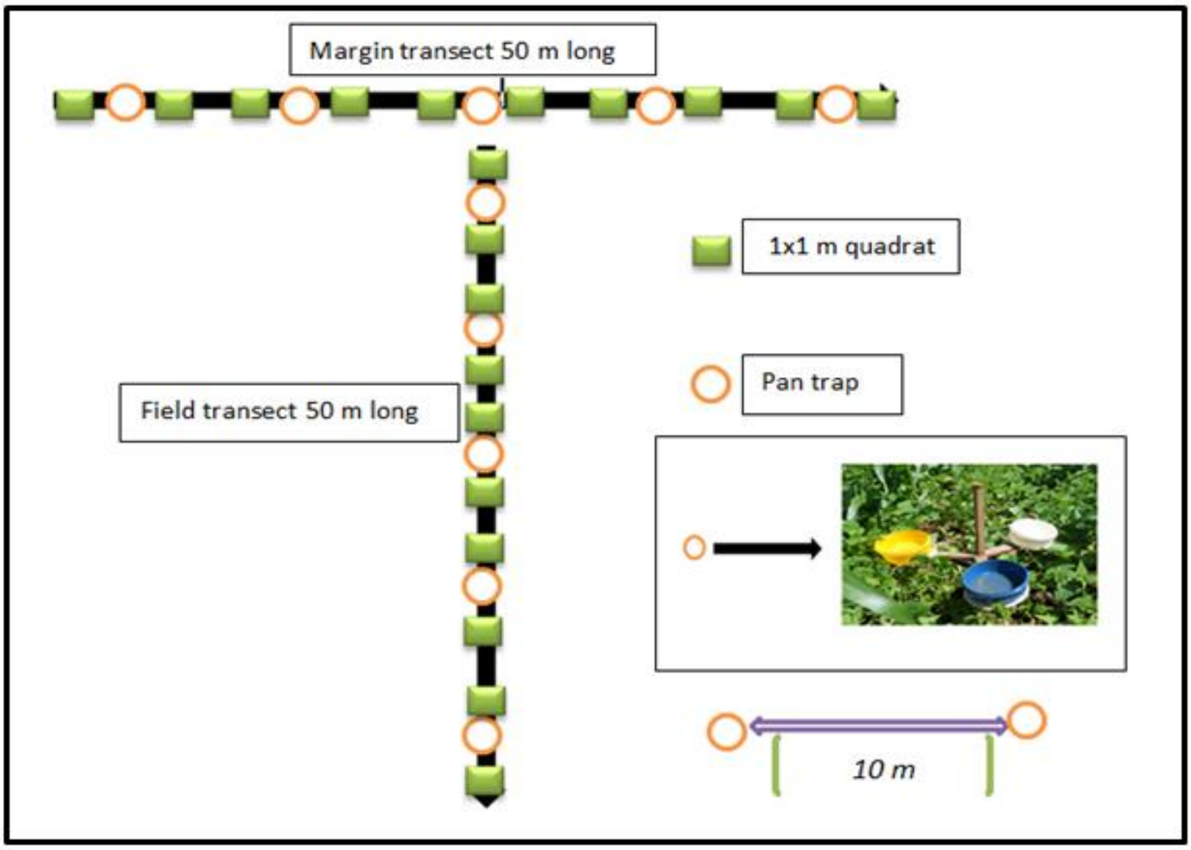

Illustration 2: Schematic diagram to illustrate the sampling design in the major sites

Weather parameters such as temperature and humidity were recorded for one year to characterize the zones. Six climate loggers were set in two fields per zone, one major site and one minor site to record temperature and humidity of the area from March 2017 to February 2018.

3.11 Assessment of the Most Preferred Margin Plants by the Natural Enemies Around the Bean Fields in the Three Elevation Zones

Assessment of the specific interaction between the field margin plants and the natural enemies was done through a standardized survey walk along the field margin with constant observation of any natural enemies found on plants within 1m of the researcher. The assessment was done for three hours, from 9.00 am to 12.00 noon, when the insects were more active. Both the natural enemy and the plant species found interacting were recorded. The standardized walks were done at similar frequency as the sampling of the insects and margin vegetation assessment in all eight sites of each zone. The observed natural enemies were counted together as either visiting or feeding the plant or resting on it and it was not necessarily for the natural enemy to be on the flower part.

3.12 Data Analysis

Statistical data analysis was conducted using the R program (R Core Team, 2017), version 3.5.1. Farmers' knowledge about natural enemies, insect pests and pesticide use was assessed at the level of their education, age, sex and between the three zones. Kruskal-Wallis test (Sheskin, 2011) (at $p \leq 0.05$ for statistical significance; denoting the test statistic by K-W and the degrees of freedom by df) was used to compare the significant difference among various variables. Pairwise Wilcoxon rank sum test was used to assess pairwise comparisons between variables with corrections for multiple testing.

The overall field insect survey data set was grouped into different categories for testing of different variables according to the sampling design involved. First, data from the minor sites were used to assess the effect of margin vs field and field size on natural enemy and pest abundance. Second, data from the major sites were used to test the effect of distance from the margin (10 m to 50 m) and sampling stages (seedling, flowering, podding and post-harvest) on arthropod abundances. As a supplement to this, the effect of pan colour (blue, white and yellow) on catches was assessed using data from both major and minor sites. Third, data collected in the second season of both years were used to test the effect of elevation on arthropod numbers. The dye experiment data was used to assess the movement of natural enemies and pests from the field margin plants to field crops at different distances. Biological control activity of the natural enemies was assessed from predation and parasitism data

The insect survey data were analyzed by generalized linear model with negative binomial for describing the interactions and associations of different categorical variables using MASS package (Venables & Ripley, 2002) and glm () function in R. The model selection based on its application to count data that are not normally distributed. Different variables and their interactions (zone + transect_name + field_size + pan_colour + year + season + pan_colour*zone + season*zone + transect_name*season + site_name|1) including site identity as a random factor were included. The non-significant terms and their interactions were dropped stepwise by comparing the models through likelihood ratio test (LRT) until the final model was obtained. Analysis of variance (ANOVA) was used to test the significant difference of the different variables to the abundance and distribution of insects in the field Data from the dye experiment were analyzed by a generalized linear regression model with Gaussian family. The model was used to test for the significance of distance from margin, elevation zone, farm size and time from dye application on the proportion of captured natural enemies and insect pests that were marked. The same model was also applied in predation and parasitism experiments. Analysis of variance was used to test the statistical significance of the different variables in the model. Tukey - HSD post hoc test was used to check where the significant difference occurred in different parameters by pairwise comparison.

The diversity of the natural enemies, insect pests and margin plants was determined using Shannon Wiener Diversity Index which takes into account both richness and evenness.

$$H' = -\sum_{i=1}^{R} p_i \ln p_i$$

Where H' = Shannon Diversity index, Pi = Proportion of species i relative to the total number or % cover of species, ln = Natural logarithm.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Results

4.1.1 Demographic Characteristics of the Smallholder Farmers

Farmers involved in the study were 39.3% (118) male and 60.7% (182) female (Table 4), reflecting the significantly greater number of women compared with men are involved in the agriculture sector in Tanzania. However, male participation in crop production was significantly different in the three elevation zones (K-W= 24.75, df = 2, $p < 0.001$) with the percent increasing from the low zone (20%) to the mid zone (45%) and to the high zone (53%). There was also a significant difference among the farmers in terms of age and gender (K-W= 10.74, df = 1, p = 0.001). The participation of female farmers within age groups: 18 to 35 years, 36 to 45 years and above 45 years was 35.7%, 34.1% and 30.2%, respectively, showing a slight decrease in farming with increasing age but broadly speaking the farmers surveyed were evenly representative of age groups. However, the same age groups for males were 23.7%, 26.3% and 50%, respectively, suggesting decreasing numbers of younger males participating in agriculture.

There was a significant difference in education level across the three elevation zones (K-W= 9.93, df = 3, p = 0.019), where farmers with incomplete primary education were more abundant in the low zone (10%), followed by the high zone (4%) and only 2% in the mid zone. Only three farmers had attained further vocational education, all from the mid elevation zone (Table 4). Overall, significant differences in farmers' age and education was apparent (K-W = 17.56, df = 3, p = 0.001). No farmers between ages 18 to 35 had an incomplete primary education in all the three zones, while there was a single farmer with incomplete primary education between ages 36 to 45 and 6 farmers at the age of above 45 years, suggesting the dropout from primary school has reduced in recent years. There was no significant gender difference (K-W= 2.19, df = 3, p = 0.533) in terms of education. The major economic activity recorded was farming, with 100% in low zone and 95% in mid and high zones. Other business activities included shoe making, tailoring and carpentry.

Table 4: Demographic characteristics of the farmers from the three elevation zones in Northern Tanzania

Zone	Farmer age	Sex		Education							
		Male	Female	IP		P		S		VETA	
		M	F	M	F	M	F	M	F	M	F
Low zone	18 - 35	5	21	0	0	3	16	2	5	0	0
	36 - 45	5	26	0	1	4	23	1	2	0	0
	Above 45	10	33	3	6	7	27	0	0	0	0
Mid zone	18 - 35	10	24	0	0	8	20	2	3	0	1
	36 - 45	15	20	0	1	14	18	1	1	0	0
	Above 45	20	11	1	0	12	10	6	0	1	1
High zone	18 - 35	13	20	0	0	13	18	0	2	0	0
	36 - 45	11	16	1	0	9	16	1	0	0	0
	Above 45	29	11	2	1	26	10	1	0	0	0
Total		118	182	7	9	96	158	14	13	1	2
% total		39.3	60.7	2.3	3.0	32.0	52.7	4.7	4.3	0.3	0.7

Key: IP = Incomplete primary; P = Primary; S = Secondary; VETA = Vocational Educational and Training Authority

4.1.2 Participation of Farmers in the IVR Mobile System Throughout the Season

The results from IVR survey showed that on average 70.4% of farmers responded to the call each week (Table 5). More farmers from the low zone were recruited compared with the mid and high zones depending on their attendance to the trial meeting and willingness to participate in the survey. Although a good number of farmers participated each week, the number of respondents to the different questions varied, where closed questions (which farmers were choosing from given options) were more often responded than open ended questions (which farmers were supposed to answer from their experience or after field observation). Among the two methodologies (face to face interview vs. IVR system) of data collection used in this study, face to face interview was the most useful as the majority of farmers in the IVR survey did not respond to all questions, whilst some farmers did not answer calls as had been agreed.

Table 5: Participation of farmers to IVR survey throughout the bean cropping season in northern Tanzania

Time	**Week 1**	**Week 2**	**Week 3**	**Week 4**	**Week 5**	**Week 6**	**Week 7**	**Week 8**	**Week 9**	**Week 10**
No. of farmers	91	93	94	102	97	106	94	90	90	92
% of farmers	67.4	68.9	69.9	75.5	71.8	78.6	69.6	66.7	66.7	68.1

4.1.3 Farmer Awareness of Natural Enemies and Their Insect Pests Before Training

The survey revealed that 98.7% of respondents at the baseline survey were unaware of the existence of natural enemies of pests (K-W = 0.25, df = 1, p-value = 0.615). The majority of farmers were not able to distinguish natural enemies from insect pests, even lady beetles, hoverflies and long legged flies (Fig. 1) despite these natural enemies being abundant in their fields (personal observation). Most farmers did not recognize the insects at all and returned a "don't know" response, or else provided an incorrect identification. Many farmers were confused between the lady beetle (the adults and larvae of which predate upon aphids) and *Ootheca* spp. (Coleoptera: Chrysomelidae) (a folivore) considering both to be pests. Farmers did not differ in their identification expertise between the three elevation zones for lady beetles (K-W= 2.53, df = 2, p = 0.282), long logged fly (K-W = 0.80, df = 2, p = 0.671) and hoverfly (K-W= 2.57, df = 2, p = 0.277). Similarly, farmers' education level had no significant influence in the identification of lady beetles (K-W= 4.14, df = 2, p = 0.126), long legged fly (K-W = 0.57, df = 2, p = 0.754) and hoverfly (K-W= 0.07, df = 2, p = 0.967). From the Voto mobile phone survey, only 3% of farmers were able to mention the lady beetle as being a beneficial insect.

The pre training results showed that the farmers in the three zones were more aware of insect pests than of natural enemies. When shown insect pests in pictures, 53.3% of the farmers were able to identify aphids (*Aphis* spp.), 37.7% caterpillars (including *Maruca* and *Helicoverpa* spp.) and 11.3% blister beetles (Mylabris oculata) (Fig. 2).

Awareness of the insect pests (aphids, caterpillar and blister beetle) differed between zones (K-W, aphid: X2 = 32.22, df = 2, $p < 0.001$; caterpillar: K-W = 4.24, df = 2, p = 0.120, ns; blister beetle: K-W = 19.55, df = 2, $p < 0.001$), with farmers in the high zone recognising aphids most accurately, and farmers in the low zone being least accurate, while farmers in the mid zone were most accurate at recognising blister beetles, followed by high zone farmers; again, low zone farmers were least accurate (Fig. 2). The education level of the farmers had no significant difference in the identification of aphid (K-W = 3.29, df = 2, p = 0.193), caterpillar (K-W = 3.05, df = 2, p = 0.218) or blister beetle (K-W = 4.43, df = 2, p = 0.109).

4.1.4 Farmer Awareness of Natural Enemies and Their Insect Pests After Training

There was a significant increase in farmer awareness of natural enemies from 1.3% during the baseline survey to 80% after the training, signifying the need of education to the farmers for improving their day to day farming practices. Farmers were able to identify the same insect species (both natural enemies and insect pests given during the baseline survey (Fig. 1 and 2). There was no significant difference in the identification of ladybird beetles between the zones (K-W = 3.26, df = 2, p = 0.196), but only for hoverfly (K-W = 20.78, df = 2, $p < 0.001$) and long legged fly (K-W = 18.92, df = 2, $p < 0.001$), where more farmers from the mid zone were able to identify both insects compared with the other two zones (Fig. 1). Similarly, there was no significant difference in the identification of aphids between the zones (K-W = 2.23, df = 2, p = 0.328), but only for caterpillar (K-W = 14.12, df = 2, $p < 0.001$ and blister beetle (K-W = 22.76, df = 2, $p < 0.001$) where more farmers from the mid zone correctly identified caterpillar and blister beetle compared with the other zones (Fig. 2).

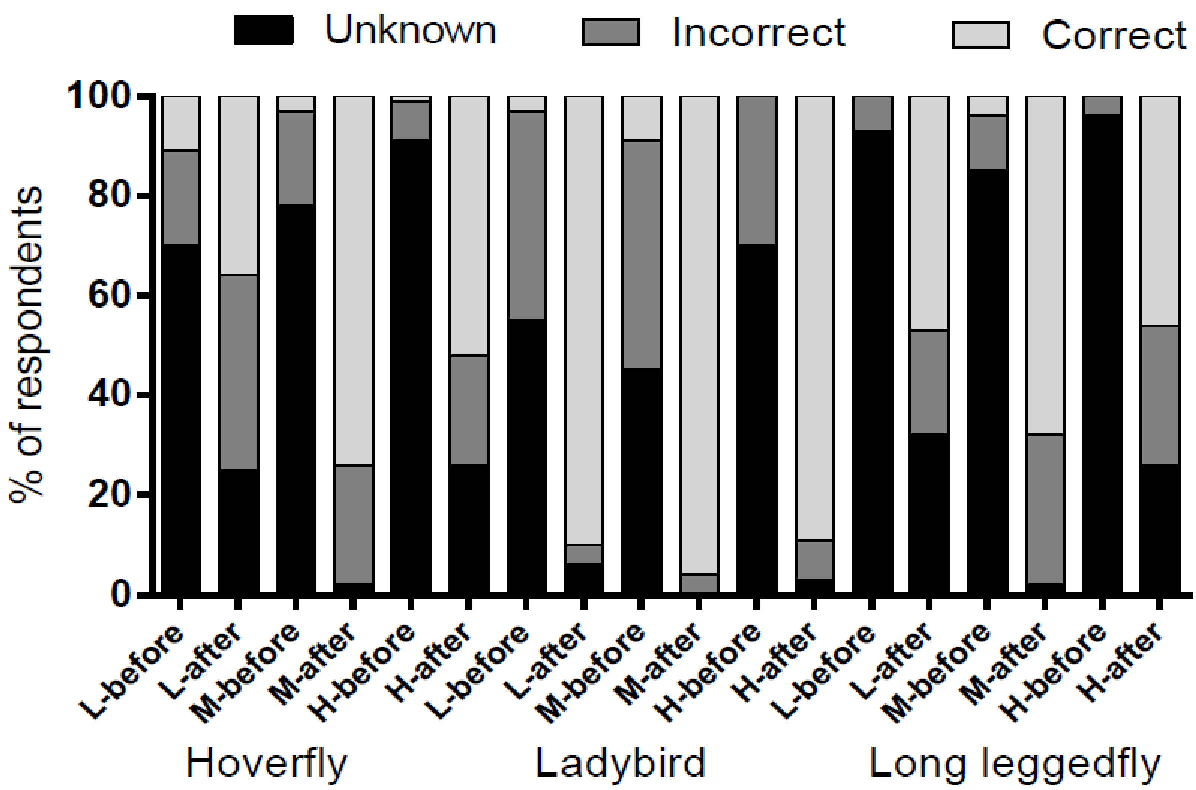

Figure 1: Percentage of farmers recognizing and correctly naming natural enemies of insect pests from visual images before and after training in low (L), mid (M) and high (H) elevation zones in northern Tanzania

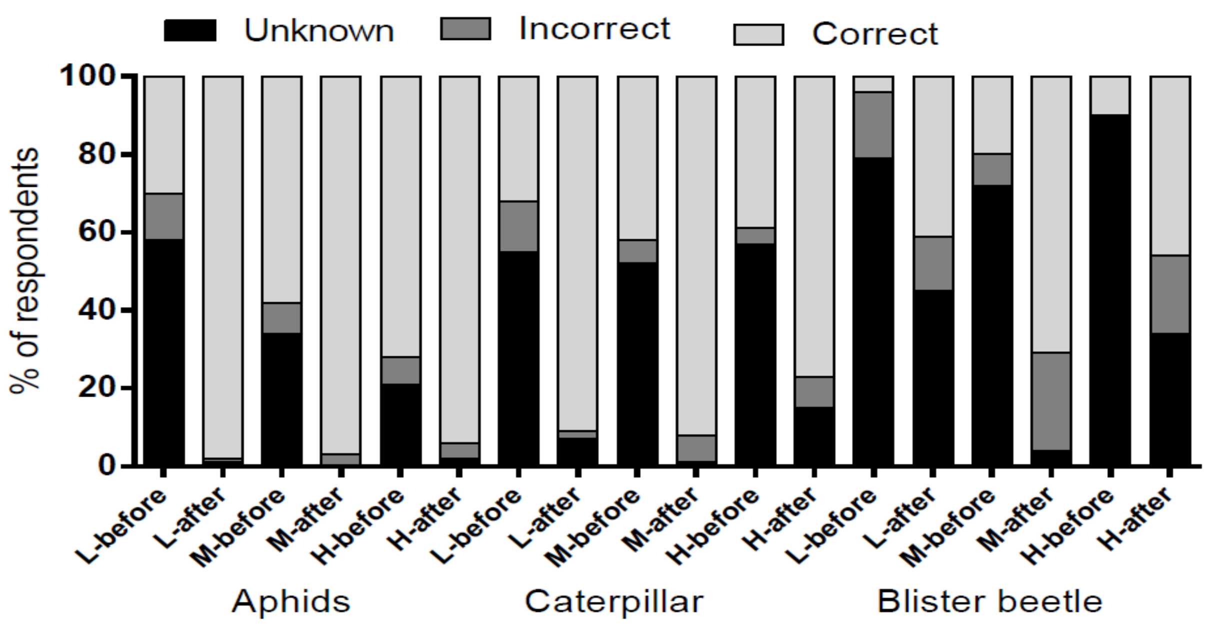

Figure 2: Percentage of farmers recognizing and correctly naming insect pests from visual images before and after training in low (L), mid (M) and high (H) elevation zones in northern Tanzania

Since most farmers were not familiar with natural enemies during the pre-training survey, they were not able to state their economic importance or agricultural relevance. Most of the farmers were unaware of the functions of natural enemies while others identified them as pests (Fig. 3). From the four categories; natural enemy, insect pest, pollinator and unknown, some farmers were able to identify the images of natural enemies as pests of their fields, while others were completely unaware, a few regarded them as pollinators. However, after the training most of the farmers were able to state the relevance of the insects in their field as shown in Fig. 3 and 4. About 30.3% of the farmers in all the three zones were able to state the economic importance of hoverfly as both a natural enemy and a pollinator, whilst 38.7% were able to state either of the two economic importances.

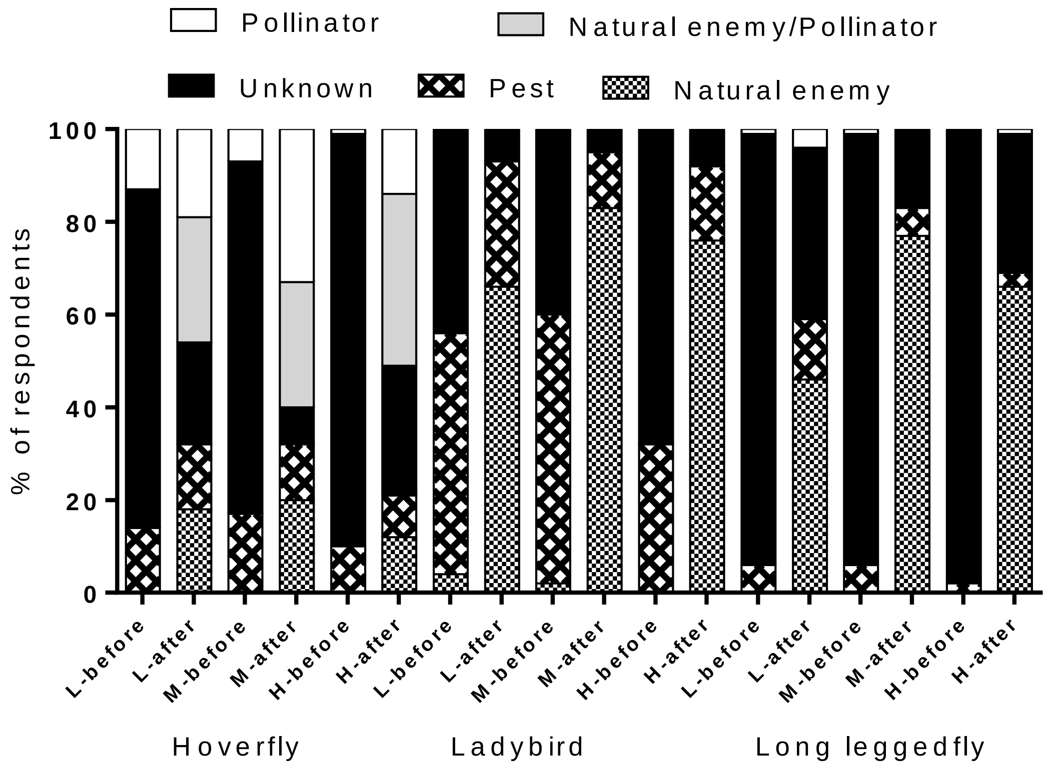

Figure 3: Percentage of the surveyed farmers (before and after training) in low (L), mid (M) and high (H) elevation zones in northern Tanzania who were able to indicate the relevance in agriculture of shown natural enemies

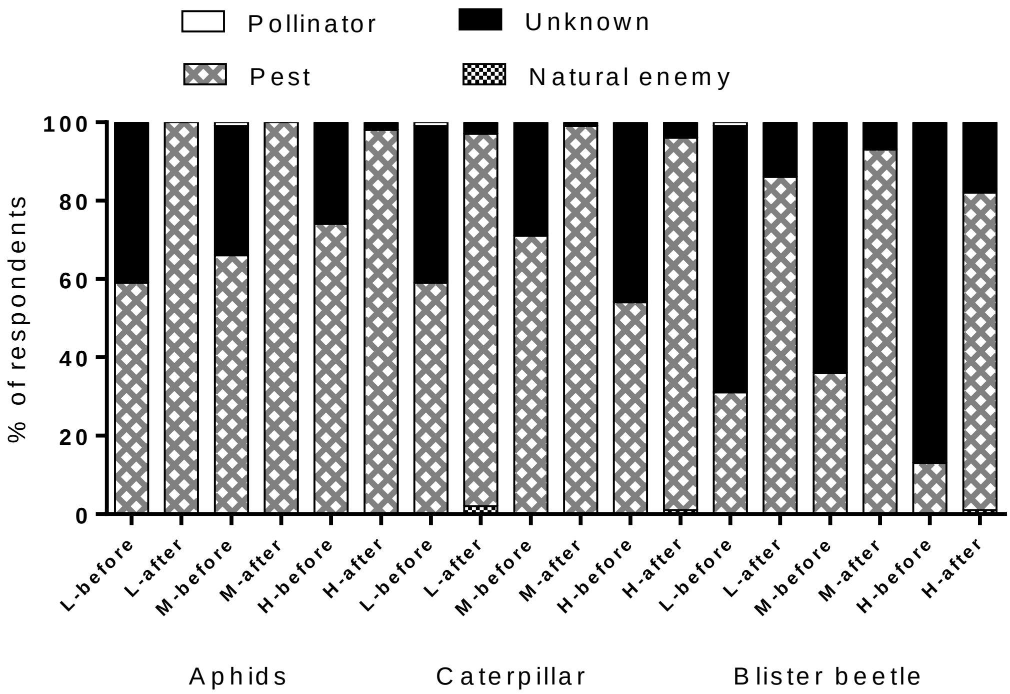

Figure 4: Percentage of the surveyed farmers (before and after training) in low (L), mid (M) and high (H) elevation zones in northern Tanzania who were able to indicate the relevance in agriculture of shown insect pests

4.1.5 Major Insect Pests and Management Practices as Reported by the Farmers

The most damaging insect pests according to 78.3% of farmers were aphids. Other reported insect pests included whitefly (Hemiptera: Aleyrodidae) and bean stem maggot/bean fly (Diptera: Agromyzidae) were not common in all the three zones (Fig. 5). Thrips (Thysanoptera: Thripidae) were not a challenge in the high zone; however, fungal diseases and bruchid beetles (Coleoptera: Chrysomelidae) were mentioned only in the high zone.

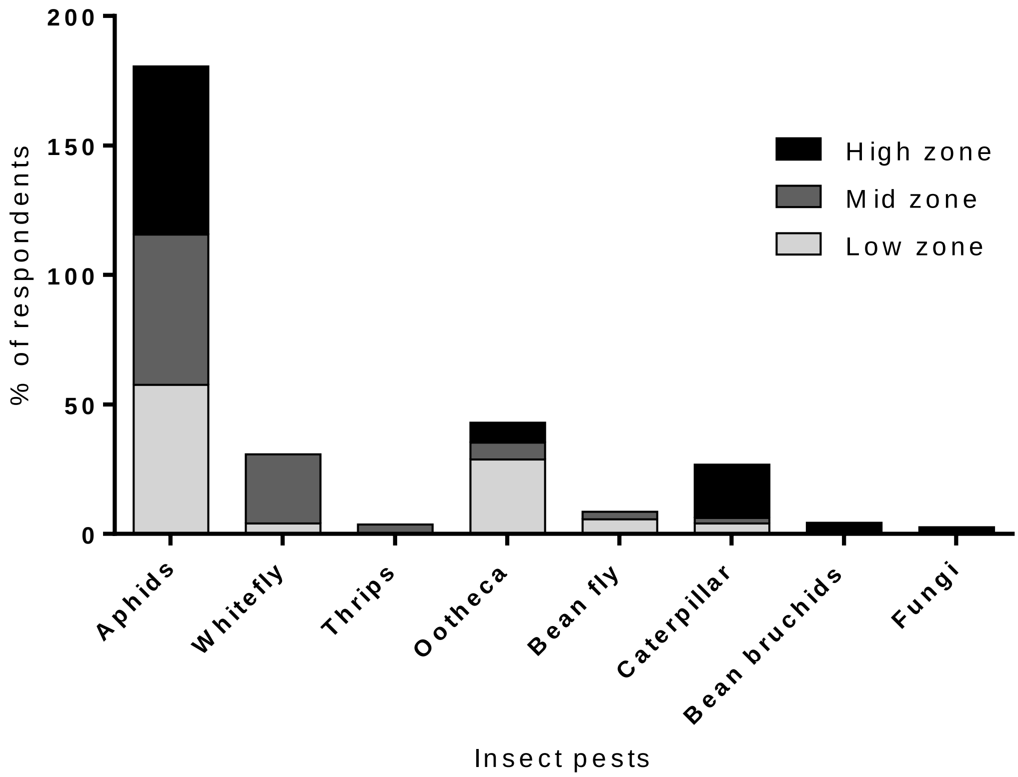

Figure 5: Most damaging insect pests mentioned by the farmers in low, mid and high elevation zones in northern Tanzania

Types of pesticides used by farmers differed between the three elevation zones (K-W = 100.91, df = 2, p = $p < 0.001$). Generally, synthetic pesticides were commonly used when compared with the other pest management techniques (Fig. 6 and 7). The most common pesticide products used by the farmers were Selecron 720EC (Profenofos), Karate 5 EC (Lambda-cyhalothrin-Pyrethroids) and Dursban 24 ULV (Chlorpyrifos). The drop in pesticide use during flowering is because farmers fear to spray the open bean flowers with the idea that the pesticide toxicity will be enclosed in the pod which will later be harmful to their health. Most of the farmers in the high elevation zone (52%) did not use pesticides to manage pests, whereas others (41%) mostly used traditional pesticide materials (non synthetics) such as botanicals, ash, cow dung and urine to manage the insect pests. In the low and mid elevation zones, farmers mostly used synthetic pesticides (86% and 92%, respectively).

Pesticide application frequency also differed significantly (K-W = 76.94, df = 2, $p < 0.001$) among the three zones. On average, the application frequency was more than two times per season for low and mid zone while in the high zone it was less than 1 (Fig. 8).

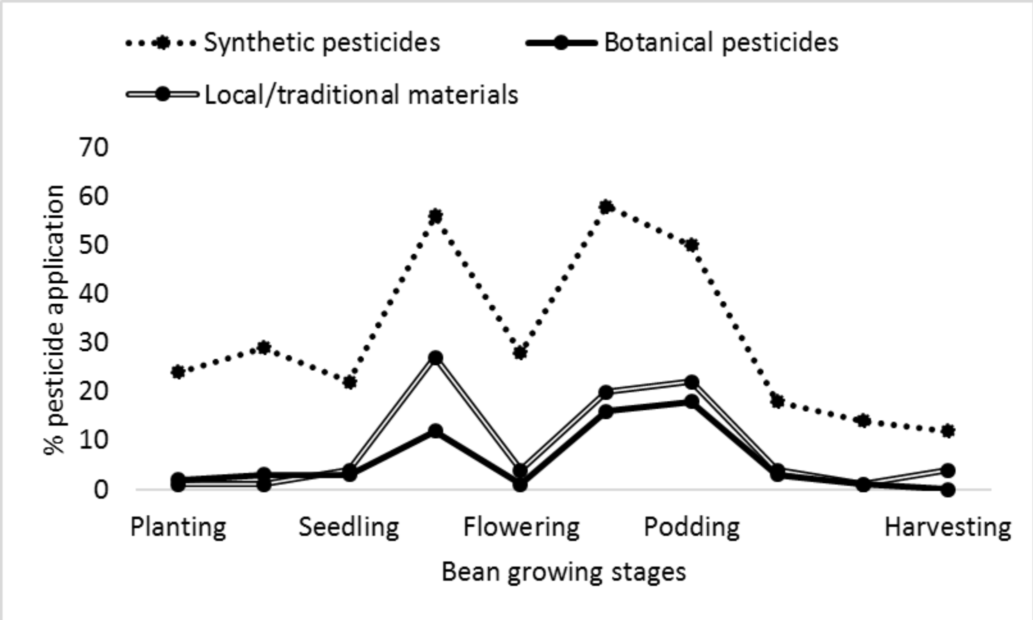

Figure 6: Trends of pesticide application by the farmers during 2016 bean season in northern Tanzania

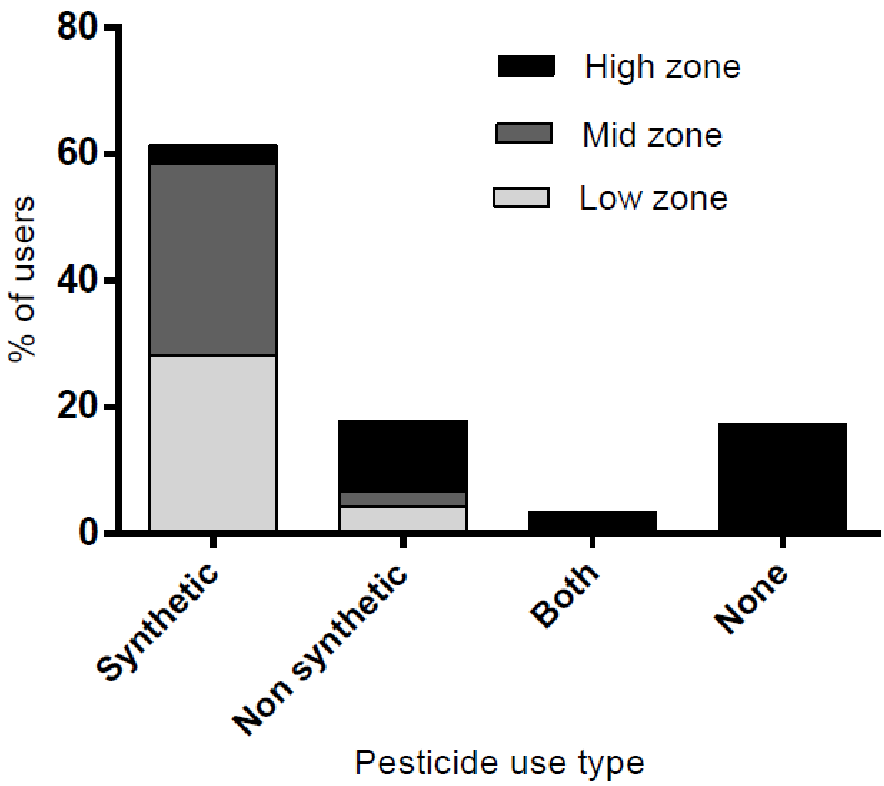

Figure 7: Type of pesticide used by the farmers in bean production for low, mid and high elevation zones in northern Tanzania

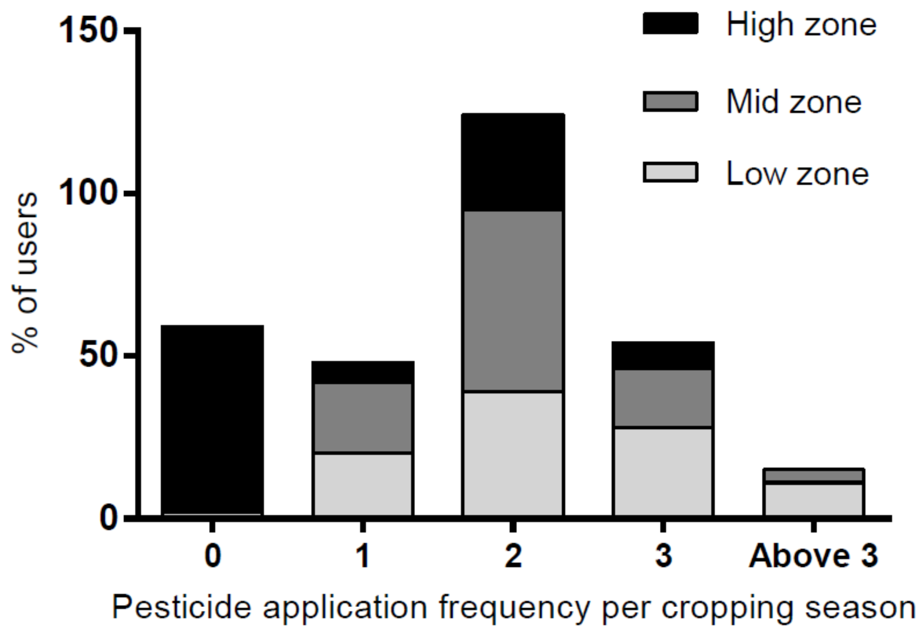

Figure 8: Percent of respondents showing pesticide application frequency for low, mid and high elevation zones in northern Tanzania

4.1.6 Recommended Type of Pesticide to Use by Farmers Before and After Training

Before training, farmers generally reported that they would be inclined to use synthetic pesticides. After the training, most proposed to use non-synthetic approaches such as pesticidal plants to reduce the impact on natural enemies. There was a significant difference in the recommended pesticide to use between the zones before (K-W = 22.68, df = 3, $p < 0.001$) and after the training (K-W = 14.75, df = 5, $p = 0.002$). Many farmers from low and mid zones reported that they would use synthetic pesticides to manage insect pests both before (19.3% and 17.3%, respectively) and after (8% and 4.3%, respectively) the training event, compared with the high zone where only 8.3% before, and 0.3% after being trained reported that they would use synthetic pesticides (Fig. 9). The percent of farmers who were undecided about which approach to use before the training increased after the training in low and mid zones, while it decreased in high zone. This suggests that changing farming practices is a major challenge and must be considered as part of outreach with continuous education, support and motivation.

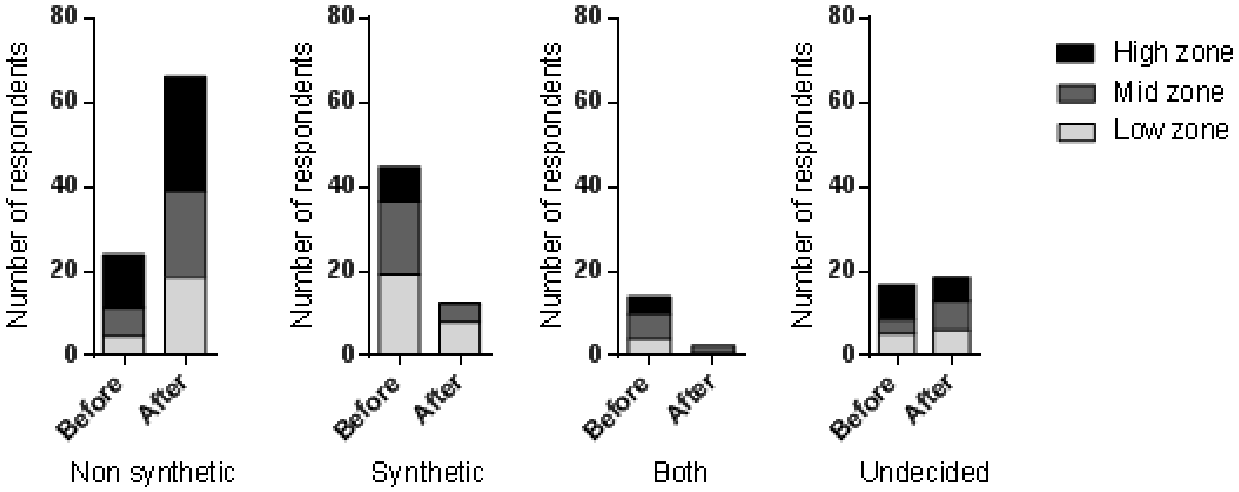

Figure 9: Type of pesticide to use as recommended by farmers before and after the training in low, mid and high elevation zones in northern Tanzania

4.1.7 Reported Disadvantages of Synthetic Pesticide Use by Farmers

Farmers mentioned various disadvantages of using synthetic pesticides, with significantly different responses between elevation zones (K-W = 28.16, df = 6, $p < 0.001$). Health problems, cost of buying pesticides, pest resistance and language problems (as most packaging is in English) were frequently mentioned in mid and low elevation zones. Most of the farmers in the high elevation zone were not using the synthetic pesticides (Fig. 10).

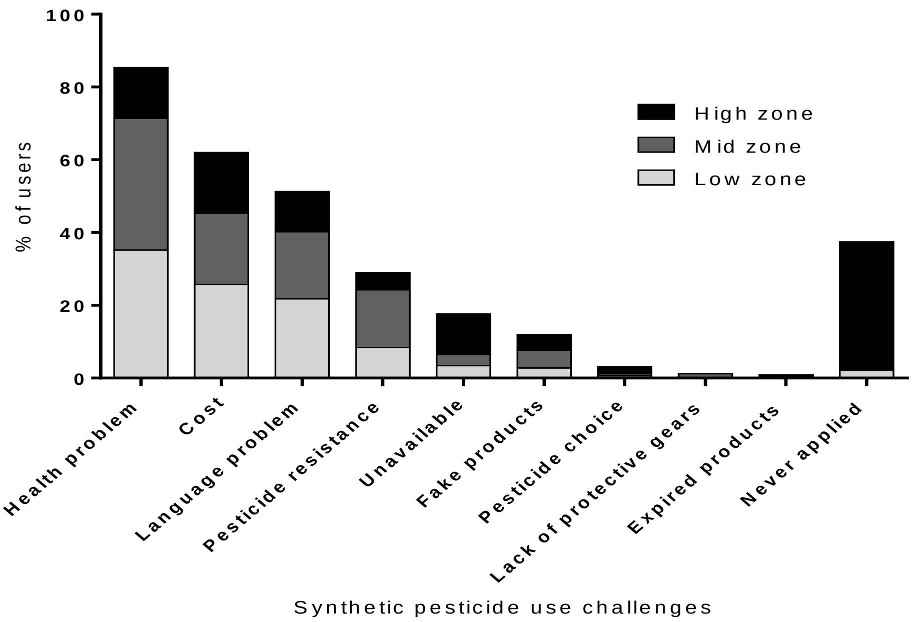

Figure 10: Farmer responses regarding the challenges involved in use of synthetic pesticides in low, mid and high elevation zones in northern Tanzania

4.1.8 Health Problems Associated With the Use of Synthetic Pesticides by the Farmers

About 86.7% of the farmers reported to have experienced health problems due to the use of synthetic pesticides. Frequently mentioned health problems in all the three zones were eye irritation, flu, skin and chest problems and headache (Fig. 11).

Farmers were questioned on the use of personal protective equipment during pesticide application. The results show that despite the health issues reported among the users of synthetic pesticides, the majority of the farmers do not use any protective equipment during pesticide application, with no significant difference between zones (K-W = 0.086863, df = 1, p = 0.7682), age groups (K-W = 2.02, df = 1, p = 0.156) and sex (K-W = 0.15, df = 1, p = 0.695). In the high zone, the majority of the farmers had never applied synthetic pesticides, thus are not using personal protection. Comparison between pesticide use types versus the use of protective gear showed many of the farmers who apply synthetic pesticides were not using any protective equipment (Fig. 12).

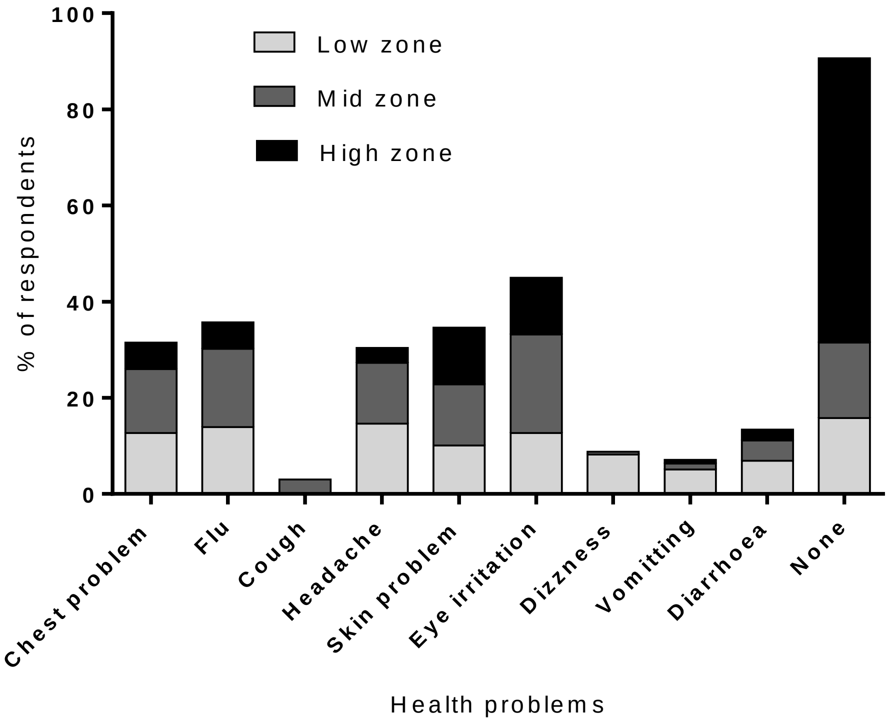

Figure 11: Health problems associated with the use of synthetic pesticides as perceived by farmers in low, mid and high elevation zones in northern Tanzania

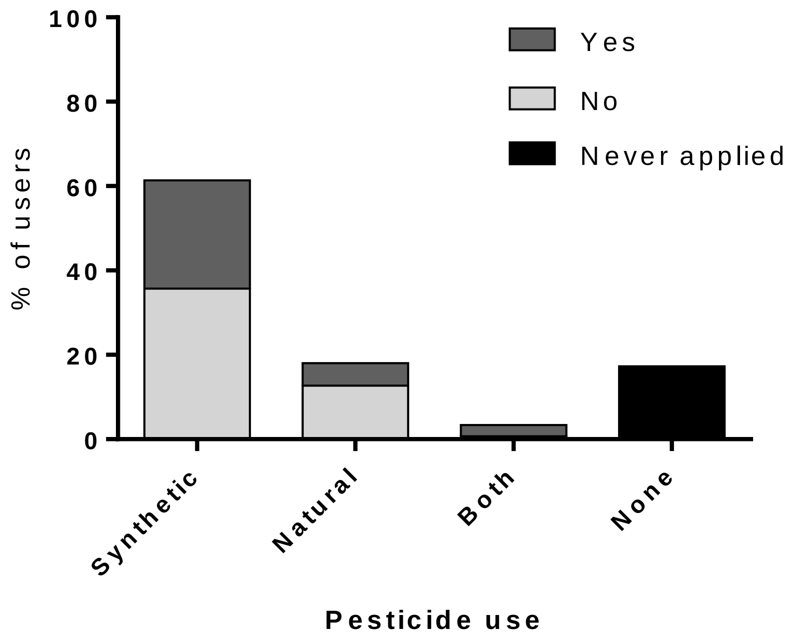

Figure 12: Comparison between the type of pesticide used and use of protective gears in northern Tanzania

4.1.9 Major Information Sources Used to Access Agricultural Information by the Farmers

From the face-to-face surveys, the major resource used by farmers to access agricultural information was stated as agricultural officers (60.4%), researchers (30.5%) and radio (19.5%). Across all zones, 8.7% of farmers had no access to agricultural knowledge and information. Similar findings were obtained from the IVR survey where agricultural officers were ranked first, followed by researchers, then fellow farmers, farmer groups and radio. Pesticide vendors were also mentioned as among the sources of information to farmers because they provided information on the type of pesticide to buy in managing certain infestations when the farmers visit their shops.

For increasing effective communication, 53.0% of farmers proposed more ways of accessing agricultural knowledge and information in addition to those which were currently used (agricultural officers, researchers and radio). The most mentioned additional information sources from the interview were seminars or meetings and mobile phones (Table 6). From the IVR results, the use of mobile phones as an information source was proposed by the majority of farmers compared with other information sources.

Table 6: Other ways to access agricultural knowledge and information as proposed by farmers in northern Tanzania

Proposed information source	(N)	(%)
Seminar/ meeting	54	18.0
Mobile phone	54	18.0
Frequent visits by experts	22	7.3
Fliers	8	2.7
Television	7	2.3
Visiting fellow farmers	7	2.3
Newspapers	6	2.0
Education at primary school level	1	0.3
Total	**159**	**53**

4.1.10 Farmers' Access to Agricultural Training

Farmers were asked if they had attended formal agricultural training and the results show more than 70.0% of farmers in all the three elevation zones had never attended any training related to agriculture. Only 24.0% in the low zone, 26.0% in mid zone and 31.0% in the high zone had attended an agricultural training event. The results showed no significant difference between farmers in the three zones (K-W = 1.68, df = 2, p = 0.432), education level (K-W = 4.73, df = 3, p = 0.193) and between male and female (K-W = 1.19, df = 1, p = 0.28) in their likelihood of having attended a training course. The kinds of training attended by some of the farmers in the study sites were related to organic farming methods, agribusiness, bean production, as well as production of other crops such as maize, vegetables, pigeon pea and coffee. The major providers of such training events were agricultural officers, governmental institutions (Kilacha, Selian Agricultural Research Institute (SARI) and Tanzania Coffee Research Institute (TACRI)), non-governmental organizations such as SEVIA (Seeds of Expertise for the Vegetable Sector of Africa) and TAHA (Tanzania Horticultural Association), together with some researchers who were doing research in their area.

4.1.11 Agricultural Knowledge and Information Needs by the Farmers

When farmers were asked what information and training topics they would like to receive, the most commonly mentioned topic was farming methods (53.7%), followed by pest and disease control (21.7%), general agricultural education (9.2%), market information (6.8%), inputs use (5.6%) and climate (2.1%). A similar trend was observed from the IVR results (Table 7). With respect to farming methods, the farmers were specifically interested in receiving more information about bean production together with production of other crops such as maize and vegetables, good agricultural practices, modern agriculture and organic farming methods. In terms of pest and disease control, the major focus was knowledge of various bean pests, pesticide use and various ways of managing pests in the field. Their major concern about climate or weather conditions was knowledge of seasonal timing such as planting as well as information on the amount of rainfall and kind of crops to plant. Knowledge and information required about inputs were typically about good seeds and fertilizers. However, some farmers were interested in receiving general agricultural knowledge and market linkages to increase their income.

Table 7: Agricultural knowledge and information the farmers would prefer to get

Type of information	**Interview results (%), n=300**	**IVR results (%), n=50**
Production methods	53.7	22.0
Pest and disease control	21.7	12.0
Agricultural education	9.2	6.0
Markets	6.8	6.0
Inputs use	5.6	-
Climate	2.1	-
Knowledge of insects	-	2.0
Vague response	-	30.0
None	1.2	22.0
Total	**100**	**100**

4.1.12 Farmer Advice for Improving Bean Production

Farmers were asked to provide suggestions on the possible strategies to improve bean production and the types of advice given were not significantly different (K-W = 2.07, df = 2, p = 0.355) between the farmers across the three elevation zones.

Table 8: Farmer advice for improving bean production in northern Tanzania

Farmers' advice	Responses	
	N	Percent of cases
Education on bean production	134	44.7
Education on pest management and other inputs use	52	17.3
Timely provision of agricultural inputs	76	25.3
Provision of loans/ capital	6	2.0
Frequent visits and seminar	51	17.0
More research	3	1.0
Training and provision of more agricultural officers	5	1.7
Adhere advices from agricultural experts	16	5.3
Use/ provision of traditional/ local pesticides and fertilizer	15	5.0
To establish irrigation system	4	1.3
Provision of short term/ drought resistant varieties	14	4.7
Soil examination	4	1.3
Provision of quality and high yield bean seeds	4	1.3
Total	**384**	**128.0**

Provision of education on bean production (44.7%) was a common request to the government as most of the farmers claimed to grow beans from experience without any training on good and modern agricultural practices. Education on pest management and other inputs use was also suggested by the farmers (17.3%) since insect pests are among the common problems affecting bean production.

About 17% of the farmers believed frequent visits of their fields by the agricultural experts and seminar provision to be the solution to most of the challenges. Farmers believed that they could easily get very useful agricultural information if the government could organize frequent seminars or workshops in their area with frequent visits in their field in order to identify instantly the problems existing in their fields and way forward.

Other given suggestions include provision of loans or capital, more agricultural research, training and provision of more agricultural officers, and an alternative way of irrigating their fields rather than depending on rain fed agriculture. In addition, they requested the government to provide quality and high yield bean varieties together with short term and drought resistant crop varieties which will be able to withstand the rainfall fluctuations. Soil examination in order to know the type of soil suitable for a certain crop was also suggested by the farmers. Generally, though the above given suggestions were given by small percent of the farmers (Table 8), they are of considerable importance since most of them are focusing on long term solutions for sustainable agriculture.

4.1.13 Sampled Natural Enemies and Insect Pests in the Three Coloured Pan Traps across the Three Elevation Zones

A total of 5 003 natural enemies (out of a total of 13 961) were collected, comprising predatory wasps (Hymenoptera: Vespidae) and parasitic wasps (Hymenoptera: Braconidae and Ichneumonidae), ants (Hymenoptera: Formicidae), robber flies (Diptera: Asilidae), long legged flies (Diptera: Dolichopodidae), tachinid flies (Diptera: Tachinidae), hoverflies (Diptera: Syrphidae), lacewings (Neuroptera: Chrysopidae), rove beetles (Coleoptera: Staphylinidae), carabid beetles (Coleoptera: Carabidae), lady beetles (Coleoptera: Coccinellidae), assassin bugs (Hemiptera: Reduviidae) and spiders (Araneae: Araneidae). Lady beetles were very abundant through field observation but they were not easily trapped by the water pan traps. Parasitic wasps and ants were the most sampled in low and mid zones, while long legged fly and rove beetle were more sampled in high zone (Fig. 13). Though hoverflies are predators only as larvae, adults were included in the analyses since these produce eggs that will hatch and provide pest regulation services so are a proxy for the predatory larvae.

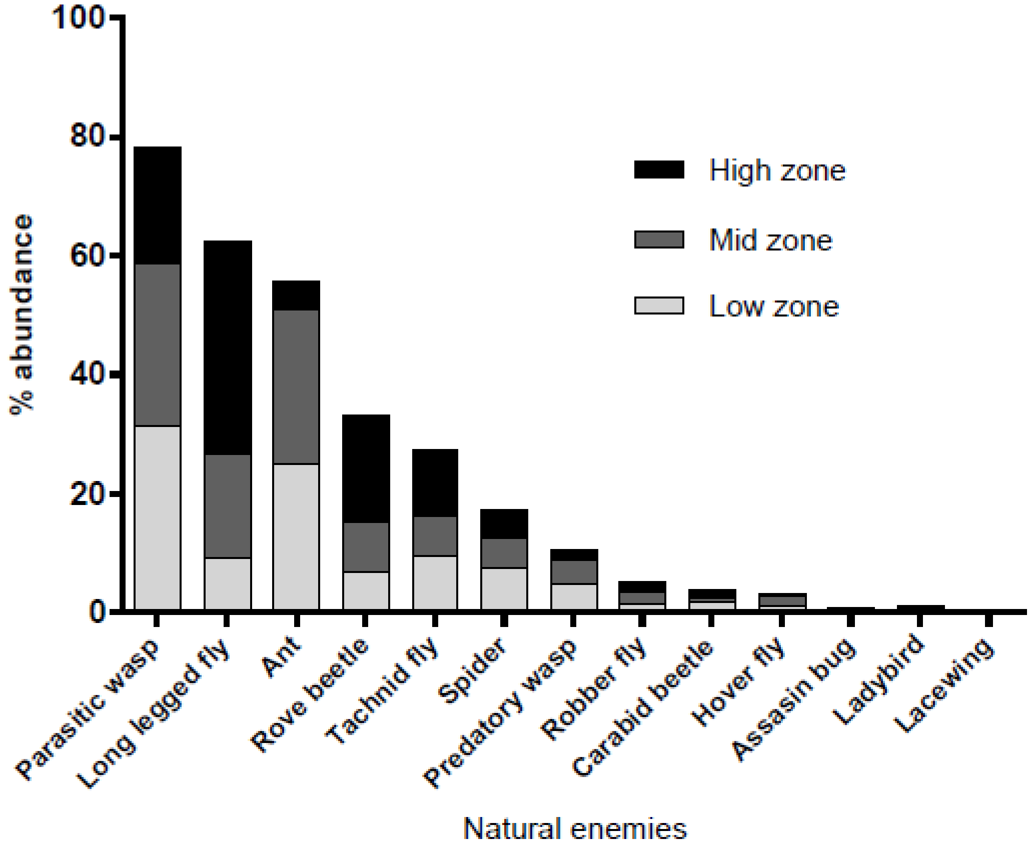

Figure 13: Percent abundance of natural enemies in smallholder bean fields across three elevation zones of Moshi rural district in northern Tanzania

There was a significant difference in the abundance of the natural enemies among the three elevation zones ($F = 15.817$, $df = 2$, $p < 0.001$); most numerous in the high zone (50.3% of catch) and declining with elevation, 31.7% and 18% in mid and low zones, respectively (Fig. 14). Tukey post hoc test showed significant difference in the natural enemy abundance between low and mid elevation zones ($p = 0.047$), mid and high elevation zones ($p = 0.004$) and low and high elevation zones ($p < 0.001$).

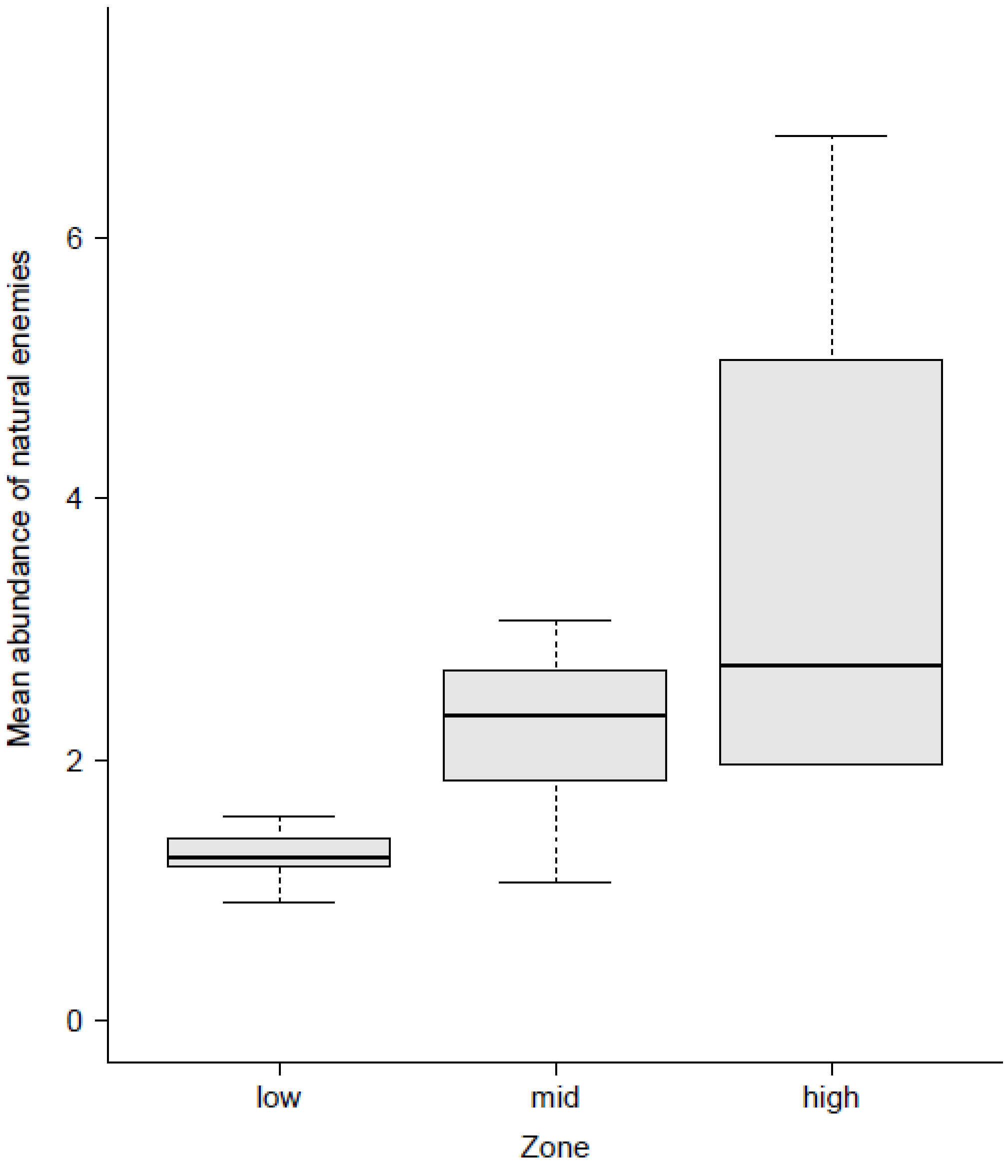

Figure 14: The effect of elevation on trap catches of natural enemies in smallholder bean fields in northern Tanzania

Shannon biodiversity index for the natural enemies was 1.77, 1.67 and 1.60 for low, mid and high elevation zones respectively. The effective number of species, ENS (the number of equally common species) from the calculated diversity index for low zone was 6 and for mid and high elevation zones were 5. Equitability of the natural enemies in low and mid zones was 0.69 which is slightly higher compared with the high zone which was 0.65, all of which show moderate level of evenness as the equitability values ranges from 0 to 1.

Aggregating natural enemies, 46.5% were caught in the yellow pans, 31.1% in the white pans, and 22.4% in the blue pans, showing a significant effect of colour ($F = 42.649$, $df = 2$, $p < 0.001$). The influence of pan colour on catch by taxon was similar for parasitic wasps, predatory wasps, robber fly, long legged fly and ants (Fig. 15). In contrast, tachinids were more abundant in the white pans ($F = 24.190$, $df = 2$, $p < 0.001$) while rove beetles were most abundant in the blue pans ($F = 3.889$, $df = 2$, $p = 0.021$). Catches of other natural enemies were not significantly influenced by pan colour. Tukey post hoc test showed the three colours differed significantly from each other at $p < 0.001$. Elevation zone had no significant effect on the responses of enemies to trap colour.

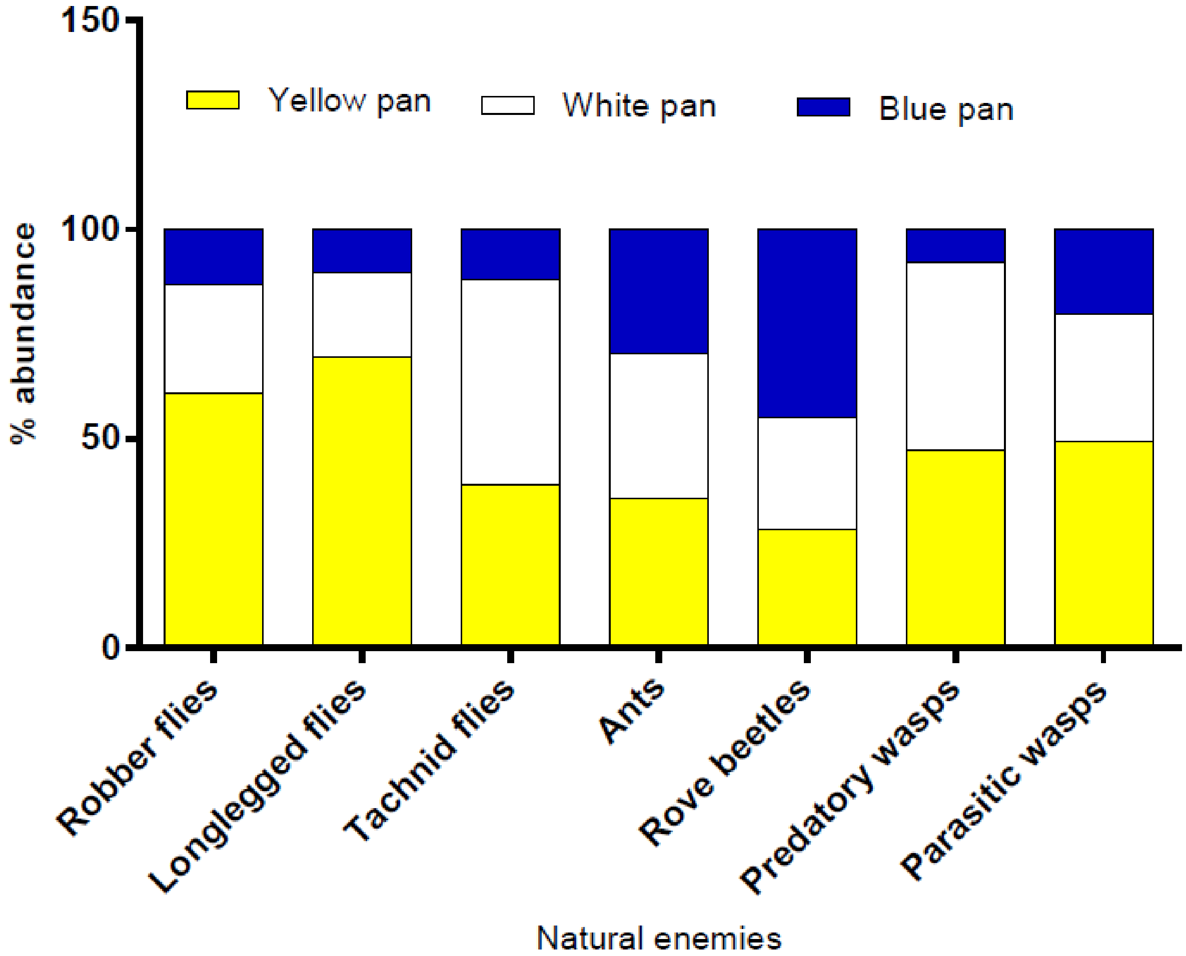

Figure 15: The effect of pan trap colour on catches of natural enemies in smallholder bean fields in northern Tanzania

A total of 2594 (out of a total of 13 961) insect pests were captured in the pan traps. With the exception of aphids, the most sampled insect pests that were present in the field were: blister beetles (Coleoptera: Meloidae), bean leaf beetles, *Ootheca* sp. (Coleoptera: Chrysomelidae), bean weevil (Coleoptera: Chrysomelidae), caterpillars (Lepidoptera: Crambidae), thrips (Thysanoptera: Thripidae), and whiteflies (Hemiptera: Aleyrodidae). Aphids are considered the most damaging insect pests in the area but they usually do not enter into the water pan traps. *Ootheca* was abundant during the seedling stage, observed in the field in the low and mid zones, but they were similarly less likely to enter into the pan traps. Unlike natural enemies, the number of insect pests caught in different pan colours were not significantly different ($F = 0.322$, df = 2, $p = 0.725$) except for blister beetle ($F = 11.010$, df = 2, $p < 0.001$) and bean weevil ($F = 4.901$, df = 2, $p = 0.007$), where in both cases they were more abundant in the blue pan, followed by the white pan, and the yellow pan captured the fewest.

There was a significant difference in the abundance of the insect pests between zones ($F = 11.983$, df = 2, $p < 0.001$); most numerous in mid elevation zone, followed by low elevation zone and high elevation zone was the least (Fig. 16). Tukey post hoc test showed no significant difference in pest abundance between low and mid elevation zones ($p = 0.191$), but with significant difference between mid and high elevation zones ($p = 0.012$) and low and high elevation zones ($p < 0.001$). Thrips and blister beetles were the most trapped insect pests in low and mid zones, while in the high zone, caterpillars were the pests most often trapped (Fig. 17).

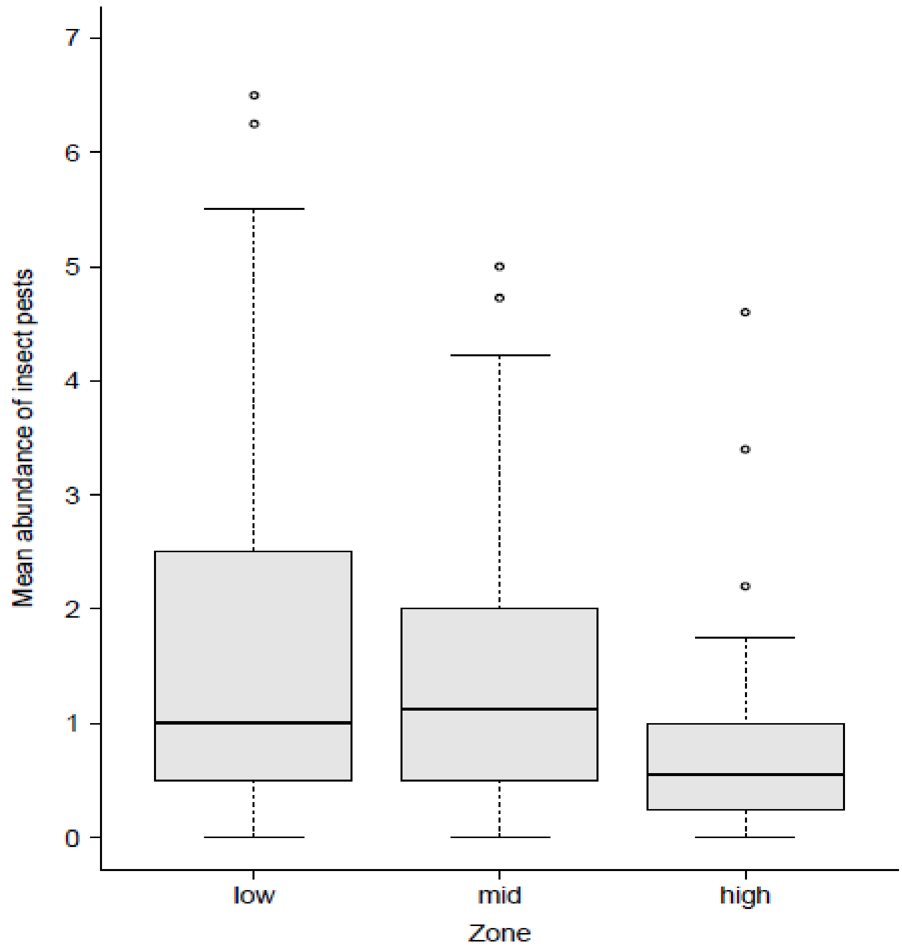

Figure 16: The effect of elevation on trap catches of pests in smallholder bean fields in Northern Tanzania

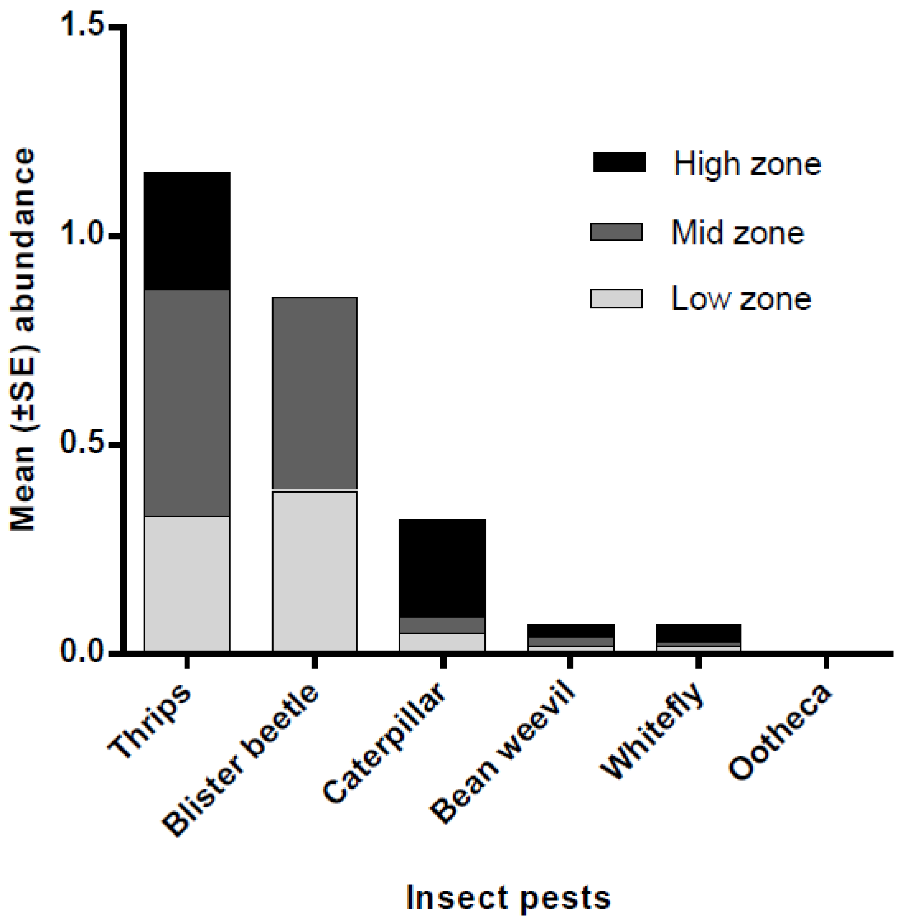

Figure 17: The effect of elevation on different insect pests in smallholder bean fields in Northern Tanzania

Apart from natural enemies and insect pests, few pollinators like honey bees were also sampled in the pan traps. Other insects belonging to different insect taxa but which were neither major natural enemies nor insect pests of common beans include plant bugs, leaf hopper, fruit flies and various beetle species.

4.1.14 Abundance of Natural Enemies and Insect Pests in Field Margins and Bean Crop

Catches of natural enemies did not generally differ significantly between the margins and fields ($F = 0.146$, $df = 1$, $p = 0.703$). However, the margin and field abundance was significantly different across the zones ($F = 30.978$, $df = 1$, $p < 0.001$) where majority of the natural enemies were found along the field margin than within the bean field for low (61.1% in margin vs 38.9% in field) and mid (52.1% in margin vs 47.9% in field) elevation zones, while in the high elevation zone they were more abundant within the field (Fig. 18). Illustration 3 is a field situation during post harvest stage in mid and high elevation zones, which may explain the differences between margin and field abundance in the three zones.

Though the size of the fields in three elevation zones was significantly different (Table 9), there was no statistical significance (F = 0.590, df = 1, p = 0.443) of the influence of fields size to the abundance of the natural enemies across the three zones.

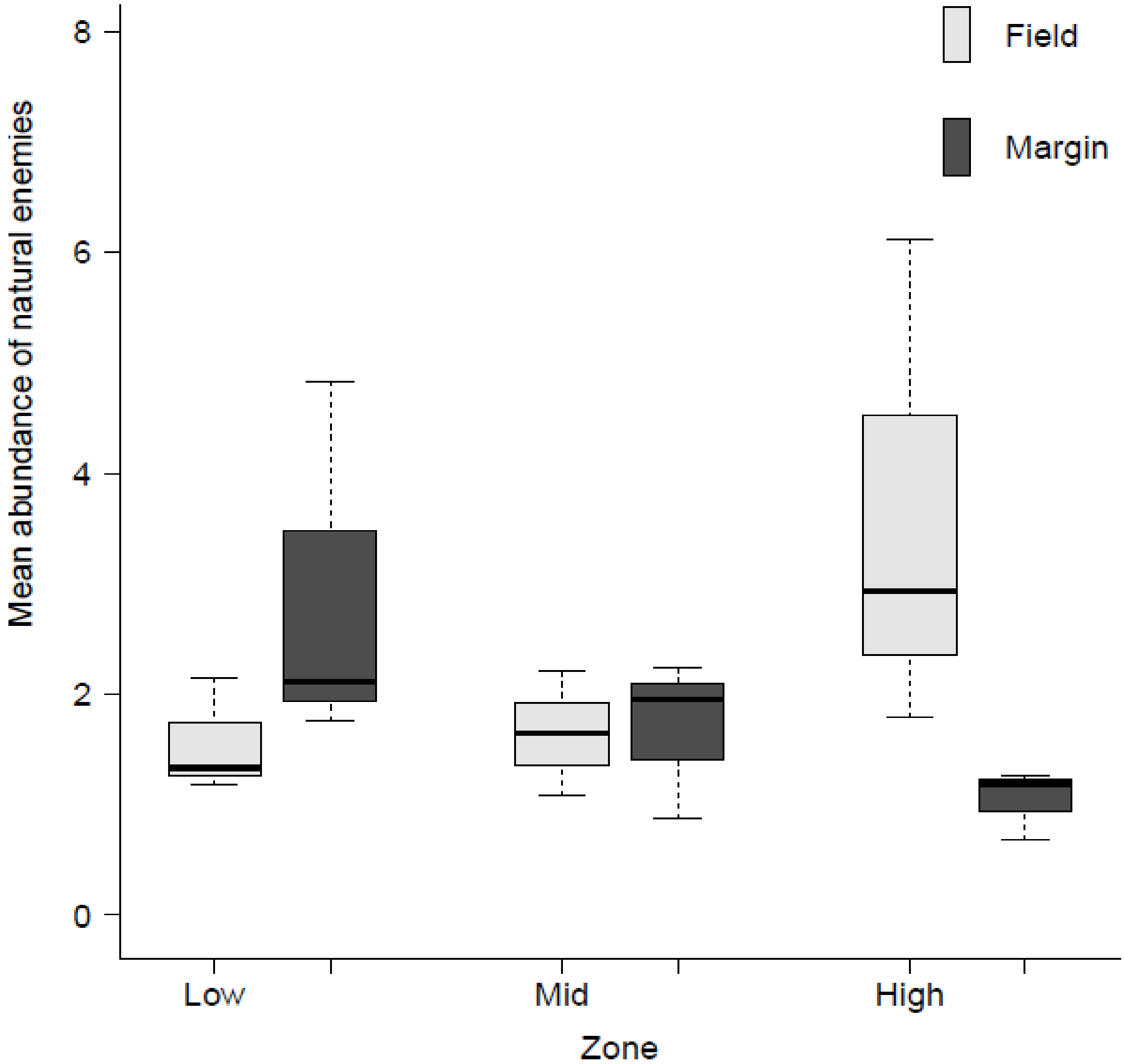

Figure 18: Margin and field abundance of natural enemies in smallholder bean fields across three elevation zones in northernTanzania

Table 9: Mean size of smallholder bean fields in three elevation zones of Moshi rural district in northern Tanzania

Zone	Number of farms (N)	Mean farm length (m)	Mean farm width (m)	Mean farm size (m^2)
Low	8	73.8 ± 2.79a	55.1 ± 6.68a	4167.5 ± 648.85a
Mid	8	71.0 ± 3.69a	56.6 ± 4.98a	4116.4 ± 568.37a
High	8	38.5 ± 2.78b	29.5 ± 1.09b	1132.9 ± 79.82b
ANOVA, F value		**39.534*** **	**9.828*** **	**12.068*** **

Each value is a mean ± standard error, *** is significant at P < 0.001. Means within the same column followed by the same letter are not significantly different at p = 0.05 from each other

Illustration 3: Bean field conditions during post harvest stage in mid (left) and high (right) elevation zones of Moshi rural district in northern Tanzania

Margin and field abundance of the natural enemies at different stages in the cropping cycle was analysed to find out whether the time in the cropping cycle significantly affected their distribution. The results generally show the abundance of the natural enemies along the field margin plants was high compared with the abundance in the bean field in all stages of bean growth, with significant difference at seedling, flowering and post harvest stages (Fig. 19)

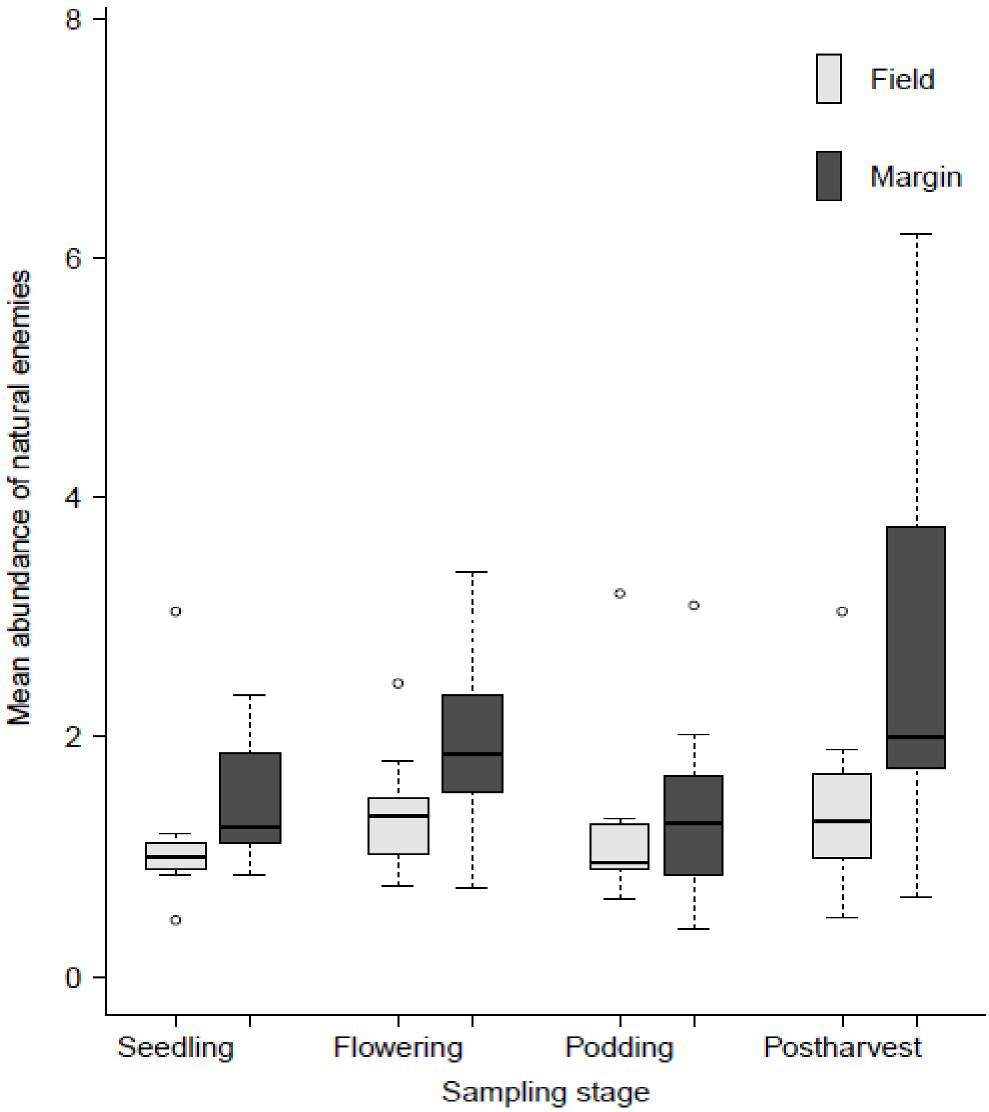

Figure 19: Margin and field abundance of natural enemies at different stages of the cropping cycle in smallholder bean fields in northern Tanzania

Catches of pests differed significantly between margins and fields (F = 9.478, df = 1, p = 0.002). Unlike natural enemies, insect pests were generally more abundant within the fields than margins in all the three zones (Fig. 20). The margin and field abundance was similarly the same for majority of individual pest species with significant difference (F = 8.221, df = 1, p = 0.004) in thrips which were also significantly more abundant in the field than margin in all elevation zones.

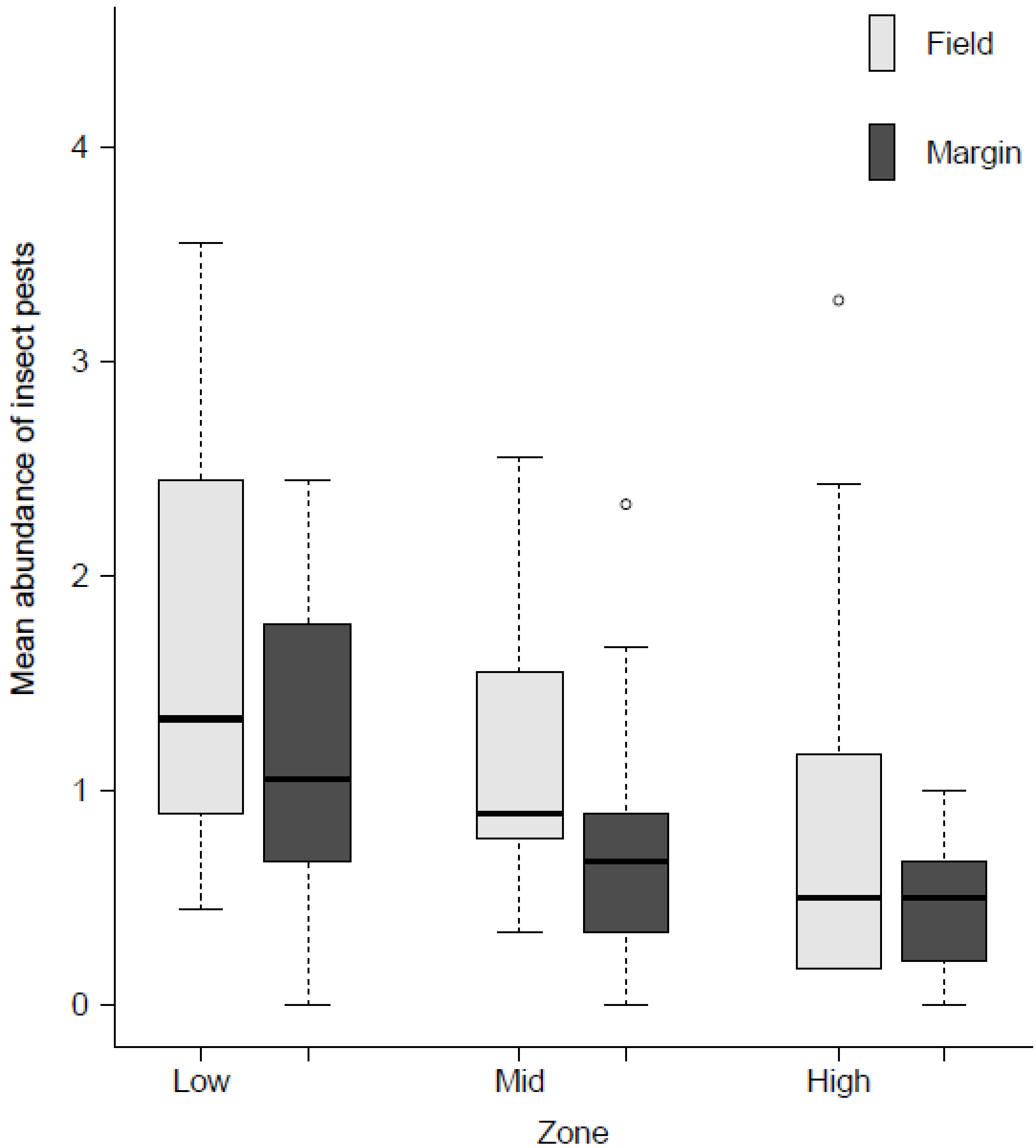

Figure 20: Margin and field abundance of insect pests in smallholder bean fields across three elevation zones in northern Tanzania

Despite the fact that the field margin vegetation supported significant number of natural enemies, farmers were not aware on the importance of these structures in biological pest control. The field margin plants were mainly used as aboundary and for feeding animals and the management methods were mainly through pruning or cutting. Some farmers were burning the margin vegetation or applied herbicides due to the bad believe that margin plants harbor insect pests.

4.1.15 Distribution of the Natural Enemies and Insect Pests at Different Distances from the Margin to the Bean Field

Overall, there was no spatial signal in insect distribution at 10 m to 50 m ($F = 0.597$, $df = 4$, $p = 0.665$) from the field margin into the bean field (Fig. 21).

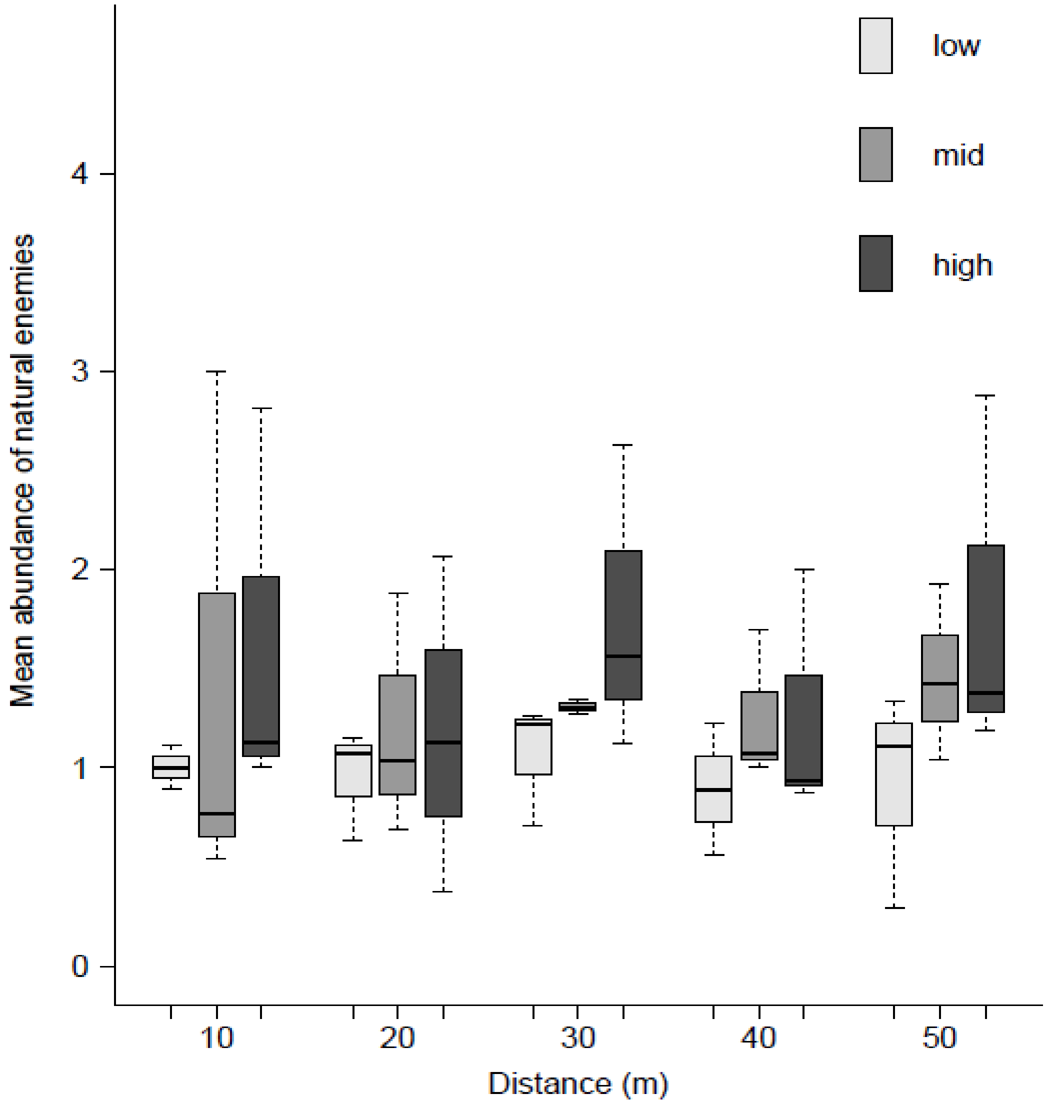

Figure 21: Spatial trend in natural enemy abundance on a transect running 10 m from the margin to 50 m into the field centre in smallholder bean fields across the three elevation zones in northern Tanzania

4.1.16 Fluorescent Dye Experiment to Monitor the Movement of the Natural Enemies and Insect Pests from the Margin Vegetation to the Bean Field

Generally, more of the natural enemies captured were marked (71%), showing they had moved from the margin vegetation, than were unmarked (29%) (Table 10). The most abundant natural enemies sampled were parasitoid wasps (Hymenoptera: Braconidae and Ichneumonidae), followed by predatory wasps (Hymenoptera: Ichneumonidae), assassin bugs (Hemiptera: Reduviidae), hoverflies (Diptera: Syrphidae) and spiders (Araneae: Araneidae).

Table 10: Total natural enemies and dye marked proportions, sampled in smallholder bean fields in northern Tanzania for three days after dye application in field margin plants

Natural enemies	**Total sampled**	**Marked insects after spray**			**Total marked**
		Day 1	**Day 2**	**Day 3**	
Parasitoid wasps	65 (27.5%)	19	17	13	49 (75.4%)
Predatory wasps	51 (21.6%)	10	19	11	40 (78.4%)
Assassin bug	28 (11.9%)	9	8	6	23 (82.1%)
Hover fly	19 (8.1%)	5	3	4	12 (63.2%)
Spider	19 (8.1%)	3	3	6	12 (63.2%)
Tachinid fly	12 (5.1%)	4	6	2	12 (100%)
Carabid beetle	10 (4.2%)	3	1	1	5 (50%)
Lady beetle	10 (4.2%)	3	0	2	5 (50%)
Long legged fly	7 (3.0%)	1	1	1	3 (42.3%)
Robber fly	5 (2.1%)	1	3	1	5 (100%)
Dragonfly	4 (1.7%)	0	0	0	0 (0%)
Rove beetle	3 (1.3%)	0	0	1	1 (33.3%)
Ants	3 (1.3%)	0	0	0	0 (0%)

There was a significant effect of elevation on the marked proportion of natural enemies ($F = 8.398$, $df = 2$, $p < 0.001$), with more marked in the high elevation than other zones (Fig. 22). Overall, distance from the field margin significantly influenced the proportion of marked insects ($F = 7.144$, $df = 3$, $p < 0.001$), with more marked close to the field margin than towards the field centre. Within each zone, the effect of distance to proportion marked was significant in low ($F = 2.982$, $df = 3$, $p = 0.039$) and mid ($F = 3.598$, $df = 3$, $p = 0.018$) zones but not in the high elevation zone ($F = 1.764$, $df = 2$, $p = 0.181$) where the sampling distance ended at 20 m due to small field size. There was no significant effect of time from dye application to sampling ($F = 2.679$, $df = 2$, $p = 0.071$) (Table 11). Post hoc testing showed the low and mid elevation zones were not significantly different ($p = 0.450$) in terms of marked proportions of natural enemies but the two zones were significantly different from the high elevation zone.

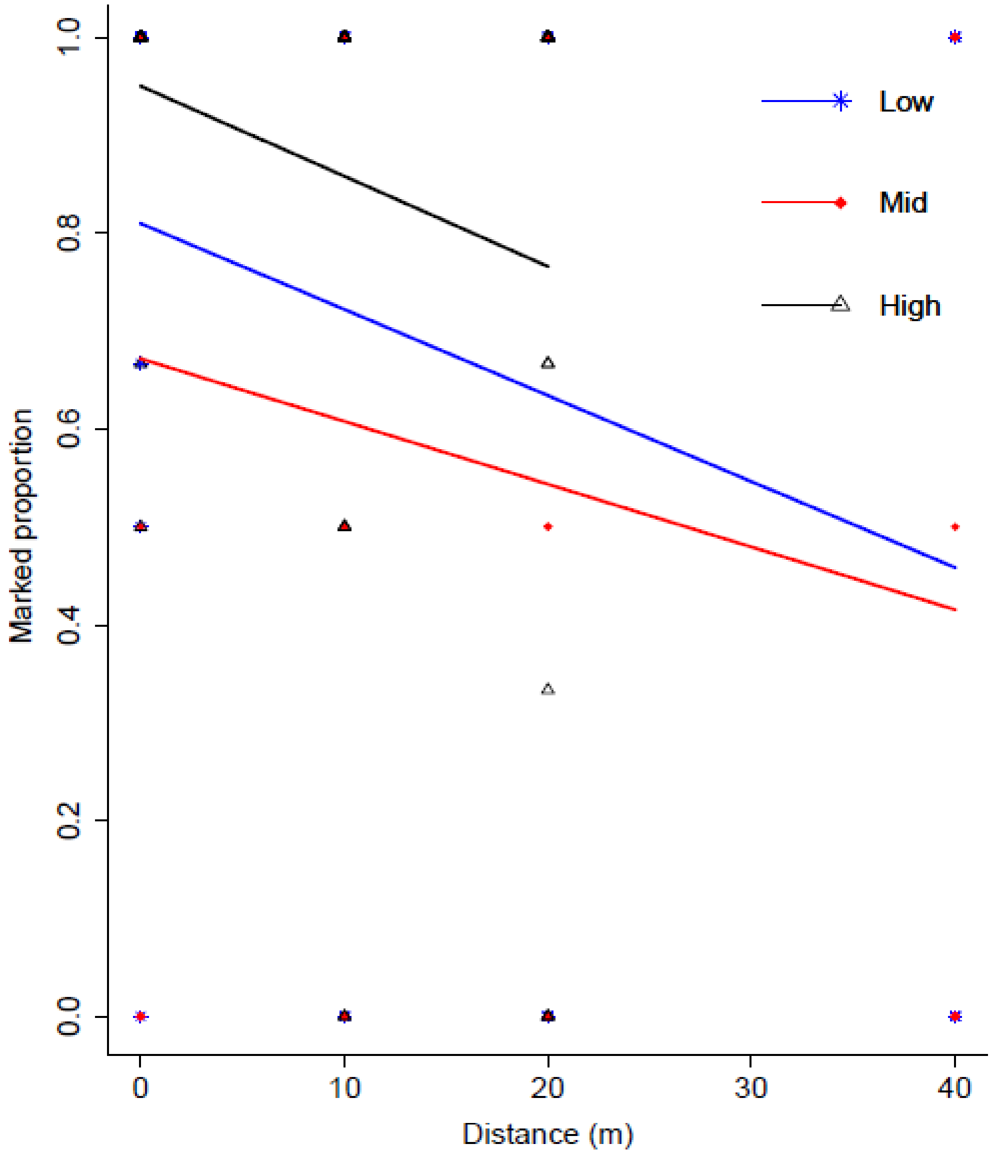

Figure 22: Effect of distance from the field margin to the dye marked proportion of natural enemies in smallholder bean fields across three elevation zones in northern Tanzania

Table 11: Results obtained from linear regression model on the effect of elevation zone, distance from the margin to the field, field size and sampling time to the marked proportion of natural enemies sampled after dye application on field margin plants

Dependent variable	**Independent variable**	**Sum of squares**	**Mean squares**	**Df**	**F value**	**p value**
Marked proportions of natural enemies	Zone	2.594	1.297	2178	8.398	< 0.001
	Distance	3.309	1.103	3178	7.144	< 0.001
	Farm size	1.242	1.241	1178	8.040	0.005
	Day	0.870	0.435	2178	2.816	0.063

The degrees of freedom, F and p values were obtained from ANOVA at p = 0.05, significant levels 0 '***', 0.001 '**' 0.01'*' 0.05 '.'

The insect pests captured were blister beetles (Coleoptera: Meloidae), bean leaf beetles (Coleoptera: Chrysomelidae), leaf hoppers (Hemiptera: Cicadellidae), stink bugs (Hemiptera: Pentatomidae), bean brown bugs and leaf footed bug (Hemiptera: Coreidae), fruit fly (Diptera: Drosophilidae and Tephritidae), locust (Orthoptera: Acrididae) and other plant bugs.

Unlike the natural enemies, fewer insect pests were marked (25.5%) compared with unmarked (74.5%) indicating that only a minority of them were in the margin during dye application (Fig. 23). There was a significant effect of elevation on the marked proportion of insect pests ($F = 4.125$, $df = 2$, $p = 0.020$). Few insect pests were marked in mid elevation zone (20%) compared with low and high elevation zones (37% and 50%, respectively). Overall, distance from the field margin significantly influenced the proportion of marked insects ($F = 12.506$, $df = 3$, $p < 0.001$) but with significant effect only in mid elevation zone ($F = 8.410$, $df = 3$, $p < 0.001$). There was no significant effect of time from dye application to sampling for low and high elevation zones, but only in mid elevation zone ($F = 4.430$, $df = 2$, $p = 0.018$) where more marked insect pests were captured on the first day compared with the other days.

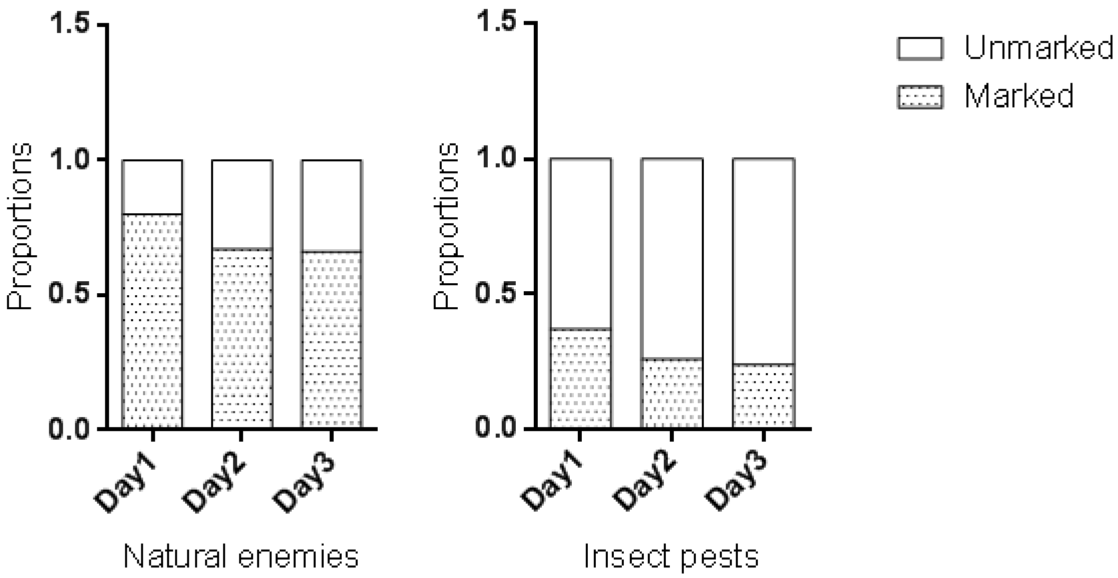

Figure 23: Marked and unmarked proportions of natural enemies and insect pests sampled in smallholder bean fields after dye application to the margin plants in northern Tanzania

4.1.17 On-station Predation Rate of Aphids by Lady Beetle

The results show on station predation rate (number of aphids consumed per hour) of aphids by lady beetle increased with increase in aphid density at the different time intervals (Table 12) and decreased with time due to the decrease in aphid density regardless of the initial aphid population. The rate of predation was not significantly different after 2 and 4 hours ($F = 1.90$, $df = 3$, $p = 0.171$ and $F = 1.87$, $df = 3$, $p = 0.175$ respectively). However, the predation rate was significantly different at 8 hours ($F = 3.36$, $df = 3$, $p = 0.045$), 12 hours ($F = 6.28$, $df = 3$, $p = 0.005$), 24 hours ($F = 97.31$, $df = 3$, $p < 0.001$) and 48 hours ($F = 185.15$, $df = 3$, $p < 0.001$) showing a significant increase in predation rate with increase in aphid density.

Table 12: Predation rate (aphids consumed per hour) by lady beetle under different aphid density

Treatments	Predation rate (aphids consumed/hour) at different time intervals					
	2 hours	**4 hours**	**8 hours**	**12 hours**	**24 hours**	**48 hours**
25 aphids	2.6 ± 1.13b	3.75 ± 0.52b	2.68 ± 0.17b	2.05 ± 0.03b	1.04 ± 0.00b	0.52 ± 0.00d
50 aphids	5.0 ± 1.10ab	4.85 ± 0.54ab	3.40 ± 0.49b	2.93 ± 0.25b	1.97 ± 0.05c	1.04 ± 0.00c
100 aphids	4.3 ± 0.81ab	5.40 ± 0.69ab	3.75± 0.30ab	3.23 ± 0.23b	2.22 ± 0.07c	1.58 ± 0.04b
200 aphids	7.5 ± 2.36a	7.65 ± 2.17a	5.88 ± 1.37a	4.95 ± 0.91a	3.76 ± 0.21a	2.12 ± 0.09a
One way ANOVA (F-statistics)	**1.896 ns**	**1.869 ns**	**3.363***	**6.277****	**97.312*****	**185.150*****

4.1.18 Field Predation and Parasitism

Aphid parasitism was higher on exposed sentinel plants placed in fields compared to caged plants (F= 8.456, df = 1, p = 0.005) (Fig. 24). Aphid mortality rates on the exposed plants, measured by parasitism levels on sentinel plants, did not differ between the three elevation zones (F= 2.704, df = 2, p = 0.076) and between field edges and field centre (F = 0.229, df = 1, p = 0.634). Mean parasitism rates varied between a maximum of 15% which was observed on open sentinel plants in low elevation zone and a minimum of 0.5% observed on caged plants in high elevation zone. The identification of parasitoids that emerged from the parasitized aphids showed 90% were *Aphidius* species (Hymenoptera: Braconidae: Aphidiinae).

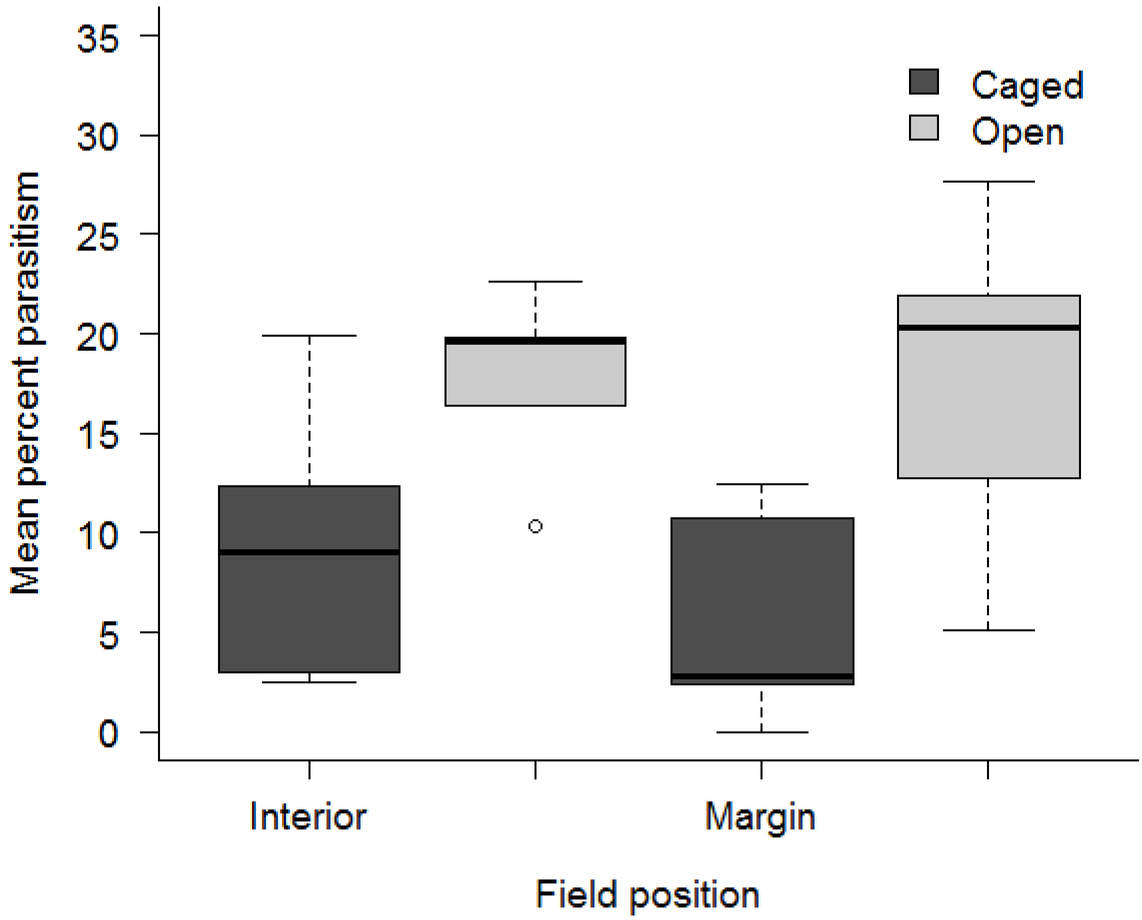

Figure 24: Mean percent parasitism of sentinel aphids under open and caged conditions at the margin and interior of smallholder bean fields in northern Tanzania

There was a significant difference between the aphid mortality recorded from control and exposed sentinel plants in the predation experiments (F= 28.973, df = 1, $p < 0.001$), whether at the field centre or near the field margin, indicating that there is a significant pest control service coming from the biodiversity on-farm (Fig. 25). In the control (caged) plants, aphid numbers increased over the course of the experiment, indicative of reproduction, whereas in the exposed plants, in all cases the aphid numbers decreased, in some cases by nearly half. Predation rate between the three elevation zones (F= 0.991, df = 2, p = 0.385) and between field edges and field centre (F = 0.914, df = 1, p = 0.348) was statistically not significant, indicating the centre of the fields in the three elevation zones still receive equivalent pest control service as the field edge.

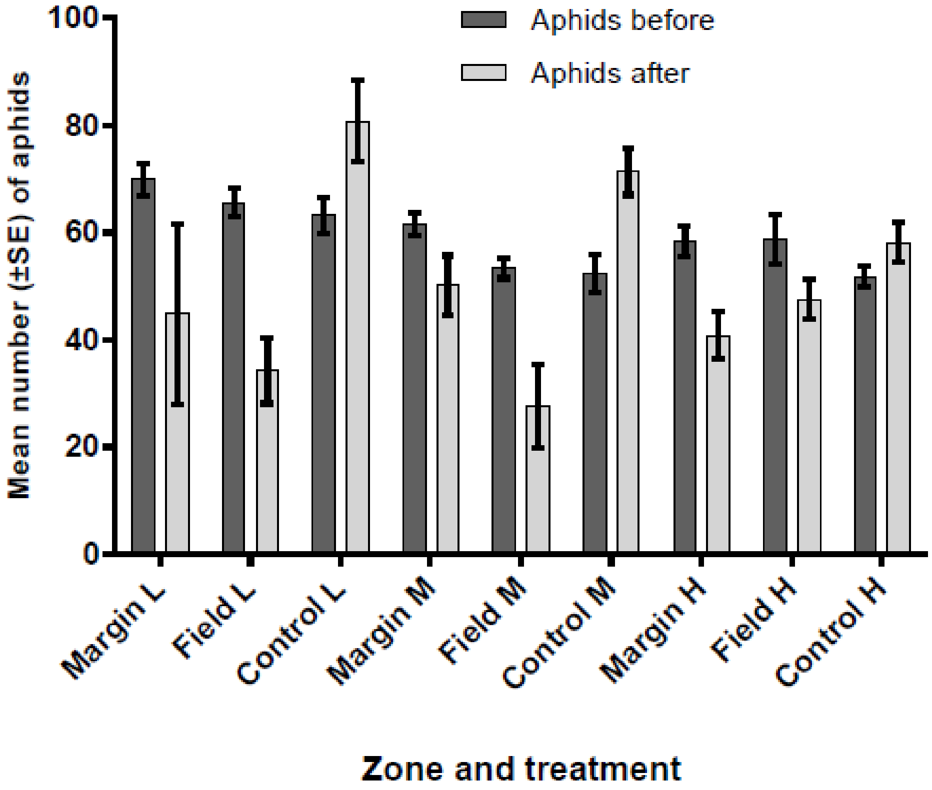

Figure 25: Margin and field predation and a control after 2 days exposure of sentinel aphids in smallholder bean fields in low (L), mid (M) and high (H) elevation zones of Moshi rural district in northern Tanzania

Regression analysis showed no significant relationship (R^2 = 0.044, F = 0.606, df = 1, p = 0.450) between the aphid density in the field and percent predation of sentinel aphids (Fig. 26)

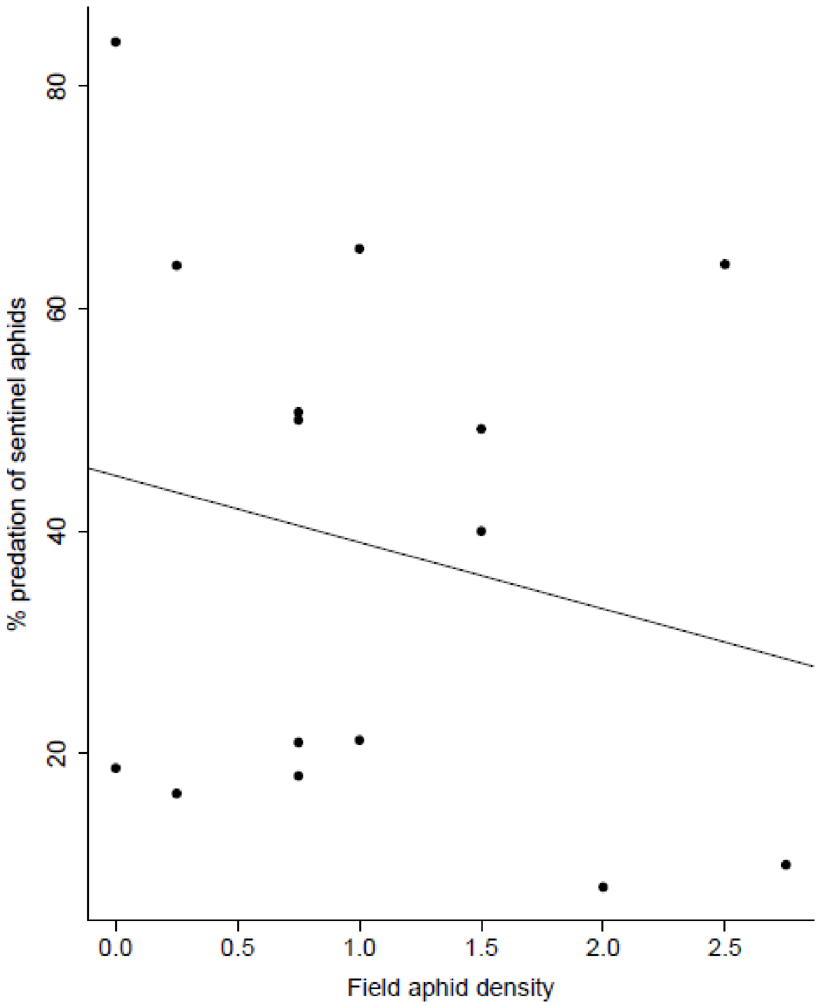

Figure 26: Regression analysis between field aphid density and percent predation of sentinel aphids in the exposed potted bean plants

Regression analysis evaluating the relationship between the aphid density and lady beetle number in the field showed significant relationship (R^2 = 0.810, F = 55.300, df = 1, $p < 0.001$), where ladybird increased significantly with increase in aphid density in the field (Fig. 27). However, the relation was significant in low (R^2 = 0.9645, F = 81.45, df = 3, p = 0.0029) and mid (R^2 = 0.8174, F = 13.43, df = 3, p = 0.035) elevation zones only, with no significant relationship in high elevation zone (R^2 = 0.255, F = 1.03, df = 3, p = 0.3849).

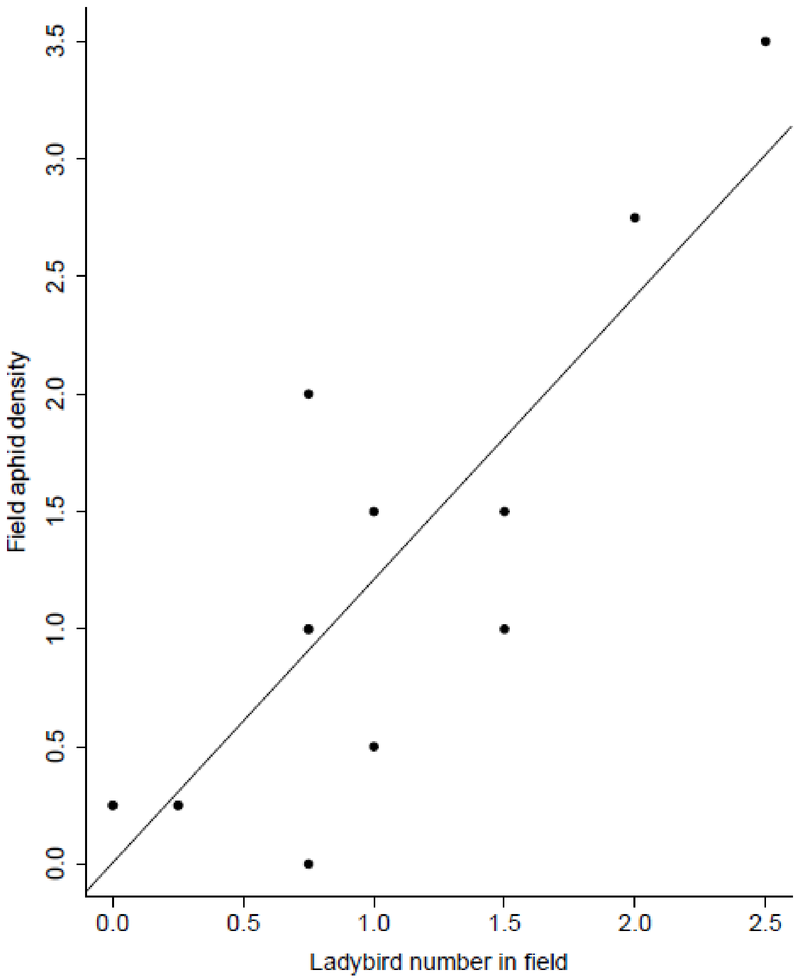

Figure 27: Regression analysis exploring the relationship between field aphid density (scored 0-5 on the basis of observed infestation level) and lady beetle number per plot on 1m x 1m plots within smallholder bean fields

4.1.19 Identified Aphid Parasitoids and Hyperparasitoids Based on Morphological Features

Based on morphological features described by Tomanović *et al*. (2014), the primary parasitoids were isolated from the rest of the parasitoid population (Fig. 28). The remaining parasitoids were grouped together as secondary parasitoids until molecular identification. The highest number of primary parasitoid species was sampled from the mid zone followed by the low zone and the lowest number from the high zone (Table 13). However, the low zone had a greater proportion of hyperparasitoids (21.98%) compared with mid and high zones. The primary parasitoids were further identified as *Aphidius* spp. based on morphological features.

Table 13: Primary and secondary parasitoids based on morphological features

Zone	Parasitoid group	Number of organisms	%
Low zone	Primary parasitoids (*Aphidius sp*)	71	78.02
	Secondary parasitoids	20	21.98
Mid zone	Primary parasitoids (*Aphidius sp*)	88	91.67
	Secondary parasitoids	8	8.33
High zone	Primary parasitoids (*Aphidius sp*)	25	92.59
	Secondary parasitoids	2	7.41

Figure 28: Images of the parasitoids emerged from the aphids (*A. fabae*) under sterio microscope (Magnification x25), Photo by Mkenda, P. A.

4.1.20 Identified Aphid Parasitoids and Hyperparasitoids Based on Molecular Analysis

One species of primary aphid parasitoid (*Aphidius colemani*) and two species of secondary parasitoids/ hyperparasitoids (*Pachyneuron sp* and *Charipinae sp*) were identified (Fig. 29). All *A. colemani* sequences obtained from experimental samples showed ≥ 99% similarity to *A. colemani* sequences in the NCBI database (Appendix 1). Therefore, these can be confidently identified as *A. colemani*. All sequences from *Pachyneuron sp.* obtained from experimental samples showed 94-95% sequence similarity to *Pachyneuron aphidis* sequences from the NCBI database. These can be confidently identified to genus (*Pachyneuron sp.*) and they are likely to be *P. aphidis* or a closely related species. The other sequence showed 90% similarity to a *Charipinae* sp. in the NCBI database, therefore the sample may be a closely related species, possibly in the same subfamily (Hymenoptera: Cynipoidea: Figitidae: Charipinae).

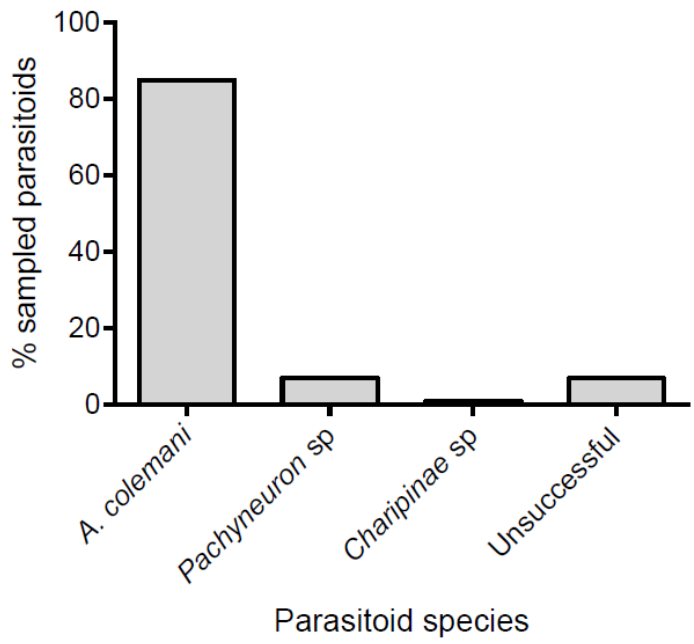

Figure 29: Parasioid and hyperparasitoid species identified from the host *A. fabae* (Hemiptera: Aphididae)

The primary parasitoids are *Aphidius colemani* (Hymenoptera: Braconidae: Aphidiinae). The hyperparasitoids are *Pachyneuron* species (Hymenoptera: Pteromalidae: Pteromalinae) and *Charipinae* species (Hymenoptera: Cynipoidea: Figitidae). The percentage of insects for which sequencing was unsuccessful is also shown.

The sequenced *A. colemani* appear to form a separate clade to those previously characterised (Fig. 30). They are most closely related to *A. colemani* sampled from the Netherlands (Koppert Biological Systems), Belgium and Canada, with a mean of 0.008 base substitutions between these groups. The Tanzania clade shows more divergence from *A. colemani* in Algeria, Greece and Libya with a mean 0.022 base substitutions per site between these groups. The phylogenetic tree (Fig. 30) was constructed using the maximum likelihood method based on the Tamura 3-parameter model (Tamura, 1992) with a bootstrap value of 1000.

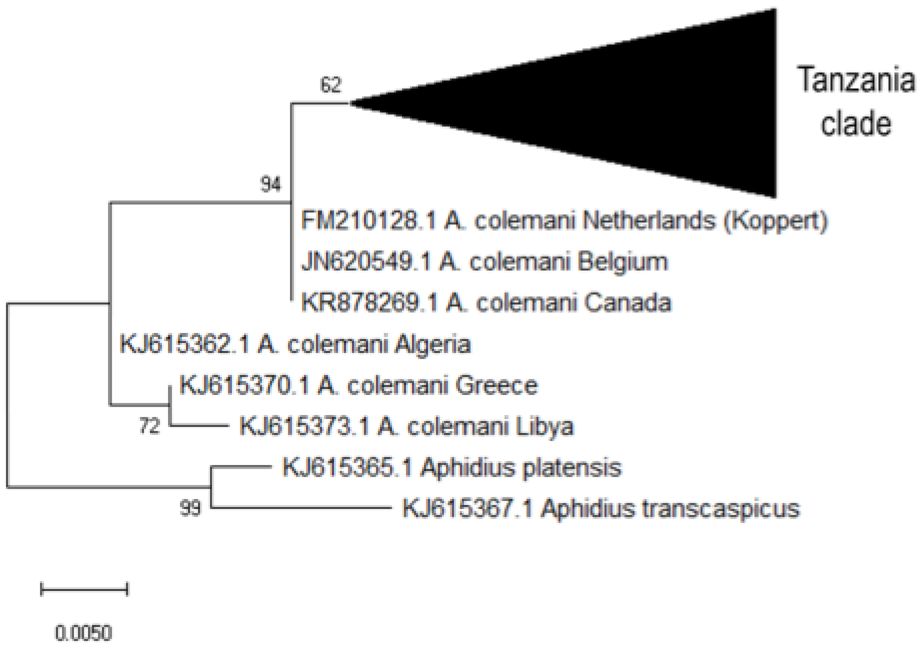

Figure 30: Phylogenetic tree for Aphidius species based on a portion of the cytochrome oxidase I gene

4.1.21 Plant Species Surveyed in the Three Elevation Zones

A total of 101 plant species belonging to 39 families were surveyed during the two years in all the three zones (Appendix 2). *Ageratum conyzoides* and *Cyperus rotundus* were the most abundant herbs in the high zone, while *Commelina benghalensis* was the most abundant in the low zone. In the mid zone, the three herbs (*A. conyzoides*, *C. rotundus* and *C. benghalensis*) which were abundant in low and high zones were also the most abundant though at lower level as compared with the other zones. A range of herbs and shrubs were common in the three zones and occupied at least 5% cover in any of the sampled quadrats (Fig. 31). All the surveyed plant species in the three zones regardless of its percent cover per quadrat and trees which were not included in the quadrat sampling are shown in Appendix 2. Other margin plants that were not common in all of the three zones and which occurred at least 5% in any of the sampled quadrats are shown in Appendix 3. Some occurred in only two of the three zones while others occurred in either of the three zones. Considering each zone separately, the most abundant margin plant in the high zone was *Tripsacum laxum* followed by *A. conyzodes,* mid zone was *Asystasia mysorensis* followed by *Sida rhombifolia* while in the low zone the most abundant plant was *S. rhombifolia.*

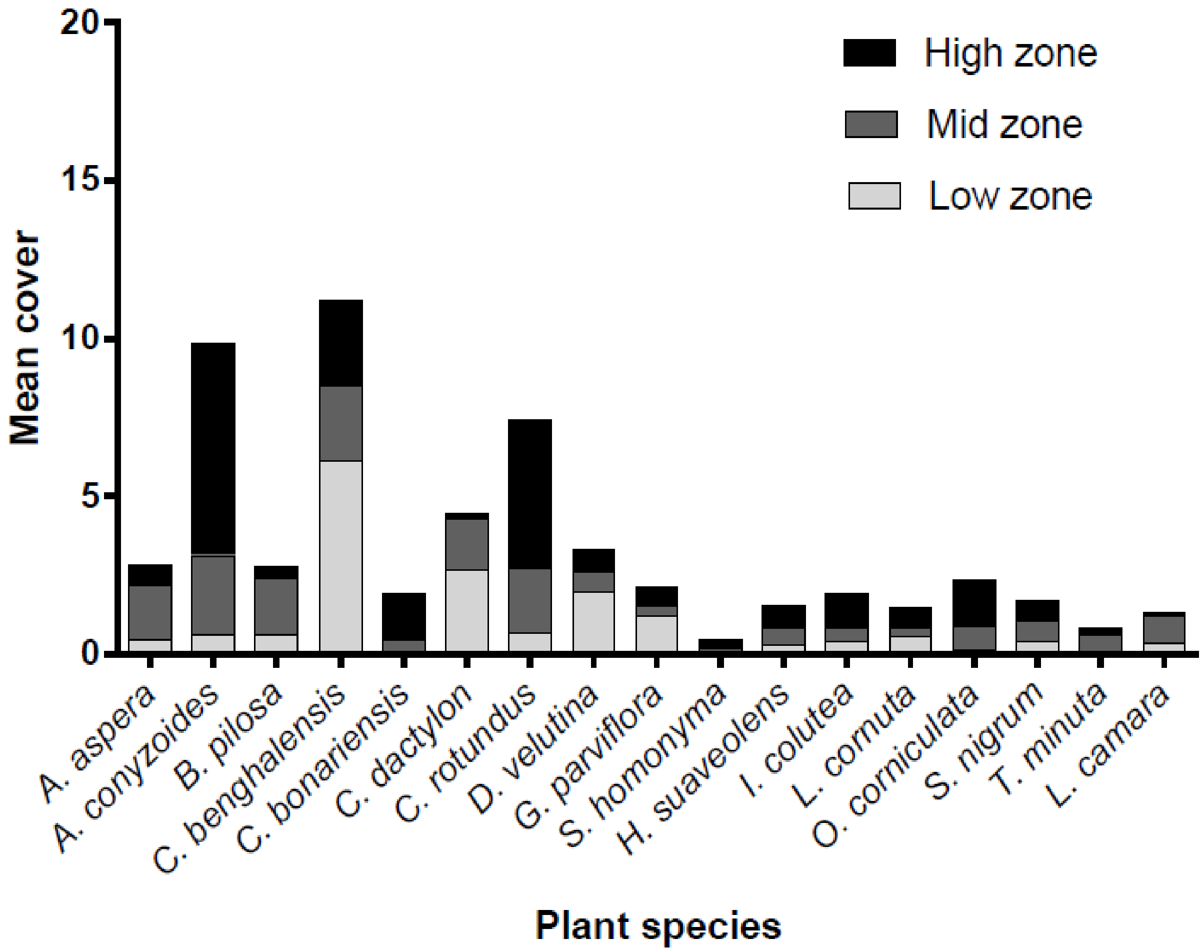

Figure 31: The common herbs and shrubs in the three elevation zones of Moshi rural district in Northern Tanzania

The above information in Fig. 31 and Appendix 3 is summarized in form of a Venn diagram in Fig. 32. Majority of the plants (17 plant species) were common in all the three zones, 13 were common in low and mid zones and 5 in mid and high zone. There was no any plant species that was found in low and high zone, but not in mid zone. The high zone had the largest number of plant species as compared with the other zones.

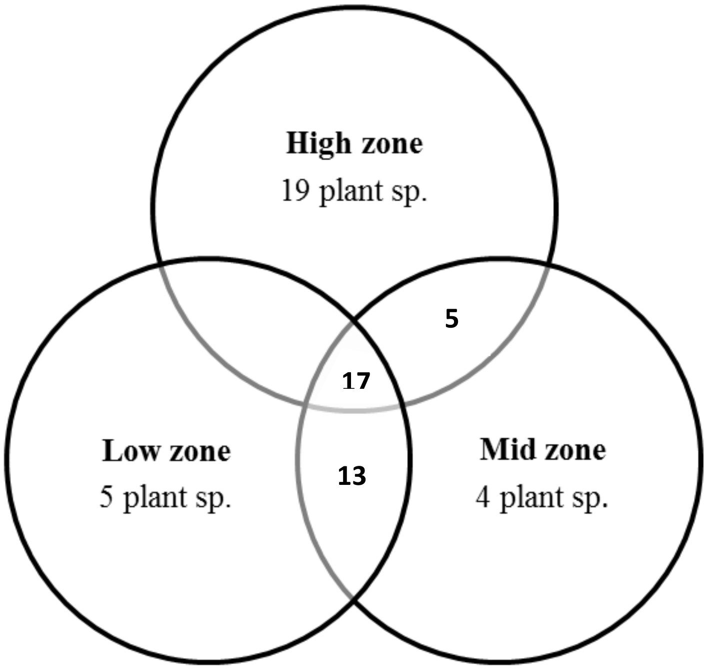

Figure 32: Venn diagram to show the number of margin plant species with at least 5% cover per $1m^2$ found in smallholder bean fields in Moshi rural district in northern Tanzania

4.1.22 The Percent Vegetation Cover and Diversity of Field Margin Plants

The three zones differ significantly in terms of the vegetation cover (Fig. 33), where the high zone had the highest vegetation cover (75%), followed by mid zones (63%) and least was the low zone (53%).

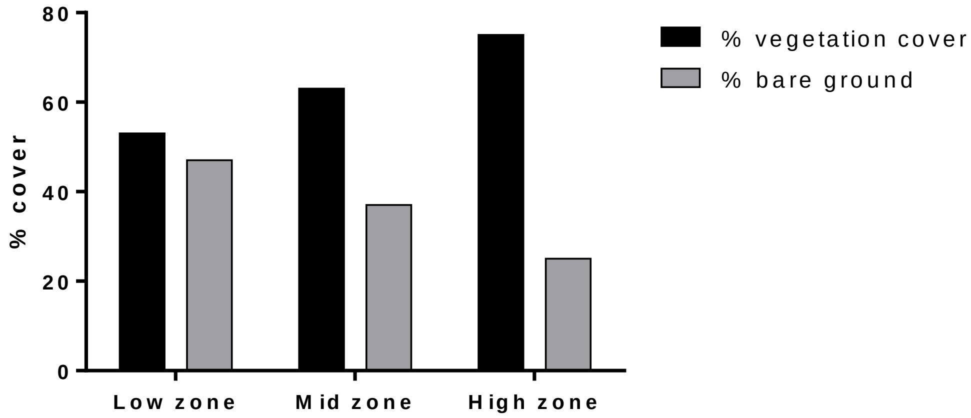

Figure 33: Percent vegetation cover within smallholder bean farming systems in three elevation zones of Moshi rural district in northern Tanzania

Plant species diversity in the three elevation zones was calculated as one of the most important indices in the assessment of ecosystem services. Shannon diversity (H`) is one of the indices used, where high values of H` refers to rich ecosystem in terms of species richness and lower values of H` refers to a less rich ecosystem. The Shannon-Weiner diversity index of the field margin plants were 2.76, 2.99 and 3.44 for low, mid and high elevation zones respectively. Effective number of species (ENS) according to the diversity index values for the low, mid and high elevation zones were 16, 20 and 31 respectively.

4.1.23 Identified Field Margin Plants Supporting Natural Enemies in the High Elevation Zone

The preferences of the natural enemies to the field margin plants was tested where the natural enemies were counted as either visiting or feeding the plant or resting on any plant part. The natural enemies that were found to interact with the field margin plants more frequently in the high zone were spiders, long legged fly and ants (Fig. 34). Spiders were found to interact mostly with creeping plant species such as *C. benghalensis*, *Drymaria cordata* and *Centella asiatica* and few non-creeping plants like *A. conyzoides* and *Conyzae bonariensis*. Long legged fly and ants were highly interacting with guatemala grass (*T. laxum)* while predatory and parasitic wasps and hoverfly were mostly interacting with *A. conyzoides* compared with other plant species.

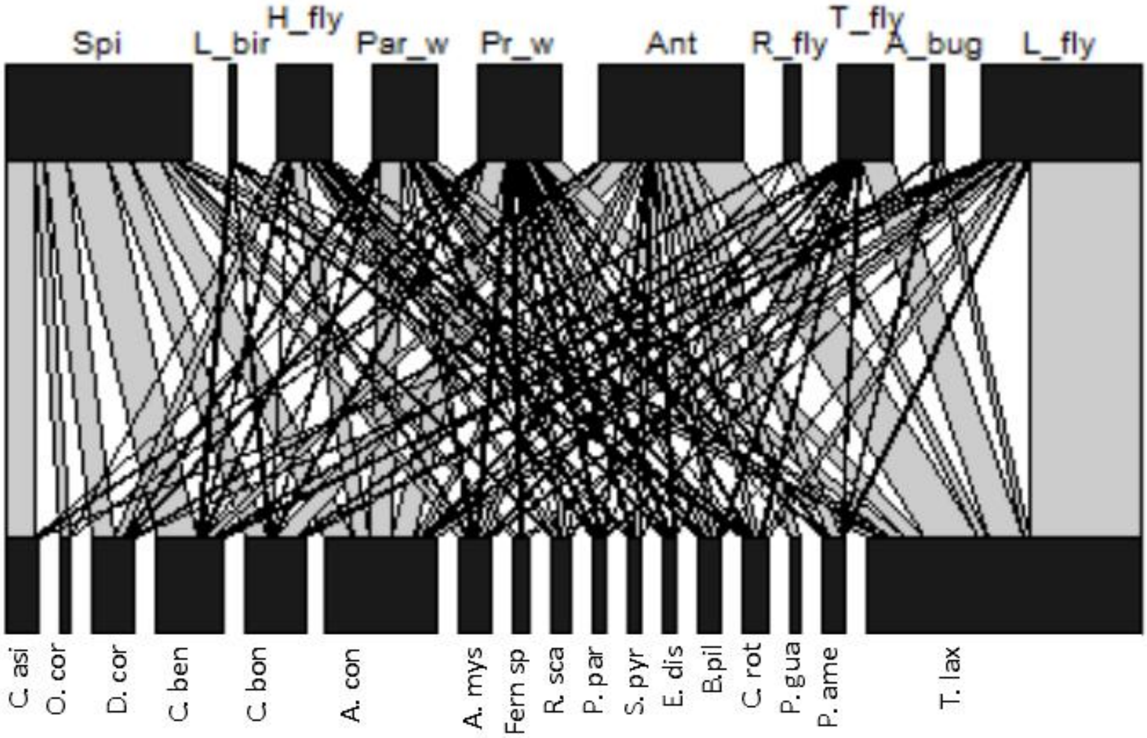

Figure 34: Bipartite network between natural enemies and field margin plants in the high elevation zone in Northern Tanzania

Each bar in the upper row representsnatural enemies and each bar in the bottom row represents field margin plant species. The width of the bars is proportional to the number of interacting partners. Full names of the natural enemies and plant species are given in Appendix 4.

4.1.24 Identified Field Margin Plants Supporting Natural Enemies in the Mid Elevation Zone

In the mid zone, ants, hoverfly, spiders and predatory wasps were the most dominant natural enemies and were found to interact with several plant species. *A. mysorensis* was the most dominant species in mid zone but not the most attractive to natural enemies. Instead, similar preferences of the natural enemies to certain plant species was observed in mid zone as found in the high zone. Spiders were more interacting with *Neonotonia wightii* and *C. benghalensis* which are mostly climbing and creeping plant species respectively compared with other plants. Ants were more attracted to napier grass (*Pennisetum purpureum*), which are structurally similar to Guatemala grass, while predatory wasps were highly interacting with *A. conyzoides*, followed by *Bidens pilosa*. Hoverfly and parasitic wasps had strong interaction with several plant species including *B. pilosa* and *Panicum maximum*, while assassin bugs were more specific to *S. rhombifolia*. Long legged fly were less abundant in mid zone as compared with high zone, thus their interaction with field margin plants in mid zone was not so strong (Fig. 35). Lady beetle is one of the natural enemies that was observed to have very low interaction with the margin plants.

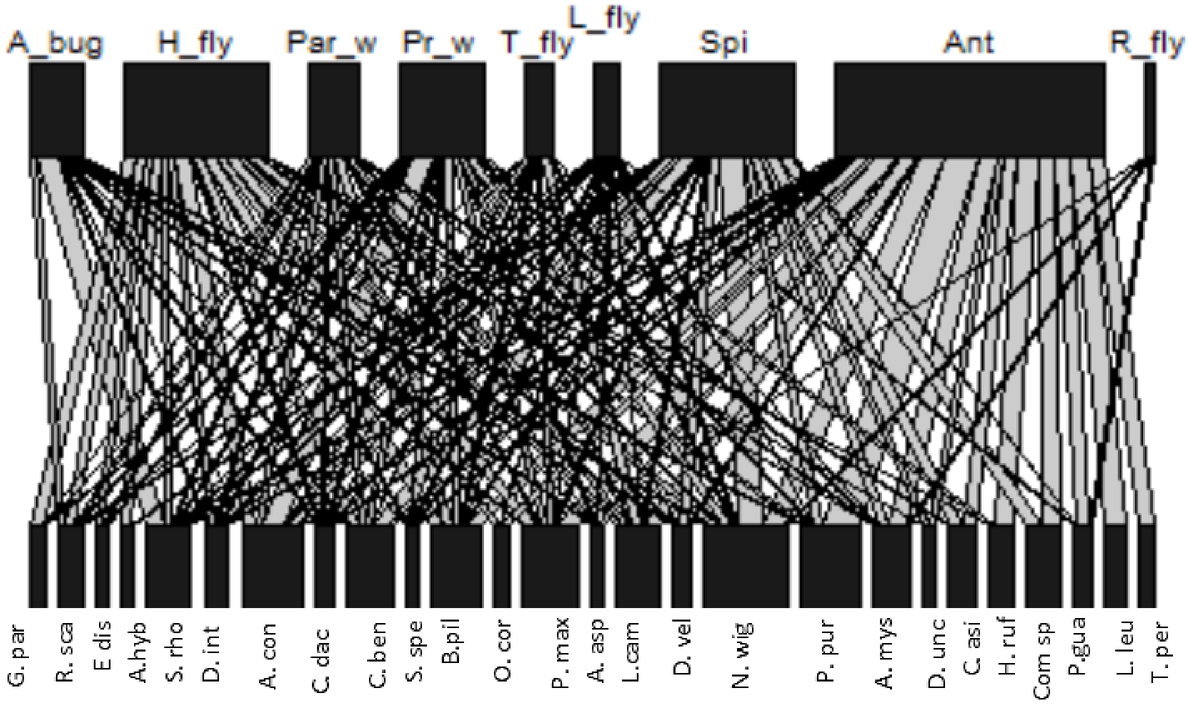

Figure 35: Bipartite network between natural enemies and field margin plants in the mid elevation zone in Northern Tanzania

Each bar in the upper row represents natural enemies and each bar in the bottom row represents field margin plant species. The width of the bars is proportional to the number of interacting partners. Full names of the natural enemies and plant species are given in Appendix 4.

4.1.25 Identified Field Margin Plants Supporting Natural Enemies in the Low Elevation Zone

Ants were the most abundant in the low zone and interacted mostly with the napier grass (*P. purpureum*) like in mid zone (Fig. 36). To reduce the complexity and to increase the visualization of other natural enemy groups, ants were excluded, and the resulting graph is shown in Fig. 37. *Richardia scabra* and *Euphorbia heterophyla* were the common margin plants in low zone after *P. purpureum* which were highly attractive to ants and hoverfly. *Bidens pilosa* was highly attractive to predatory wasps. Only few long legged fly were present in low zone and they interacted more with *Panicum maximum* compared with elephant grass. Other natural enemies were less abundant with no strong interaction to particular plant species.

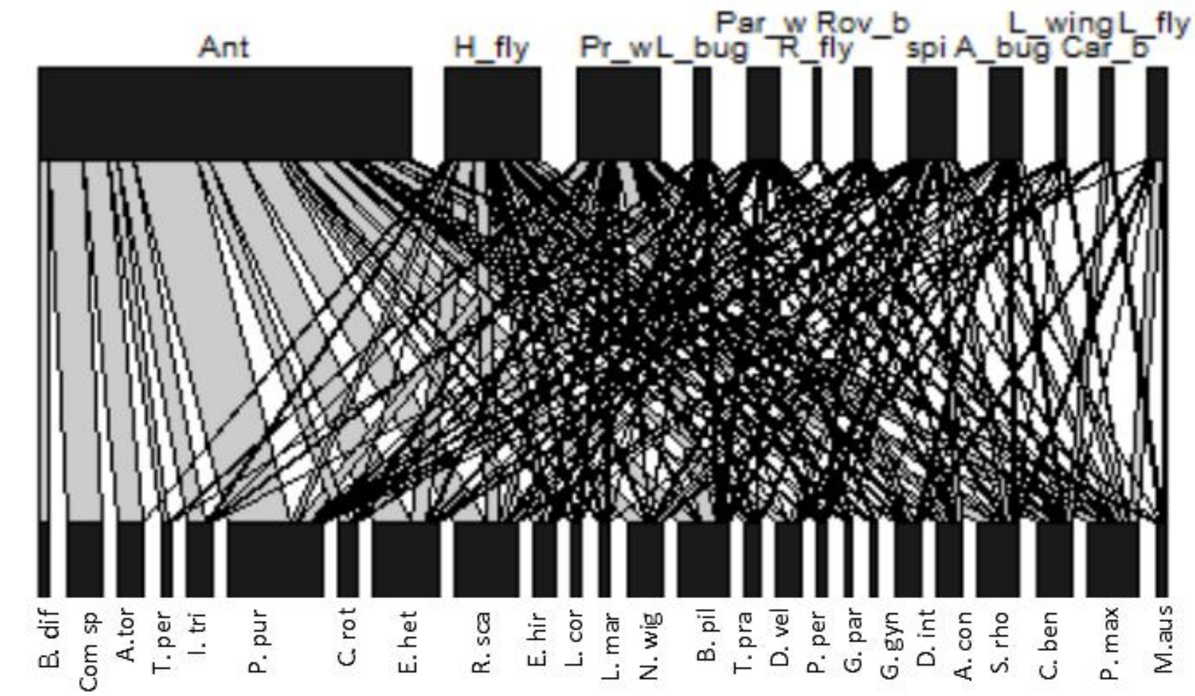

Figure 36: Bipartite network between natural enemies and field margin plants in the low elevation zone in Northern Tanzania

Each bar in the upper row represents natural enemies and each bar in the bottom row represents field margin plant species. The width of the bars is proportional to the number of interacting partners. Full names of the natural enemies and plant species are given in Appendix 4.

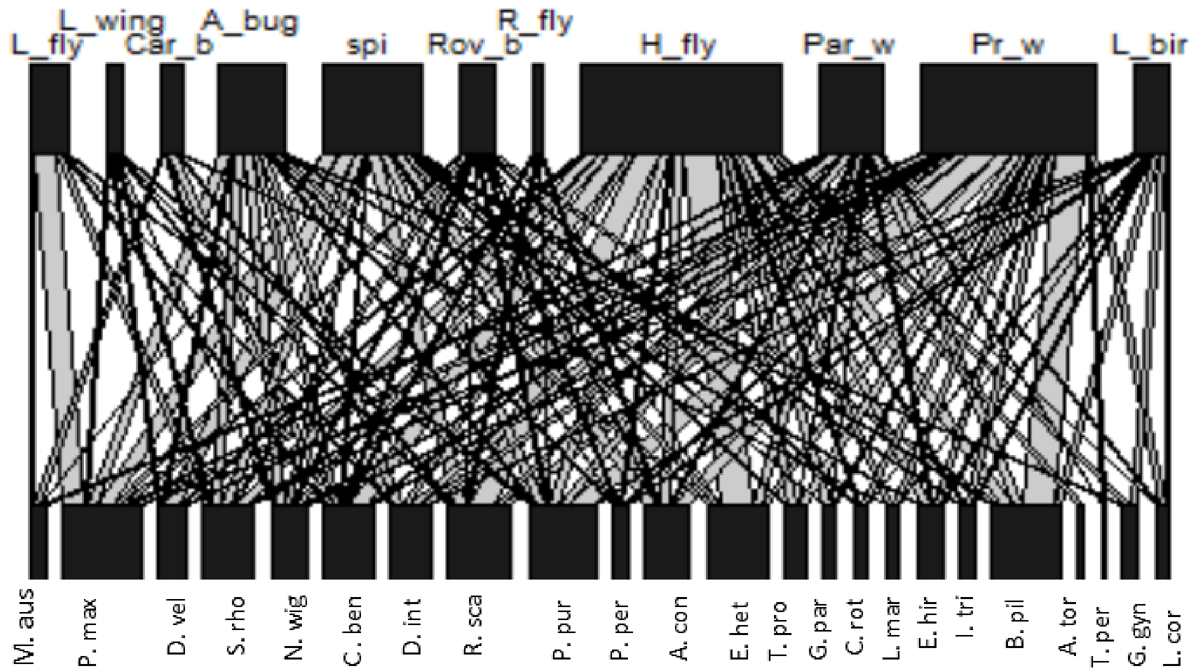

Figure 37: Bipartite network between natural enemies and field margin plants in the low elevation zone, excluding ants which were the most dominant group

4.2 Discussion

A significantly greater number of women compared with men were involved in bean farming, which is consistent with earlier studies (Aina, 2006; Isaya *et al*., 2016; Oyeniyi & Olofinsawe, 2015). Male participation in agriculture increased from the low zone to the high zone, a trend that may be influenced by differences in the cropping system where in the high zone the cropping system was mainly polyculture (beans, maize, coffee, banana, vegetables, potatoes and other crops), whereas in low and mid zones it was usually monocrop (beans or maize only) or mixed cropping (beans, maize and sunflower).

Prior to training the majority of the farmers were not aware of the natural enemies and considered them as insect pests. Lady beetles were among the common natural enemies in the area but farmers considered them to be similar to *Ootheca* which is a pest. Blister beetles are among the most apparent insect pests in the area (personal observation) but the majority of farmers did not identify them as as a pest. This agrees with Banjo *et al*. (2003) and Blodgett *et al*. (2010) who found the blister beetles were not considered as a serious pest despite being found infesting several crops, and causing considerable damage due to their gregarious and polyphagous nature. A possible reason is that beetles feed on the flowers and may be confused with honey bees. This is also revealed by Lebesa *et al*. (2012) who reported that majority of farmers did not employ any control measure against blister beetles due to poor knowledge. Aphids were the most identified pest by the farmers and were mentioned as the most damaging insect pest. This concurs with published literature about the most common insect pest for this crop in Africa (Abate & Ampofo, 1996).

Pest management was very much oriented to chemical pesticide use by the calendar rather than using damage assessments and with little knowledge on the side effects of the chemicals. A large percent of the farmers from low and mid zones were highly dependent on synthetic pesticides, a practice also reported by several studies conducted in Tanzania (Halimatunsadiah *et al*., 2016; Ngowi *et al*., 2007; Williamson *et al*., 2008). Synthetic pesticides are registered products, so farmers do not see a reason why they should not be used because they did not consider the impacts of the misuse of synthetic pesticides to the environment (Korir *et al*., 2015). Overuse of synthetic pesticides may be partly due to farmers' lack of knowledge of other pest management options (especially biological control) together with lack of awareness on the impacts of synthetic pesticides on potentially beneficial non-target organisms such as natural enemies of pests. Post-training results confirmed this, where majority of the farmers proposed to use non-synthetic approaches in pest control such as pesticidal plants which have lower impacts on natural enemies (Amoabeng *et al*., 2017; Mkenda *et al*., 2015; Mkindi *et al*., 2017; Tembo *et al*., 2018). Agricultural training is one of the ways that could help the farmers to be better informed of current agricultural techniques and practices. The percent of farmers who had never attended any training is high compared with the findings of a similar study conducted in the Kilolo district in the Iringa region of Tanzania where 51% of respondents had never attended any training (Mwamakimbula, 2014). There is a need to assess whether it is due to few training events available or is due to lack of information regarding those training events among the farmers, thus resulting in only a few farmers attending. Mwamakimbula (2014) also found that of those who never attended training, 51.7% said it was because they did not get information about the training while 40% did not know when the training events are conducted. Unlike other reported studies (Mtega *et al*., 2016; Mudege *et al*., 2017; Riley, 1995) suggesting women had less access to formal education or training events, the results of this study showed no significant difference between males and females.

Other reported motives for increased chemical pesticide use include increased insecticide resistance, planting of crop varieties that are highly susceptible to pests, ineffective pesticides, market growth in ‘discount’ and often unauthorized pesticides, subsidy and donations and lack of attention to the economics of pest management (Williamson *et al*., 2008). Among the agricultural subsidies that were provided by the government in the study area were pesticides and fertilizers. However, there is a need to rethink whether the agricultural subsidies are causing more harm or good with regard to sustainability in agriculture (Dorward, 2009). This is because the agricultural subsidies may lead farmers to overuse fertilizers and pesticides, leading to negative environmental impacts including impacts on beneficial arthropods. Sustainability in agriculture requires production practices that are less dependent on external inputs such as chemical pesticides and fertilizers, otherwise food security will never be achieved and damage to environment and other non-target organisms will persist (Kremen & Miles, 2012). The frequency of pesticide use was again very high (more than two times per season) in low and mid zones as compared with the high zone (less than one per season). A similar study in Tanzania by Ngowi *et al*. (2007) found pesticide applications to be up to 5 times per cropping season and where 53% of the farmers reported an increasing trend in pesticide use. Several studies have reported on the increased pest infestation with decreased beneficial insects in the fields as a result of misuse and/or overuse of synthetic pesticides (Belmain *et. al*., 2013; Heitala-Koivu *et al*., 2004; Landis *et al*., 2000; Wyckhuys *et al*., 2013).

Synthetic pesticide use challenges expressed by the farmers were similar to the findings of other studies (Ngowi *et al*., 2007; Ntow *et al*., 2006). The most frequently reported negative perception of pesticide use was health problems, which are usually associated with poor pesticide use practices. Similar results have been reported by Ashburner and Friedrich (2001), Matthews *et al*. (2003) and Sibanda *et al*. (2000) as very common problem in African countries. Common misuse practices include use of inappropriate products, incorrect dosage, leaking application equipment, use of cocktail mix of several pesticides, tongue testing of concentration and non-use of protective gear such as face masks, gloves and shoes. This study found majority of the farmers were not using any protective equipment during pesticide application, a clear evidence of the poor pesticide use practices, as also reported by Amoabeng *et al*. (2017) that 77% of the farmers surveyed were not using protective gears during synthetic pesticide application. Although the health of the farmers is clearly affected by misuse of synthetic pesticides, farmers usually do not report the symptoms to local health centres and are unlikely to understand longer term chronic effects of exposure. According to Margni *et al*. (2002) most of the health problems associated with synthetic pesticides use are neurological and may not be easily recognized by the medical community due to the fact that pesticides consist of active ingredients as well as inactive ingredients which are difficult to identify. Farmers need to be given all the appropriate information on the negative effects associated with the use of chemical pesticides as well as alternative eco-friendly methods of managing pests.

Many farmers identified that they lacked important agricultural knowledge and information which could help them in making an informed decision in their day to day agricultural practices, due to limited number of information distribution sources. A study by Adhiguru *et al*. (2009) and Ronald *et al*. (2014) also found most of the smallholder and marginal farmers had poor access to agricultural knowledge and information due to insufficient information sources available. Aina (2006) reported that some farmers were unable to access agronomic information and may even go for five years without coming into contact with extension officers. While agricultural officers were found to be the major source of information, many farmers were not satisfied with their service because of inadequate frequency of interaction owing to few officers to cover all areas. A major concern by farmers was the need for government to increase the number of agricultural officers so that they could have access to better knowledge and information and more frequently. This concurs with other studies conducted in Tanzania by Adam *et al*. (2015), Aina (2006), Elly and Silayo (2013), Mtega *et al*. (2016), Siyao (2012) and Lwoga *et al*. (2011) who also found that the limited number of extension officers did not allow for effective information dissemination. The second most important source of information was found to be researchers. These findings are supported by Daniel *et al*. (2013), Lwoga *et al*. (2011), Msoffe and Ngulube (2016) and Mtega *et al*. (2016) who also found researchers as an important source of knowledge and information to the farmers. However, in our study it was found that while many researchers provided useful information at the beginning of their research projects, once projects finished no one returned to the farmers to monitor longer term implementation and scale up of the knowledge gained. There is a need for researchers to work very closely with farmers as well as agricultural extension officers for effective knowledge dissemination and sustainability even after research projects cease. Various research findings which could have increased efficiency in agricultural productivity are not known or applied by the farmers due to poor research dissemination (Lwoga *et al*., 2011). Farmers have limited access to much of agricultural information from research institutions, universities and public offices despite being the target group for this information. Farmer research networks (FRN) have been cited as an effective option of involving farmers in research for more uptake of knowledge (Nelson *et al*., 2016). Farmer Field Schools (FFS) have also been promoted as a practical approach of disseminating knowledge among farmers (Nelson *et al*., 2001). Khatam *et al*. (2010) reported some of the advantages of FFS to be self-confidence, skills and knowledge improvement, helping farmers in learning by doing and discouraging the use of pesticides while motivating farmers in using homemade pesticides thereby conserving the environment. These information sources were also found to be useful from other studies (Isaya *et al*., 2016; Lwoga *et al*., 2011; Magesa *et al*., 2014; Mtega *et al*., 2016).

These results support the findings that biological control may be well-practiced in many developed countries (Pretty & Bharucha, 2015), but it is poorly applied in most sub-Saharan African countries (Wyckhuys *et al*., 2013). The reason for such poor applicability is associated with poor knowledge about natural pest control, indicating the need to bridge the gap that exists between research institutions and smallholder farmers. Pest management through conservation biological control will reduce the cost of production by smallholder farmers who usually have poor access to external inputs. Mkenda *et al*. (2017) reported the need to identify innovative and acceptable ways of integrating biodiversity in food production systems for sustainable agriculture with emphasis on conservation biological control.

The field survey revealed a significant number of natural enemies from different taxa that could be exploited through conservation biological control. The differences in the abundances of natural enemies between zones can be explained by both environmental and human factors associated with management practices. The findings of objective one of this thesis showed the high zone was mostly dominated with organic farming as compared with mid and low zones where they mostly apply synthetic agricultural inputs. Organic agriculture promotes and maintains the beneficial insects since it involves the augmentation of ecological processes for sustainable agricultural production, with no harmful effect to the environment and non-target organisms (Kremen *et al*., 2012; Pimentel *et al*., 2005). Most of synthetic pesticides are associated with negative effects to the environments and non target organisms including the beneficial insects. Likewise, the use of synthetic pesticides for low and mid zones may have resulted to pesticide resistance which consequently increased pest infestation levels as also reported by Lekei *et al*. (2014) and Ngowi *et al*. (2001). The fact that the high zone was leading in terms of natural enemy abundance while was the least in insect pest abundance possibly suggests the existence of pest control service where the insect pests were reduced by the natural enemies.

Terrestrial flora may also play a significant role in natural enemy population and several studies show the abundance of natural enemies is high with low insect pest abundance in ecosystems rich in non-crop vegetation than in simplified landscapes (Alomar *et al*., 2006; Bianchi *et al*., 2006). Assessment of the field margin plant composition showed the high zone had more plant species compared with low and mid elevation zones, and in most cases the low and mid elevation zones shared most of the plant species than the high elevation zone. This is because the climate conditions for low and mid zones were closely related as compared with the high zone, which consequently influenced the plant composition. During the dry season, bean fields in the low and mid elevation zones are almost bare, with the plant vegetation being found only in the margin, whereas in the high elevation zone the fields retain significant in-field weeds and wild plants throughout the year. This was manifested from the vegetation cover assessment which increased from low elevation zone to high elevation zone. The natural enemy abundance also followed a similar trend, possibly suggesting the importance of vegetation cover to natural enemy population. This is in agreement with Bischoff *et al*. (2016) who also found vegetation cover significantly influenced the abundance of beneficial insects. However, the Shannon-Weiner diversity index of the natural enemies decreased with elevation from low to high elevation zone, while the Shannon-Weiner diversity index of the margin vegetation increased from low to high elevation zone. According to Fonge *et al*. (2013), a rich ecosystem should have a Shannon diversity index ≥ 3.5, therefore the diversity index for the high zone which was 3.44 was very close to a rich ecosystem while the low and mid zones were less rich ecosystems in terms of plant species. Similarly, the ENS for the high zone was close to ENS for a rich ecosystem that is 33 according to Beck and Schwanghart (2010), meaning that there were more plant species evenly distributed in the high elevation zone as compared with other zones.

The insect pest abundance was not related to the % vegetation cover since the high zone with the highest vegetation cover had fewer insect pests compared with the other zones. This agrees with earlier findings that the non-crop vegetation around agricultural lands increases the natural enemy population while decreasing the insect pest population (Alomar *et al*., 2006; Bianchi *et al*., 2006; Bischoff *et al*., 2016). Quality of vegetation around agricultural systems throughout the year determines food and habitat provision to beneficial insects all the time, the opposite of which may lead to fewer natural enemies with increase in pest population. Semi natural habitats around agricultural fields act as reservoirs and source of natural enemies to recolonize the crop area after disturbance, ensuring sufficient population of natural enemies for pest control (González *et al*., 2016). The overall landscape structure across the three zones may also explain the differences in natural enemy and insect pest abundances, pressing the need for landscape assessment in these areas.

The fact that the natural enemy abundance was higher within the field margin than within the bean field for low and mid elevation zones provides evidence that non-crop vegetation around agricultural lands act as refuge sites during agronomic disturbance like pesticide application. The farmers from low and mid elevation zones were highly using synthetic pesticides compared with the high elevation zone. Consequently, natural enemies were more abundant along the field margin than within the bean field for low and mid elevation zones, unlike in the high elevation zone where they were more abundant within the bean field. This agrees with other studies that found the non crop vegetation around agricultural lands as useful in supporting the survival and activities of natural enemies especially under hostile field conditions (Amaral *et al*., 2016; Atakan, 2010; Rouabah *et al*., 2015, Torretta & Poggio, 2013). The flowering vegetation along the field margins are useful in provision of pollen and nectar as alternative food resources to different natural enemy groups. For example, Bianchi and Wäckers (2008) found the parasitoids were more enhanced at the field margin as a result of attractivenes of the flowers and nectar of the margin plants. However, despite the fact that natural enemies were more abundant along the field margin than within the bean field, there was no significant difference in biological control between the margin and field centre. This show the centre of the field still received comparable pest control service as the field edge. This was confirmed by the use of a dye marker applied to margin vegetation which demonstrated common natural enemy taxa (including parasitoid and predatory wasps, assassin bugs and hoverflies) were frequently moving from the margin to the crop. The proportion of dye marked natural enemies (showing their origin to be margin vegetation) sampled from the crop was above 60% for common taxa, suggesting high levels of spatial flux in the arthropod assemblage.

The difference among elevation zones in the movement of the dye marked natural enemies from the margin to field was associated with the marked difference in field sizes. The bean fields in the high zone are around one quarter the size of fields in other zones. This small size makes it easier for any given insect from the field population being in the margin at the time of spray of dye with less distance to move between the two locations, hence higher proportions of marked insects were found in high elevation zone than in low and mid elevation zones. The fact that the dye marked insect proportions decreased with distance from the margin to the field in low and mid elevation zones with no significant difference in the high elevation zone can also be explained by the effect of field size. A similar study by Heimoana *et al*. (2017) also found a decreasing number of dye marked insects from the margin up to 100 m distance into the field regardless of the type of margin vegetation. This is further supported by Denisow and Wrzesien (2015) where the effect of distance from the field margins to the crops was considered to influence the movement of beneficial insects and hence the ecosystem services provision in the crop.

However, with time, the marked natural enemies would be uniformly distributed within the field as revealed from the insects sampled by the pan traps at different distances within the bean fields. The effect of small field size which is a characteristic of many smallholder farming systems (Timler *et al*., 2014) accounts for the uniform distribution of the natural enemies in the fields. This is contrary to other studies (Boetzl *et al*., 2018; Fusser *et al*., 2018; Rouabah *et al*., 2015) that reported a significant edge effect in the distribution of ground dwelling natural enemies that were sampled by pitfall traps within 60 m distance from the margin. The use of pan traps in this study biased the catch of more mobile natural enemies compared with less mobile, which may account for the relatively uniform distribution within the field. Previous studies have established that some beneficial insects are highly mobile and can move up to 100 m into a field away from the margin (Heimoana *et al*., 2017). Therefore, the edge effect to the natural enemies mainly depends on the mobility of the natural enemies, the distance or farm size as well as the sampling technique involved as revealed in this study.

Unlike the natural enemies, the insect pests were more abundant within the bean field than along the field margin in all the three zones. This provides evidence of the importance of field margin vegetation around the smallholder tropical farming systems in supporting beneficial insects as also reported in other agricultural systems (Amaral *et al*., 2016; Atakan, 2010; Landis *et al*., 2000; Rouabah *et al*., 2015, Torretta & Poggio, 2013). However, it should be noted that there are circumstances where field margin may be the source of insect pests in the field, like the presence of host or susceptible margin plants which lead to build up of insect pests and subsequent infestation in the field (Arnó *et al*., 2016; Diepenbrock *et al*., 2016; Kenis *et al*., 2016). In this study, there was no evidence of the presence of host plant of incect pests in the margin that could lead to more insect pests in the field. However, continous monitoring of the influence of field margin plants to different insect population is important for effective pest management.

The natural enemies showed similar preferences to certain field margin plants across the three elevation zones. For example, ants were found to interact more with napier grass (*P. purpureum*) in low and mid elevation zones and in the high elevation zone to guatemala grass (*T. laxum*) which are structurally similar. Predatory wasps, parasitic wasps and hoverfly were highly interacting with *A. conyzoides* in all the three zones, justifying the importance of these plants to natural enemies in different areas. Most of creeping and climbing plants were found to support several ground dwelling natural enemies due to their potential in providing microhabitats with increased vegetation complexity. *Drymaria cordata* and *C. asiatica* both of which are creeping plant species are reported to harbour several natural enemies especially spiders (Mukti *et al*., 2014; Sadof *et al*., 2014; Withaningsih *et al*., 2018) as also observed in the high zone. Likewise, in the mid elevation zone spiders were more interacting with *N. wightii* and *C. benghalensis* which are mostly climbing and creeping plant species respectively compared with other plants. These weed plant species are among the most reported plants of agricultural importance within the small holder farming communities of Africa (Hillocks, 1998). *Ageratum conyzoides* is one of the known plant species with several floral visitors searching for pollen and nectar (Amaral *et al*., 2013; Lin *et al.*, 1993; Ngongolo *et al*., 2014), signifying its importance as a food resource to beneficial insects when grown around agricultural land. The importance of *A. conyzoides,* and *B. pilosa* in promoting the survival and activities of predators is also reported by Amaral *et al*. (2013). Assassin bug were highly attracted by *Sida rhombifolia*, and according to Cruz *et al*. (2013), it is among the spontaneous plants in agro ecosystems that habour predatory mites and other several species important in natural pest control. It can therefore be considered as potential field margin plant for enhancing the beneficial insects within the smallholder farming systems. *Tripscum laxum* is a commonly known fodder plant in tropical countries including Tanzania due to its high nutritive values (Singh, 1999). However, there is limited information on whether the plant is useful in attracting beneficial arthropods. This study therefore, gives useful information on the additional benefits of *T. laxum* as an enhancer of natural enemies, particularly long legged fly in the field. Most of the field margin plants that had strong interaction with the natural enemies are reported by other studies to be potential in enhancing their population through provision of alternative food resources, nesting sites and refuge sites. For example, *R. scabra* and other several margin plants are reported as potential in maximizing multiple ecological services (Olson & Wäckers, 2007). *Panicum* and other grass species are highly used in the construction of beetle banks (Hopwood *et al*., 2016) and as fodder for animals (Fernandes *et al.,* 2014) with very limited information on its importance in habouring natural enemies around agricultural lands. This study has therefore added some useful information on the multiple uses of these grass species, particularly *Panicum maximum*, *P. purpureum* and *T. laxum* for enhancing natural pest control in smallholder farming ecosystems. Lady beetles were very abundant in the field but very few along the margin plants, and this is supported by Olson and Wäckers (2007) who also found the abundance of ladybeetle to increase from the margin towards the field centre. They are known to prefer floral resources only when their host insect pests, particularly the aphids are scarce (Hatt *et al*., 2017; Lundgren *et al*., 2009).

Assessment of predation rate of aphids by lady beetle under green house conditions showed an increased rate of predation with aphid density because the aphids were readily available for consumption by lady beetle at higher aphid density compared with low density where it required more time for searching. This is in agreement with another study by Shrestha and Parajulee (2013) who also reported on the increased feeding rate with increase in aphid density. Taleb and Sardar (2007) and Zhang *et al.* (2001) also reported the rate of consumption by predators to be correlated with the prey density where the consumption rate increased significantly with time and prey density. This indicates the potential of lady beetle in eradicating aphids and raised an interest to assess the predation rates in field conditions in comparison with the aphid density. Field results showed the number of lady beetles increased with aphid density, an indicator that, the natural enemies in the field usually increase with increases in pest density below the economic threshold level. Hesler (2014) reported similar results that the predators (arachnids and coccinellids) were positively correlated with aphid density. This is because lady beetles oviposit where there is sufficient aphid density to ensure the survival of their larvae, since larvae are flightless and less mobile and may suffer starvation if aphids become locally extinct before they are full developed (Hemptinne *et al*., 2000). There was no significant relationship between field aphid density and percent parasitism of sentinel aphids in all the three zones, unlike other studies (Alaserhat & Canbay, 2017; Hatt *et al*., 2017) that found a significant increase in number of mummies and parasitism rate with increased aphid density. This shows biological control activity may be influenced by several factors leading to erratic pest control service in different areas as also reported by Karp *et al*. (2018) that both insect pests and natural enemies exhibit inconsistent responses to the surrounding landscape. This calls for a need to assess the landscape features and other environmental factors that affect the extent of ecosystems services in a particular area.

Field size in relation to non-crop vegetation abundance explains the ecosystem services provided within the agricultural land. Other reported factors that may influence natural enemy abundance and biological control activity in field include weather conditions, plant composition, pest density, age structure of the pests, intraguild predation and poor dispersal of the biocontrol agents from the field margin vegetation (Fischer *et al*., 2013; Parajulee *et al*., 1994; Tscharntke *et al*., 2016). Therefore, understanding the fundamentals of interactions between prey and predator and the influence of other environmental factors on biological activity is important for effective pest control.

Aphidius *colemani* was a primary parasitoid of bean aphids, *A. fabae* within the smallholder bean farming tropical ecosystems. *A. colemani* was also accompanied by two species of secondary parasitoids which were *P. aphidis* and *Charipinae* species. *Aphidius colemani* is a solitary endoparasitoid, potentially known biological control agent against several species of economically important aphids including *Aphis fabae*, *Aphis gossypii*, *Rhopalosiphum padi* and *Myzus persicae* (Benelli *et al*., 2014; Vásquez *at al*., 2006). It is widely used in biological control programs since 1970s (Prado *et al*., 2015). Due to its potential in pest management, it is commonly reared in commercial scale and released in crops for pest control in most European countries (Benelli *et al*., 2014). Some of the characteristics which make *A. colemani* a potential biocontrol agent include greater dispersal distance and high searching ability (Heinz, 1998). A study by Vásquez *at al*. (2006) found no significant difference between *A. colemani* and synthetic pesticide (imidacloprid) in managing aphid population in greenhouse conditions, signifying the potential of this parasitoid wasp in aphid control. However, the efficiency of *A. colemani* is affected by both biotic and abiotic factors where hyperparasitism is reported among the most important biotic factors since it affects the abundance of the primary parasitoids as well as modification of their behaviour (Prado *et al*., 2015). Some of the reported behavioral change includes abandonment of the patches by the primary parasitoid females in presence of hyperparasitoids regardless of aphid density in order to minimize the mortality rate of their progeny (Acebes & Messing, 2013). This means at high hyperparasitoid population, there is more dispersal of the primary parasitoids from the patches with no complete exploitation of the aphids. Another study by Höller *et al*. (1993) investigated the relationship between primary and secondary parasitoids, to establish whether or not the hyperparasitoids interfere the primary parasitoids and found 33% aphid parasitism by primary parasitoids and up to 100% hyperparasitism where multiple linear regression models confirmed that the female primary parasitoids leave the patches under high hyperparasitoids density. With regard to this, it is possible that the aphids may have evolved some mechanisms that attract more secondary parasitoids as already reported that some of the secondary parasitoids are attracted by the volatiles from aphid honeydew (Budenberg, 1990). It is further reported that, aphid reproduction increased in the presence of volatile chemicals released from secondary parasitoids without physical contact in the field, signifying some kind of communication between the aphids and secondary parasitoids (Boenisch *et al*., 1997; van Veen *et al*., 2001). However, there is a need for more field experiments to investigate the aphid-primary parasitoids-secondary parasitoids interactions and the possible consequences in pest control. The level of hyperparasitism of *A. colemani* in agricultural systems range from low to very high and sometimes it may go up to 100% (Gariepy & Messing, 2012). In our study, the low zone had high percent of hyperparasitism compared with the other two zones and this may vary depending on cropping season. It is reported that hyperparasitism did not interrupt aphid control during spring season in the Netherlands while in summer the aphid control failed completely due to hyperparasitism (Van Steenis & El-Khawass, 1995). This being the case, there is a need for continuous monitoring of the hyperparasitism levels in different cropping seasons to find the range of maximum and minimum percent hyperparasitism and their implications in aphid control. Further field manipulations that will promote more primary parasitoids like provision of food resources that increase their fecundity without favouring the hyperparasitoid population are also important.

Colours of pan traps varied significantly in the numbers of insects caught, with important effects of taxon. Specifically, the yellow pans caught highest numbers of most natural enemy taxa, with the exception of tachinid flies (most abundant in white pans) and rove beetles (most abundant in blue pans), and some taxa such as lacewings and spiders showed no preference. This is likely to relate to the visual ecology of different species and the cues they use to navigate the landscape. These findings accord with various other studies on natural enemy groups using pan trap sampling, finding preferences for yellow traps in Syrphidae (Laubertie *et al*., 2006; Campbell *et al*., 2010), parasitic wasps (Abrahamczyk *et al*., 2010) and analogously, Coccinellidae on yellow sticky cards (Udayagiri *et al*., 1997). Rodriguez-Saona *et al*. (2012) also found a lack of colour preference among lacewings and spiders as it was found in this study. However, our findings contrast with other studies, such as Leksono *et al*. (2005), which did find a blue preference when pan-trapping Staphylinidae, but only amongst the traps set at 10 m and 20 m, rather than at 0.5 m which is more analogous to the approach taken here, and Hoback *et al*. (1999) who observed higher Syrphidae catches in blue traps.

Conversely, pests were caught in highest numbers in the blue pans in our study. This corresponds to numerous studies of thrips, which show a preference for blue traps (Devi & Roy, 2017), to the point where blue sticky traps are commercialized for thrips control, whereas aphids are more typically caught using yellow traps (De Barro, 1991; Webb *et al*., 1994) as were Chrysomelidae when both blue and yellow pan traps were deployed (Leksono *et al*., 2005). Similar results were reported by Ashfaq *et al*. (2005) where it was found 42-51% of insects pests were attracted to black colour light followed by blue colour (18-22%) and yellow colour was only 8-10%. In our study blister beetles showed a particular preference for blue, which accords with other studies from East Africa (Lebesa *et al*., 2011). Overall this emphasizes the importance of trap colour on attractiveness to differing arthropod taxa such that studies aiming to generate a broad understanding of an arthropod community need to use more than one colour. Further, assumptions on the optimal colour for a given taxon based on data from temperate regions do not consistently hold true.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The present study identified a critical lack of knowledge among smallholder farmers about beneficial insects which will impact the uptake of conservation biological control. Farmers lack understanding of the importance of biodiversity on farms and its role in pest management, and lack training around use of local and botanical pest control methods. The current practice in pest management has been the use of synthetic pesticides that is usually applied at inappropriate rates and based on calendar rather than damage assessment, leading to not only pesticide resistance but also health problems to the farmers, consumers and the non-target organisms in the environment.

The field survey revealed a significant number of natural enemies from different taxa that potentially can be enhanced through conservation biological control within the smallholder farming systems. The field margin vegetation around the smallholder bean production systems is an important donor habitat for natural enemies and could support biological pest control in adjacent crop fields. However, farmers have been killing the natural enemies by synthetic agricultural inputs and destroying or uprooting the margin weeds due to lack of knowledge about natural pest control and the importance of farm biodiversity in enhancing the biocontrol agents. Farmers were not only fumbling in dark, but also unknowingly destructing the environment with the associated biodiversity and ecosystem services. Africa is well known worldwide in terms of its biodiversity, however, it is not sufficiently integrated into agriculture sector due to several reasons including limited research. Low adoption of different agricultural techniques is associated with the lack of agricultural information among the farmers due to poor linkages between knowledge providing institutions and farming communities. Researchers are failing to disseminate their findings effectively to farmers, the end-users. Addressing these barriers will enable movement towards more environmentally sustainable crop production.

5.2 Recommendations

i) The results of this study indicate a need to improve farmer knowledge through training events or farmer field schools to demonstrate good farming practices that will enhance conservation biological control. Education on alternative ways to manage the pests as well as safe use of various agricultural inputs will reduce the reliance on and use of chemical pesticides, thereby promoting natural pest control.

ii) Farmers should be trained on the importance of checking the presence of pests and the level of damage before application of any pest management technique in order to break the practice of calendar based pesticide use.

iii) Improved knowledge among technical officers is necessary for enhancing information dissemination to the farmers. This can be achieved through in-service trainings and involvement of agricultural extension officers to scientific meetings, seminars, workshops and conferences where they will receive updates of the current agricultural issues important in improving crop production. The curricular for training the agricultural officers need to be frequently updated in order to include the current agricultural technologies and other emerging issues in agriculture sector.

iv) Development and adoption of phone based information dissemination system that will help farmers in identification of insects in the field by sending the picture of the insect through the mobile system or get information on appropriate use of pesticides by scanning the pesticide label and send it through the phone for details and advice.

v) Further studies on ecological intensification including the manipulation of specific vegetation types in comparison with fields where there is no margin vegetation over a long period are important in the assessment of contribution of margin vegetation to biological pest control and bean yield within smallholder bean farming systems.

vi) Assessement of economic viability of conservation biological control is necessary for its better adoption among the smallholder farmers. However, there is a need to consider socio economic as well as ecological factors in the assessment due to the fact that, conservation biological control is a sustainable pest management option which fous on the needs of the current and future generation rather than only on the current yield.

vii) Network analysis confirmed that many of the natural enemy guilds interacted with diverse wild plants, including several species with pesticidal or medicinal properties (e.g. *A. conyzoides*, *Bidens* sp., *Tithonia diversifolia*, and *Ocimum gratissimum*).

Other plants like *C. benghalensis*, *C. asiatica*, *T. luxum*, *P. purpureium, N. wightii*, *Richardia scabra* and *Euphorbia heterophyla* were also found to enhance several predators and parasitoids. Many of these plants have a longer flowering season than the crop itself so play a role in supporting natural enemy communities, as well as conferring further ecosystem services. However, promotion of these species should proceed with care and sensitivity as many are introduced exotics from other tropical biomes.

Farmers should be encouraged to observe and identify the best field margin vegetation for enhancing the beneficial insects with proper field margin management practices which will ensure high population of beneficial insects within the bean fields. Addressing all these will enable movement towards a more environmentally sustainable crop production system.

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APPENDICES

Appendix 1: Sequencing results of aphid (*A. fabae*) parasitoids sampled in smallholder bean fields of Moshi rural district in Tanzania

Sample ID	BLAST match species	BLAST accession	Percentage similarity
1	*Aphidius colemani*	MF958484	99
2	Unsuccessful		
3	*Aphidius colemani*	MF958484	99
4	Unsuccessful		
5	Unsuccessful		
6	Unsuccessful		
7	*Pachyneuron aphidis*	KY844368	94
8	*Pachyneuron aphidis*	KY844368	94
9	*Pachyneuron aphidis*	KY844368	94
10	Unsuccessful		
11	*Charipinae* sp.	KR934949	90
12	*Aphidius colemani*	MF958484	99
13	*Aphidius colemani*	MF958484	99
14	*Aphidius colemani*	MF958484	99
15	*Aphidius colemani*	MF958484	99
16	*Aphidius colemani*	MF958484	99
17	*Aphidius colemani*	MF958484	99
18	*Aphidius colemani*	MF958484	99
19	*Aphidius colemani*	MF958484	99
20	*Aphidius colemani*	MF958484	99
21	*Aphidius colemani*	MF958484	99
22	*Aphidius colemani*	MF958484	99
23	*Aphidius colemani*	MF958484	99
24	*Aphidius colemani*	MF958484	99
25	*Aphidius colemani*	MF958484	99
26	*Aphidius colemani*	MF958484	99
27	*Aphidius colemani*	MF958484	99
28	*Aphidius colemani*	MF958484	99
29	*Aphidius colemani*	MF958484	99
30	*Aphidius colemani*	MF958484	100
31	*Aphidius colemani*	MF958484	99
32	*Aphidius colemani*	MF958484	99
33	*Aphidius colemani*	MF958484	99
34	*Aphidius colemani*	MF958484	99
35	*Aphidius colemani*	MF958484	99
36	*Aphidius colemani*	MF958484	99
37	*Aphidius colemani*	MF958484	99
38	*Aphidius colemani*	MF958484	99

39	*Aphidius colemani*	MF958484	99
40	*Aphidius colemani*	MF958484	99
41	*Aphidius colemani*	MF958484	99
42	*Aphidius colemani*	MF958484	99
43	*Aphidius colemani*	MF958484	99
44	*Aphidius colemani*	MF958484	99
45	*Aphidius colemani*	MF958484	99
46	*Aphidius colemani*	MF958484	99
47	*Aphidius colemani*	MF958484	99
48	*Aphidius colemani*	MF958484	99
49	*Aphidius colemani*	MF958484	99
50	*Aphidius colemani*	MF958484	99
51	*Aphidius colemani*	MF958484	99
52	*Aphidius colemani*	MF958484	99
53	*Aphidius colemani*	MF958484	99
54	*Aphidius colemani*	MF958484	99
55	*Aphidius colemani*	MF958484	99
56	*Aphidius colemani*	MF958484	99
57	*Aphidius colemani*	MF958484	99
58	*Aphidius colemani*	MF958484	99
59	*Aphidius colemani*	MF958484	99
60	*Aphidius colemani*	MF958485	100
61	*Aphidius colemani*	MF958484	99
62	*Aphidius colemani*	MF958484	99
63	Unsuccessful		
64	*Aphidius colemani*	MF958484	99
65	*Aphidius colemani*	MF958484	99
66	*Aphidius colemani*	MF958484	99
67	*Aphidius colemani*	MF958484	99
68	*Aphidius colemani*	MF958484	99
69	*Aphidius colemani*	MF958484	99
70	*Aphidius colemani*	MF958484	99
71	Unsuccessful		
72	*Aphidius colemani*	LC260570	99
73	*Aphidius colemani*	MF958484	99
74	*Aphidius colemani*	MF958484	99

Appendix 2: Plant species within the smallholder bean farming systems of Moshi rural district in Tanzania

SN	Family	Species number	Scientific name
1	Leguminosae	15	*Crotalaria polysperma* Kotschy, *Indigofera colutea* (Burm.f.) Merr., *Desmodium triflorum* (L.) DC., *Desmodium intortum* (Mill.) Urb., *Neonotonia wightii* (Wight & Arn.) J.A.Lackey, *Tephrosia villosa* (L.) Pers., *Indigofera colutea* (Burm.f.) Merr., *Delonix regia*, *Acasia tortilis* (Forssk.) Hayne., *Leucaena leucocephala*, *Senna siamea*, *Senna bicapsularis*, *Desmodium uncinatum*, *Senna spectabilis*, *Acrocarpus fraxinifolius*
2	Asteraceae	15	*Ageratum conyzoides* L., *Ageratum houstonianum* Mill. var. houstonianum, *Tridax procumbens* L., *Synedrella nodiflora* (L.) Gaertn., *Launaea cornuta* (Oliv. & Hiern) C.Jeffrey, *Emilia discifolia* (Oliv.) C.Jeffrey, *Acanthospermum hispidum* DC., *Conyza bonariensis* (L.) Cronquist, *Bidens pilosa* L., *Galingsoga parviflora*, *Tagetes minuta*, *Vernonia amygdalina* Del., *Lactuca capensis* L., *Bidens schimperi*, *Bidens pilosa* L.
3	Poaceae	10	*Hyparrhenia rufa* (Nees) Stapf, *Brachiaria xantholeuca* (Schinz) Stapf, *Digitaria velutina* P.Beauv., *Sporobolus pyramidalis* P.Beauv., *Aristida adscensionis* L., *Cynodon dactylon* (L.) Pers, *Panicum maximum* Jacq., *Eragrostis curvula* (Schrad.) Nees, *Pennisetum purpureum* Schumach., *Phleum pratense* L.
4	Euphorbiaceae	9	*Acalypha indica* L., *Acalypha ornata* A.Rich., *Acalypha fruticosa* Forssk. var. fruticosa, *Phyllanthus fischeri* Pax., *Euphorbia inaequilatera* Sond., *Euphorbia Pekinensis* Rupr., *Euphorbia hirta* L., *Euphorbia heterophylla* L., *Ricinus communis* L.
5	Solanaceae	5	*Solanum campylocanthum* A.Rich., *Solanum nigrum* L., *Solanum incanum* L., *Datura Stramonium* L., *Physalis peruviana* L.,
6	Malvaceae:	4	*Malvastrum coromandelianum* (L.) Garcke., *Sida*

	Malvoideae		*rhombifolia* L. var. afrorhomboidea Verdc., *Sida alba* L., *Hibiscus calyphyllus* Cav.
	Malvaceae: Dombeyoideae	1	*Melhania velutina* Forssk.
7	Lamiaceae	3	*Leucas martinicensis* (Jacq.) R. Br., *Hyptis suaveolens* L., *Ocimum gratissimum* L.,
8	Acanthaceae	3	*Asystasia gangetica* (L.) T.Anderson, *Justicia flava* (Vahl), *Asystasia mysorensis*
9	Oxalidaceae	2	*Oxalis corniculata* L., *Oxalis corymbosa* DC.
10	Amaranthaceae	2	*Achyrnthes apera* L, *Amaranthus hybridus* L.
11	Nyctaginaceae	2	*Boerhavia erecta* L., *Boerhavia diffusa* L.
12	Polygonaceae	2	*Rumex abyssinicus* Jacq., *Oxygonum sinuatum* (Meisn.) Dammer
13	Commelinaceae	2	*Commelina foliacea* Chiov. subsp. Foliacea, *Commelina benghalensis* L.
14	Apiaceae	1	*Centella asiatica* (L.) Urb
15	Caryophyllaceae	1	*Drymaria cordata* (L.) Roem. & Schult.
16	Rubiaceae	1	*Richardia scabra* L.
17	Boraginaceae	1	*Trichodesma zeylanicum* (Burm.f.) R.Br.
18	Bignoniaceae	1	*Markhamia*
19	Sterculiaceae	1	*Melhania velutina* Forssk
20	Moraceae	1	*Morus australis* Poir.
21	Resedaceae	1	*Caylusea abyssinica* (Fresen.) Fisch. & Mey.
22	Burseraceae	1	*Commiphora caudate* (Wight & Arn.) Engl.
23	Capparaceae	1	*Gynandropsis gynandra* (L.) Briq.
24	Cyperaceae	1	*Kyllinga* sp
25	Verbenaceae	1	*Lantana camara* L.
26	Papaveraceae	1	*Argemone Mexicana* L.
27	Meliaceae	1	*Azadirachta indica* L.
28	Myrtaceae	1	*Psidium guajava* L.
29	Apocynaceae	1	*Thevetia peruviana* (Pers.) Schumann
30	Proteaceae	1	*Gravillea robusta* A.Cunn. ex R.Br.
31	Convolvulaceae	1	*Dichondra repens* J.R.Forst. & G.Forst.
32	Lauraceae	1	*Persea americana* Mill.
33	Geraniaceae	1	*Geranium arabicum* Forssk.

34	Araliaceae	1	*Hydrocotyle sibthorpioides*
35	Rosaceae	1	*Alchemilla kiwuensis* Engl.
36	Selaginellaceae	1	*Selaginella goudotiana* Spring var. abyssinica (Spring) Bizzarri
37	Urticaceae	1	*Pilea tetraphylla* (Steud.) Blume
38	Anacardiaceae	1	*Mangifera indica* L.
39	Phyllanthaceae	1	*Phyllanthus sepialis Müll.Arg.*
Total	**39 families**	**101 species**	

Appendix 3: Plant species in smallholder bean farming systems that occured in only one or two of three elevation zones of Moshi rural district in Tanzania

Plant species	Low zone	Mid zone	High zone
Acalypha fruticosa	-	✓	-
Acalypha indica	✓	✓	-
Aristida adscensionis	✓	-	-
Asystasia mysorensis	-	✓	✓
Bidens fondosa	✓	✓	-
Boerhavia diffusa	-	✓	-
Centella asiatica	-	✓	✓
Crotalaria polysperma	-	✓	-
Desmodium intortum	✓	✓	-
Desmodium triflorum	✓	-	-
Dichondra repens	-	-	✓
Drymaria cordata	-	✓	✓
Eragrostis curvula	✓	-	-
Euphorbia heterophylla	✓	✓	-
Euphorbia hirta	✓	✓	-
Fern plant	-	-	✓
Sporobolus pyramidalis	-	-	✓
Hydrocotyle sibthorpioides	-	-	✓
Hyparrhenia rufa	-	✓	✓
Lactuca carpensis	-	-	✓
Leucas martinicensis	✓	✓	-
Neonotonia wightii	✓	✓	-
Ocimum gratissimum	-	✓	-
Oxalis corymbosa	-	-	✓
Panicum maximum	✓	✓	-
Pennisetum purpureum	✓	✓	-
Physalis peruviana	✓	-	-
Pilea tetraphylla	-	-	✓
Richardia scabra	-	✓	✓

Sida alba	✓	✓	-
Sida rhombifolia	✓	✓	-
Selaginella goudotiana	-	-	✓
Tridax procumbens	✓	✓	-
Tripsacum laxum	-	-	✓
Senna bicapsularis	✓	✓	-
Solanum incanum	✓	-	-
Pergularia daemia	-	-	✓
Ageratum houstonianum	-	-	✓
Synedrella nodiflora	-	-	✓
Trichodesma zeylanicum	-	-	✓
Boerhavia erecta	-	-	✓
Bidens schimperi	-	-	✓
Commelina foliacea	-	-	✓
Rumex abyssinicus	-	-	✓
Alchemilla kiwuensis	-	-	✓
Geranium arabicum	-	-	✓
Total	**18**	**22**	**24**

Appendix 4: Full names of the plant species and natural enemy abbreviations involved in the bipartite graph

Plant species	**Plant species symbol**	**Natural enemy**	**Natural enemy symbol**
Ageratum conyzoides	A.con	Predatory wasp	Pr_w
Emilia discifolia	E.dis	Assasin bug	A_bug
Bidens pilosa	B.pil	Hoverlfy	H_fly
Centella asiatica	C.asi	Long legged fly	L_fly
Commelina benghalensis	C.ben	Tachnid fly	T_fly
Conyzae bonariensis	C.bon	Parasitic wasps	Par_w
Cyperus rotundus	Cyp	Robber fly	R-fly
Drymaria cordata	D.cor	Spider	Spi
Tripsacum laxum	T.lax	Ladybird beetle	L_bir
Fern species	Fern	Rove beetle	Rov_b
Galingsoga parviflora	G.par	Carabid beetle	Car_b
Oxalis corniculata	O.cor	Lacewing	L_wing
Persea Americana	P.ame		
Psidium guajava	P.gua		
Richardia scabra	R.sca		
Sporobus pyramidalis	S.pyr		
Asystasia mysorensis	A.mys		
Achyranthes aspera	A.asp		
Amaranthus hybridus	A.hyb		
Commiphora sp	Com		
Desmodium intortum	D.int		
Desmodium uncinatum	D.unc		
Pennisetum purpureum	P.pur		
Neonotonia wightii	G.wig		
Cynodon dactylon	C.dac		
Digitaria velutina	D. vel		
Lantana camara	L.cam		
Leucaena leucocephala	L.leu		
Panicam maximum	P.max		

Sida rhombifolia	S.rho		
Senna spectabilis	S.spe		
Thevetia peruviana	T.per		
Hyparrhenia rufa	H.ruf		
Acacia tortilis	A.tor		
Boerhaovia difusa	B.dif		
Euphorbia hirta	E.hir		
Euphorbia heterophyla	E.het		
Gynandropsis gynandra	G.gyn		
Indigofera trita	I.trita		
Launaea cornuta	L.cor		
Leucas martinicensis	L.mar		
Morus astralis	M.aus		
Tridax procumbens	T.pro		

Appendix 5: Questionnaires for interview

Face to face interview questionnaires for farmers

Zone………………………….

A: Personal information

Name -- Age --------------------- Sex: M / F

Education--- Occupation -------------------------------------

B: Agricultural Information

1. Through which ways do you access agricultural information? Tick the most appropriate
   A: Agricultural officer B: Radio C: Researchers/FFS D: None
   E: Others (mention) ---
2. What other ways would you prefer to be used in accessing agricultural information? (mention)

   ----
3. Which agricultural information would you prefer to get? --
4. Have you attended any agricultural related training? (Yes/ No)
   If yes, what was the training about and who provided it? --
5. How do you prepare your farm before planting?
   A: Through Ploughing B: Use of weed killer (weedicide) C: Others (mention) ---
6. Which pesticide do you use to manage pests in bean crop? Tick the most appropriate
   A: Natural pesticides (botanicals and local/ traditional) B: Synthetic pesticides C: None
7. What challenges have you encountered when using synthetic pesticides? (Tick all possible answers). A: Language problem B: Cost of buying C: Health problems D: Pest resistance E: Unavailable in shops F: Others (mention)---
8. How many times do you apply pesticides to bean fields per season? ------------
9. Mention the most damaging insect pests in bean production ---
10. Are you aware of natural enemies? Yes ( ) No ( )

11. What insect is this shown to you in a picture? For every insect, assess the response and tick appropriately: (Fill the response in the table below)
    A. Right answer ( )   B. Wrong answer ( )   C. I don't know ( )
12. What is the significance or implication of the insect shown on the picture to your bean field?
    A. Pollinator ( )   B. Pest ( )   C. Natural enemy ( )   D. I don't know ( )

Response	**Insect 1**	**Insect 2**	**Insect 3**	**Insect 4**	**Insect 5**	**Insect 6**
Right						
Wrong						
Unknown						
Implication						
Pollinator						
Pest						
Natural Enemy						
I don't know						

13. Do you use protective gears when applying pesticides? (Yes/ No)
14. What health challenges have you encountered through the use of synthetic pesticides? Mention ---
15. Give suggestions on the possible ways to improve bean production ---

Appendix 6: Interactive Voice Response (IVR) survey questionnaires

Week 1 questionnaires

Q1. Have you seen aphids in your fields this week?
Q2. Thank you! Now, have you come across any bees in your field over the past week?
Q3. In your field, is there any damage from insects?
Q4. In which face is your crop? Planting, seedling, flowering, podding, harvesting?
Q5. Have you used pesticide during the past week?
Q6. Which pesticide did you use?
Q7. Which beneficial insects do you know?

Week 2 questionnaires

Q1. Have you seen more, or less or the same amount of aphids in your fields this week compared to last week?
Q2. Thank you, have you come across more, less or the same amount of bees in your field and in the margins over the past week compared to the week before?
Q3. In your field, is there more, less or the same amount of damage from insects as there was last week?
Q4. In which phase is your crop? Planting, seedling, flowering, podding, harvesting?
Q5. Have you used pesticide during the past week?
Q6. Which pesticide did you use?
Q7. Which plants do you know that attract insects?

Week 3 questionnaires

Q1. Have you seen more, or less or the same amount of aphids in your fields this week compared to last week?
Q2. Thank you, have you come across more, less or the same amount of bees in your field and in the margins over the past week compared to the week before?
Q3. In your field, is there more, less or the same amount of damage from insects as there was last week?
Q4. In which phase is your crop? Planting, seedling, flowering, podding, harvesting?
Q5. Have you used pesticide during the past week?
Q6. Which pesticide did you use?
Q7. Which plants do you know that repel insects?

Week 4 questionnaires

Q1. Have you seen more, or less or the same amount of aphids in your fields this week compared to last week?
Q2. Thank you, have you come across more, less or the same amount of bees in your field and in the margins over the past week compared to the week before?
Q3. In your field, is there more, less or the same amount of damage from insects as there was last week?
Q4. In which phase is your crop? Planting, seedling, flowering, podding, harvesting?
Q5. Have you used pesticide during the past week?
Q6. Which pesticide did you use?
Q7. Do you access agricultural information?

Q8. Which information do you access?
Q9. Which channels do you use to access this information?
Q10. Which information would you like to access?
Q11. Which channels would you like to access this information?

Week 5 questionnaires
Q1. Have you seen more, or less or the same amount of aphids in your fields this week compared to last week?
Q2. Thank you, have you come across more, less or the same amount of bees in your field and in the margins over the past week compared to the week before?
Q3. In your field, is there more, less or the same amount of damage from insects as there was last week?
Q4. In which phase is your crop? Planting, seedling, flowering, podding, harvesting?
Q5. Have you used pesticide during the past week?
Q6. Which pesticide did you use?
Q7. How would you like to access research information from projects conducted in your area?

Week 6 questionnaires
Q1. Have you seen more, or less or the same amount of aphids in your fields this week compared to last week?
Q2. Thank you, have you come across more, less or the same amount of bees in your field and in the margins over the past week compared to the week before?
Q3. In your field, is there more, less or the same amount of damage from insects as there was last week?
Q4. In which phase is your crop? Planting, seedling, flowering, podding, harvesting?
Q5. Have you used pesticide during the past week?
Q6. Which pesticide did you use?
Q7. Which plants do you know that repel insects?

Week 7 questionnaires
Q1. Have you seen more, or less or the same amount of aphids in your fields this week compared to last week?
Q2. Thank you, have you come across more, less or the same amount of bees in your field and in the margins over the past week compared to the week before?
Q3. In your field, is there more, less or the same amount of damage from insects as there was last week?
Q4. In which phase is your crop? Planting, seedling, flowering, podding, harvesting?
Q5. Have you used pesticide during the past week?
Q6. Which pesticide did you use?
Q7. Do you access agricultural information?
Q8. Which information do you access?
Q9. Which channels do you use to access this information?
Q10. Which information would you like to access?
Q11. Which channels would you like to access this information?

Week 8 questionnaires

Q1. Have you seen more, or less or the same amount of aphids in your fields this week compared to last week?
Q2. Thank you, have you come across more, less or the same amount of bees in your field and in the margins over the past week compared to the week before?
Q3. In your field, is there more, less or the same amount of damage from insects as there was last week?
Q4. In which phase is your crop? Planting, seedling, flowering, podding, harvesting?
Q5. Have you used pesticide during the past week?
Q6. Which pesticide did you use?
Q7. Which plants do you know that attract insects?

Week 9 questionnaires

Q1. Have you seen more, or less or the same amount of aphids in your fields this week compared to last week?
Q2. Thank you, have you come across more, less or the same amount of bees in your field and in the margins over the past week compared to the week before?
Q3. In your field, is there more, less or the same amount of damage from insects as there was last week?
Q4. In which phase is your crop? Planting, seedling, flowering, podding, harvesting?
Q5. Have you used pesticide during the past week?
Q6. Which pesticide did you use?
Q7. How would you like to access research information from projects conducted in your area?

Week 10 questionnaires

Q1. Have you seen more, or less or the same amount of aphids in your fields this week compared to last week?
Q2. Thank you, have you come across more, less or the same amount of bees in your field and in the margins over the past week compared to the week before?
Q3. In your field, is there more, less or the same amount of damage from insects as there was last week?
Q4. In which phase is your crop? Planting, seedling, flowering, podding, harvesting?
Q5. Have you used pesticide during the past week?
Q6. Which pesticide did you use?
Q7. Which beneficial insects do you know?