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Assessing the potentials of agricultural ecosystem pollination services to improve bean yield in smallholder farming systems

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ASSESSING THE POTENTIALS OF AGRICULTURAL ECOSYSTEM POLLINATION SERVICES TO IMPROVE BEAN YIELD IN SMALLHOLDER FARMING SYSYTEMS

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ABSTRACT

Pollination services by insects contribute to production in 75% of food crop species. When promoted through agro-ecological intensification (AEI), pollination can narrow yield gaps in smallholder farming systems. The study evaluated the contribution of insect pollinators on common beans (*Phaseolus vulgaris* L.) yields, and the knowledge gaps pre and post-training of smallholder farmers (n=300) in pollinators and field margins in a bean agro-system were investigated. Also, the role of field margin as a refuge for flower-visitors, and how plants and pollinator richness and diversity can influence strength of pollination networks in three agro ecological zones were investigated. Baseline and end-line surveys, pollinator exclusion and fluorescent dye-experiments, insects and vegetation surveys were carried out to obtain data for each specific objective of the study. While the majority of farmers were unaware of pollinators and their importance as pollinators before training, the end-line survey one year after training showed an increase in knowledge. The majority of farmers subsequently recognized honeybees, hoverflies and solitary bees, by names and their role as crop pollinators and natural enemies (for the case of hoverflies). Higher yield based on pods per plant and seeds per pod on open pollinated and hand pollinated flowers were significantly recorded compared with plants from which pollinators had been excluded suggesting that pollinators contribute significantly to crop yield. Similarly, it was found that field margin plants are essential in supporting higher number of pollinator taxa and can influence their richness in adjacent bean field. Collectively these results showed that improving understanding among smallholder farmers of ecosystem services and their ecological requirements are both feasible and essential for conservation of insect pollinators, which are important for optimising yield in this production system, and that crop margin vegetation provides habitat for these ecosystem service providers. Field margins with high plant diversity displayed extended and more robust pollination networks compared to those with low plant diversity, and consequently these habitat strips should be managed with sensitivity for pollinating insects and for the stability and persistence of plant-pollinator interactions in this agro-system.

DECLARATION

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

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The above declaration is confirmed

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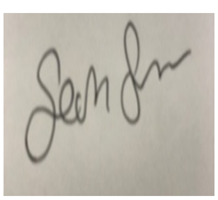

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CERTIFICATION

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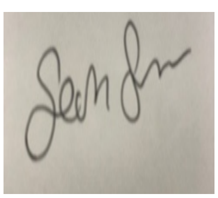

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DEDICATION

This work is dedicated to my family.

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LIST OF ABBREVIATIONS AND SYMBOLS

Ac	*Ageratum conyzoides*
AEI	Agricultural Ecological Intensification
Af	*Acalypha fruticose*
Ah	*Acanthospermum hispidum*
Am	*Asystasia mysorensis*
ANOVA	Analysis of Variance
Bd	*Boerhavia diffusa*
Bf	*Bidens frondosa*
Bp	*Bidens pilosa*
C	Connectance
C.sp	*Cyperaceae* species
Cb	*Commelina benghalensis*
Cbon	*Conyza bonariensis*
Cd	*Cynodon dactylon*
Cp	*Crotalaria polysperma*
CRDB	Cooperative Rural Development Bank
CSU	Charles Sturt University
D	Simpson's Diversity Index
Dc	*Drymaria cordata*
Di	*Desmodium intortum*
Dv	*Digitaria velutina*
E	Species Evenness
Eh	*Euphorbia heterophyla*
Ehir	*Euphorbia hirta*
FAO	Food and Agriculture Organisation of the United Nations
Gg	*Gynandropsis gynandra*
GLM	Generalised Linear Model
Gp	*Galinsoga parviflora*
Gw	*Glycine wightii*

H	Shannon Diversity Index
Hs	*Hyptis suaveolens*
HSD	Tukey’s Honest Significant Difference
Ic	*Indigofera colutea*
It	*Indigofera trita*
KW	Kruskal-Wallis Rank Sum Test
Lc	*Launaea cornuta*
Lm	*Leucas martinicensis*
LSD	Least Significant Difference
Ma	*Morus alba*
MANOVA	Multivariate Analysis of Variance
Mt	Mountain
NE	Natural Enemy
NM-AIST	Nelson Mandela African Institution of Science and Technology
Oc	*Oxalis corniculate*
Os	*Oxygonum sinuatum*
Pg	*Psidium guajava*
Pm	*Panicum maximum*
Pp	*Physalis peruviana*
R	Robustness
Rs	*Richardia scabra*
S	Species richness
Sa	*Sida acuta*
SE	Standard Error
Si	*Solanum incanum*
Sm	*Solanecio mannii*
Sn	*Solanum nigrum*
So	*Senna occidentalis*
Sova	*Sida ovate*
Sp	*Sporobolus pyramidalis*
Ss	*Senna spectabilis*

SSA	Sub-Saharan Africa
Td	*Tithonia diversifolia*
Tm	*Tagetes minuta*
Tp	*Tridax procumbens*
TSh	Tanzanian Shilling
Tt	*Tribulus terrestris*
USD	United States Dollar
UV	Ultraviolet

CHAPTER ONE
INTRODUCTION

1.1 Background of the Problem

Insect pollination contributes to the production of many crop species (Klein *et al*., 2007; Potts *et al*., 2016) and can enhance crop quality and yield even in autogamous crops (Bartomeus *et al.*, 2014; Bishop *et al.*, 2016). An increase in seed and fruit set in these crops has been reported to occur when insects are permitted to visit flowers (Deprá *et al.*, 2014; Pounders *et al.*, 2006; Roldán & Guerra-Sanz, 2006). As these pollinating insects move between crop flowers, they improve fitness by reducing inbreeding due to self-pollination by maximizing pollen flow which improve crop quality and yield (Bartomeus *et al*., 2014; Senapathi *et al*., 2015). Yield increases resulting from pollinator visitation can arise through enhanced size, number and weight of seeds or fruits (Bommarco *et al.*, 2012; Classen *et al.*, 2014; Klatt *et al.*, 2013; Ricketts, 2004; Tschoeke *et al.*, 2015).

However, agricultural intensification has resulted in large-scale losses of abundance and diversity of pollinators and, consequently, this can impact crop yields (Klein *et al.*, 2007). Decline in beneficial insects globally are predicted to lead to catastrophic outcomes (Sánchez-Bayo & Wyckhuys, 2019) including pollination deficits, resulting in severe declines in global agricultural production (Giannini *et al*., 2017; Novais *et al*., 2016). This is exacerbated by increasing demand for pollination services as agriculture has become more pollinator dependent (Aizen *et al.*, 2008; Aizen & Harder, 2009). Maximum deposition of pollen in flowering crops (and thus yield) is likely to be achieved when there are high numbers of pollinators visiting flowers and moving between non-crop and crop habitats (Cusser *et al.*, 2016; Roldán *et al*., 2006). Consequently, the link between pollinator populations, semi-natural habitats and food security is becoming increasingly apparent.

Non-crop vegetation in agrarian landscapes is important in enhancing pollinator communities (Garratt *et al.*, 2017; Sardiñas & Kremen, 2015) so supporting these habitats can mitigate against pollinator declines. Considerable data about pollinator declines and their support through enhanced habitats has been generated from Europe and North America (Balfour *et al.*, 2018), but there is little equivalent information on African pollinators which are neither safeguarded nor protected due to rapid environmental changes (Donaldson *et al.*, 2002; Guenat *et al.*, 2018). Climate and land use change have altered the vegetation composition in agrarian landscapes and reduced nesting sites and pollen and nectar resources for pollinators (Ferreira *et al.*, 2013; Kearns & Oliveras, 2009). Conservation strategies require specific information about which insects pollinate which crops, enabling targeted and tailored conservation interventions (Garratt *et al.*, 2014). The same applies to smallholder bean farming systems where most crops including coffee, beans, fruits and some vegetables benefit from insect pollination service.

Common beans (*Phaseolus vulgaris*) are among crops that benefit from insect pollination (Ibarra-Perez *et al.*, 1999). They are consumed as a primary source of protein by low income households in many developing countries (Katungi *et al.*, 2009). Common beans provide other fundamental nutritional elements such as iron, zinc and calcium (Brigide *et al*., 2014; McConnell *et al*., 2010) as well as being one of the cheapest dietary protein sources (Hillocks *et al.*, 2006). Interventions in these production systems are continually required to secure and increase yields. In Tanzania, *P. vulgaris* is largely cultivated by smallholder farmers around the lake zone regions and in the northern part of the country (Hillocks *et al*., 2006). Although many species of beans are autogamous, pollination by insects can improve yield and quality (Bartomeus *et al.*, 2014; Ibarra-Perez *et al.*, 1999; Kingha *et al.*, 2012). While many studies have investigated the effects of pollinators on crop yield in fruits and vegetables (Feltham *et al.*, 2015; Klatt *et al.*, 2013; Shin *et al.*, 2007; Tschoeke *et al.*, 2015), relatively few have studied beans. Information on *P. vulgaris* pollination is particularly scarce with most studies on legumes focused on faba beans (Andersson *et al.*, 2014; Bartomeus *et al.*, 2014; Cunningham & Le Feuvre, 2013; Nayak *et al.*, 2015). Knowledge about pollinator-dependence of *P. vulgaris* in different agricultural systems, however, is scarce but can practically be determined through the use of exclusion experiments (Birkin & Goulson, 2015). For the successful transition to sustainable agriculture, the integration of existing indigenous knowledge and scientific evidence is vital to raise farmers awareness and implement the desired change (Woodley, 1991). Well informed farmers are better placed to transform unproductive farming systems to sustainable and productive ones (Marques *et al.*, 2017) through the augmentation of ecosystem biodiversity (Cardinale *et al.*, 2003).

This study has therefore evaluated the awareness and knowledge gaps among smallholder farmers from three different elevation zones (low, mid and high) in a Tanzanian agro-system of pollinators and their contribution in crop yields. Also, the potential importance of farm margin vegetation in sustaining pollinators as well as farming practices used in this region is discussed here. The study also discuss how knowledge through direct training can rapidly lead to change in farming behaviours towards Agricultural Ecological Intensification (AEI) that can support pollinators and other ecosystem services. The study explored the efficacy of pollination service in bean yields and studied the common pollinators of *P. vulgaris* that deliver this ecosystem service along an altitudinal gradient. Also, fluorescent dye methodology was deployed to track movements of flower visitors between the margin and field to understand the role of the field margin, in this smallholder farming system, in supporting pollinators.

1.2 Statement of the Problem

Ecosystem services such as pollination, can narrow yield gaps and support sustainable food production generating resilient agro-systems that buffer against future risks (Bartomeus *et al*., 2014; Bishop *et al*., 2016; Bommarco *et al*., 2012; Rader *et al*., 2016). However, agricultural intensification has resulted in large-scale losses of abundance and diversity of pollinators in the world and, consequently, this can impact crop yields (Giannini *et al*., 2017; Novais *et al*., 2016). Many studies which have attempted to test the contribution of pollination services on yield of various crops, have been conducted in large scale farming systems in Europe and America (Bishop *et al.*, 2016; Marzinzig *et al.*, 2018).

In East Africa, the value of pollination service for many tropical crops which heavily or partially depends on unmanaged-wild pollinators, are poorly understood (Kasina *et al*., 2009; Munyuli, 2011; Otieno *et al*., 2011). In smallholder farming systems of Tanzania, none of the studies has tested the efficacy of insect pollination in common bean yield.

1.3 Rationale of the Study

No available information regarding the contribution of pollination services on common bean yield, and how non-crop vegetation influences ecosystem services in Tanzania's smallholder farming systems. Therefore, this study aimed at bridging the information knowledge gap on the value of pollination service in improving common bean yield in smallholder farming system.

1.4 Objectives

1.4.1 Main Objective

To assess the importance of pollinators and plant biodiversity in increasing pollination services and their effect in bean yield in smallholder farming systems.

1.4.2 Specific Objectives

(i) To evaluate the awareness and knowledge gaps on the role of pollinators and value of field margins among smallholder in bean agro-systems.
(ii) To determine the effects of insects' pollination on common bean yields in smallholder bean agro-systems.
(iii) To develop pollination networks for the three selected agro-ecosystems, and evaluate the effects of plant diversity on their complexity and stability.
(iv) To determine the diversity and richness of pollinators in association with their host plants across three selected agro-ecosystems.

1.5 Research Questions

(i) Do farmers have knowledge on pollinators and their implications in common bean production?
(ii) Do beans yield in bean agro-systems dependent on insect pollination services?
(iii) Do complexity and stability of plant-pollinator networks in bean agro-systems differ with elevation gradient?
(iv) Do pollinators, plant diversity and richness in bean agro-system vary with elevation gradient?

1.6 Significance of the Study

Many of the world's valued crops depend on insects' pollination. However, knowledge of farmers in smallholder farming systems regarding the importance of pollination services in bean production was very limited. The study has provided justification for pollinator conservation in smallholder farming systems since we found that insect pollination was essential for enabling common beans to produce maximum yield, and that the insects visiting bean plants frequently visited the field margins. Also, this study has equipped farmers with knowledge regarding the economic importance of beneficial insects for crop yield, and thus led to change in farmers' negative perceptions of insects, facilitating on-farm pollinator conservation. Moreover, the study has provided baseline information on diversity and richness of pollinators and their host plants in three agro-ecosystems. The information generated by this study was necessary for notifying farmers, agro-ecologists, researchers and other stakeholders on the importance of conserving agricultural ecosystem biodiversity for sustainable food production in smallholder farming systems.

1.7 Delineation of the Study

This study focused on assessing the importance of pollinators and plant biodiversity in increasing pollination services for improved bean yields in smallholder farming systems in Moshi Rural District in Northern Tanzania. Thus, the study did not consider the role of pollinators on other crops.

CHAPTER TWO
LITERATURE REVIEW

2.1 Importance of Common Beans in Sub-Saharan Africa

Agriculture continues to remain a major economic and production activity in Sub-Saharan Africa (SSA) enabling poor households to sustain while alleviate the poverty level (Davis *et al.*, 2017; Staatz & Dembélé, 2008). A large group of people in this region depend on agriculture for food and as main source of income for their living (Davis *et al*., 2017). Although limited large-scale farming do exists, most farmers are small-scale holders practicing rain-fed agriculture in small sized farms (Cooper *et al*., 2008). Modern and sustainable production technologies such as drip irrigation and improved seeds are less practiced in this region (Binswanger-Mkhize & Savastano, 2017). For the past few decades, agricultural production in this region has become challenging due to various factors including environmental stresses (Arndt *et al.*, 2012; Ghini *et al.*, 2011; Kutywayo *et al.*, 2013). Major crops cultivated in this region include both local and breed variety of cereals, legumes and nuts (Altieri, 2004). While maize, millet and sorghum are main staple cereals in the region (Haggblade *et al.*, 2017; Magrini *et al.*, 2017; Porteous, 2017), common beans (*Phaseolus vulgaris* L.) are consumed as the main source of protein in many households (Katungi *et al.*, 2009). Common beans also provides other important elements required by the body for its normal function (Margaret *et al.*, 2014). In SSA, common beans are consumed in various forms and provides up to 15% and 30% of the total amount of energy and protein intake respectively required in daily basis (Katungi *et al*., 2009; McConnell *et al*., 2010). In Tanzania, *P. vulgaris* is largely cultivated by smallholder farmers in the northern and lake zone regions of the country (Hillocks *et al*., 2006). Being essential and cheapest dietary protein in these countries, intervention in production systems is required to increase yields.

2.2 Importance of Pollinators and Pollination Service in Crop Production

Sustainable intensification depends on regulating ecosystem services such as pollination and is being increasingly adopted in smallholder farming (Pretty *et al.*, 2018). In a wide perspective, pollination may be biotic or abiotic depending on pollen-transporting agent (Bolmgren *et al.*, 2003;

Dar *et al.*, 2017). Biotic pollination occurs when the agent involved is a living organism (animal) unlike abiotic pollination whereby a physical agent such as wind and water facilitate the process (Ackerman, 2000). There are numerous groups of biotic pollinators ranging from insects, birds to mammals (Waser *et al.*, 1995). Of these, bees are the most known and important insect pollinators of many crops and plant species in the world (Hegland *et al.*, 2009; Waser *et al.*, 1995). Other common pollinating insects include some species of diptera (Larson *et al.*, 2001; Winfree *et al.*, 2011), coleoptera (Mawdsley, 2003; Suinyuy *et al.*, 2009) and lepidoptera (Winfree *et al*., 2011), and they may be either specialists or generalists.

Pollinators contribute to production in 75% of crops (Klein *et al.*, 2007). About 87.5% of 308 006 species of angiosperms receive pollination benefits by animals, and particularly insects (Ollerton *et al.*, 2011). In 2005, the economic value of pollination service estimated to be around 172 USD billion for the world agriculture production (Gallai *et al.*, 2009), which fruits, nuts, vegetables, edible oil crops and stimulant crops being major service beneficiaries (Irshad & Stephen, 2014). However, current studies have reported the increase in value of animal pollination to global crop production by additional USD 235 – 577 billion yearly (Lautenbach *et al.*, 2012; Potts *et al.*, 2016). The increase in yield is accomplished when pollinators move pollen grains between anthers and stigmas of flowers and thus enabling fertilization process to occur (Kevan, 1999; Klein *et al.*, 2007; Power, 2010). However, conventional technologies that rely on agrochemical inputs degrade most of ecosystem services and goods from non-crop vegetation (Basu *et al.*, 2016; Cusser *et al.*, 2016; Dale & Polasky, 2007; Krauss *et al.*, 2011; Potts *et al.*, 2016; Winqvist *et al.*, 2012). Therefore, proper management and conservation of the agricultural ecosystems is necessary to ensure sustainable provisioning of pollination services and associated benefits.

2.3 Knowledge among Farmers on the Importance of Pollinators in Crop Production

Knowledge of pollinators and their importance in crop production is important for smallholders to fully understand the relationship between pollinating insects and agricultural productivity and the conflicting impacts of conventional inputs such as pesticides and herbicides. However, evidence of farmer knowledge about pollinators is scarce, and in many regions this knowledge maybe limited (Tengö & Belfrage, 2004). In East African agro-systems, smallholder farmers have limited knowledge about the importance of beneficial insects as far as crop production is concerned (Munyuli, 2011; Otieno *et al*., 2011). Instead, they see insects in a broadly negative and collective way as crop pests or disease vectors (Marques *et al.*, 2017; Smith *et al.*, 2017). However, knowledge enhancement through training is possible (Mvena *et al*., 2013), and such techniques can be used to equip farmers and enrich their understanding about pollinators. Training of school-age youths by professionals about the identity and importance of common pollinators using school gardens, demonstration field plots, entomological specimens and audio-visual resources also can help to build students' knowledge and use it at older age (Marques *et al*., 2017). In other areas for example, local beliefs, local ecological knowledge and social protection techniques have been used to protect pollinators in horticultural landscapes (Tengö & Belfrage, 2004). However, to make the system work better in smallholder farming systems there is a need for knowledgeable extension officers and pollination ecologists to spread the knowledge about the role of pollinators in crop production which may help to change farmers' negative perceptions of insects, facilitating on-farm conservation of beneficial insects for improved pollination services.

2.4 Importance of Non-crop Vegetation in Maintaining Pollination Service

Non-crop agricultural landscapes provide refuge, nesting sites and forage for beneficial insects (Gillespie *et al.*, 2016; Gurr *et al.*, 2003; Landis *et al.*, 2000; Nicholls & Altieri, 2013; Paredes *et al.*, 2013; Sidhu & Joshi, 2016). The presence of suitable habitats around crop fields can support large communities of pollinators leading to increased interactions with nearby crops (Denisow & Wrzesień, 2015; Otieno *et al.*, 2011, 2015), enhanced pollination services, and ultimately, higher yield (Dar *et al.*, 2017; Garibaldi *et al.*, 2013; Kevan *et al.*, 1990; Kevan, 1999; Klein *et al.*, 2007; Ricketts, 2004). Moreover, many beneficial insects interact with non-crop vegetation as they build their nests and dwell on non-crop habitats adjacent to crops (Denys & Tscharntke, 2002; Klein, 2009; Marshall & Moonen, 2002). To keep the pollinator-plant interaction persisting, there is a need to enhance plant diversity and thus ensure adequate forage for pollinators (Rands & Whitney, 2011). In agricultural landscapes where vegetation density and pollination services have been lowered due to human activities (Kovács-Hostyánszki *et al*., 2017), planting of native flowering plants along the farm edges may further provides basic requirements for pollinators (Denisow & Wrzesień, 2015). Increased richness of such plants may possibly maintain high number pollinators even when crops in the field are not blooming (Hannon & Sisk, 2009; Sidhu & Joshi, 2016), therefore, these plants should be well recognized when managing the farmland.

2.5 Other Ecosystem Benefits Associated with Non-crop Vegetation

Effective management of field margins to maintaining non-crop vegetation is important in providing requirements for pollinators, but field margins also provide multiple ecosystem services, for example, in some AEI systems, *Desmodium* spp. have been reported to control parasitic striga weeds in a mixed cereal-legume cropping systems (Khan *et al.*, 2011; Pickett *et al.*, 2014; Tsanuo *et al.*, 2003). Species such as *Solanum nigrum* (Ashagre *et al.*, 2016; Mavengahama *et al.*, 2013), *Bidens pilosa* (Mavengahama *et al.*, 2013), *Galinsoga parviflora* (Jaca & Kambizi, 2011) and *Amaranthus* spp. (Bvenura & Afolayan, 2015) have been consumed as a wild vegetables in smallholder farming systems. Moreover, while most of natural enemies' larvae are carnivorous (Harris, 1991; Van Rijn & Wäckers, 2016), some plant species can support great number of adult insects by providing alternative nectar and pollen (Gurr *et al.*, 2016; Paredes *et al.*, 2013; Rijn *et al.*, 2013). Field margin may consist of various plants with pesticidal properties such as *Ageratum conyzoides* L. (Rioba & Stevenson, 2017), *Tagetes minuta* L. (Phoofolo *et al.*, 2013; Silveira *et al.*, 2009), *Tithonia diversifolia* (Hemsl.) (Green *et al.*, 2017; Mkindi *et al.*, 2017), *Hyptis suaveolens* (Pavunraj *et al.*, 2014), *Bidens pilosa* (Mkindi *et al.*, 2017) which can be used as botanical pesticides to control pests. Also, marginal plants can directly repel pests and block them from reaching the nearby crops but they can also suppress pests when intercropped with the key crops (Ratnadass *et al.*, 2012; Silveira *et al.*, 2009). When conserved and maintained around farmlands, farmers may be assured to obtain continuous natural ecosystem services and associated benefits from natural vegetation for improved food production and farmers' livelihoods.

2.6 Factors Affecting Richness and Diversity of Pollinators in Agri-systems

Global decline of both managed and wild pollinators in recent years has raised concern to both conservationists and ecologists (Dicks *et al.*, 2013; Potts *et al.*, 2010). The decline has been caused by a range of factors including agricultural intensification (González-Varo *et al.*, 2013; Klein *et al.*, 2007), climate and land use changes (De Palma *et al.*, 2016; Sala *et al.*, 2000; Weiner *et al.*, 2014), unsustainable farming approaches such as intensive monoculture (Wilcove & Koh, 2010) and use of industrial pesticides (Henry *et al.*, 2012; Whitehorn *et al.*, 2012). A good understanding of these factors is necessary for planning appropriate conservation programs as well as setting priorities both at national and global scale (Archer *et al.*, 2014).

2.6.1 Climate Change

There is evidence from other regions of the world like North America showing that climate change has impact on pollinator populations (FAO, 2016; Sala *et al*., 2000). Extreme weather may affect the overall ecosystem functioning and performance due to damages of biodiversity and other abiotic components within the system (Garcia *et al.*, 2014; Jentsch & Beierkuhnlein, 2008). Changing the ecosystem functioning not only disrupts the distribution and abundance of pollinators but also their effectiveness (Millennium Ecosystem Assessment, 2005). Climate changes may affect pollination service provisioning in agro-ecosystems by changing pollinators' community composition (Harrison & Winfree, 2015). In many African countries, information on pollination ecology and especially at country level is scarce. The extent to which climate change has impacted the availability of food and other essential requirements for wild pollinators in smallholder farming systems has not been clearly discussed. Information on the magnitude in which the pollination networks have been affected by change in climate for tropical crops and plants is still unclear (FAO, 2016). Since we need to understand the correlation between changing in climatic factors and pollinators within the ecosystems, there is a need to clearly explore the mechanism behind this relationship. For instance, it has been reported that temperature controls the access of pollinators to food resources (Classen *et al.*, 2015) and may also affect visitation rate of both Lepidopterans and Hymenopterans when it increases (Pandit & Choudhury, 2001). However, to what degree of temperature change will continue to favour pollinators' activities needs a detailed investigation. Continued rise of global warming is expected to be more detrimental in the tropics, where biological diversity is also higher (Deutsch *et al*., 2008). Populations of insects confined in tropical lowland areas that experience low and highly variable temperature, are projected to undergo severe declines due to their inability to tolerate changes in temperature (Bonebrake & Deutsch, 2012). Nevertheless, basic information on the ecological consequences of increasing temperature on pollination ecology is still limited (Hegland *et al*., 2009). It is also unknown whether temperature affects only foraging behaviour of pollinators or even the quality and quantity of the pollen produced by flowering plants when subjected to extreme temperature. All these issues need to be addressed for a better understanding of possible detrimental factors related to climatic perturbations.

2.6.2 Parasites and Fungi in Bees

Pollinator activity can be lowered by diseases and/or parasites as they affect metabolic activities that determine their performance (González-Varo *et al*., 2013). Parasites such as varroa mites have been reported to affect bee colonies in South Africa (Allsopp, 2004). The threat is even higher when a disease happens to affect multiple host species from managed to wild pollinators. A study conducted by Graystock *et al.* (2013) has found the ability of disease infection, *Nosema ceranae* between different pollinator species of bumble bees and honey bees. Anderson and Giacon (1992) also highlighted the effect of diseases on pollinators' population. However, sufficient information on this area is still lacking particularly in tropical region (FAO, 1995). Identifying common diseases and parasites threatening survival of pollinator species particularly in understudied areas in smallholder farming systems of tropical Africa, may help to understand the level of the problem and thus suggesting appropriate solution to reduce infections and spread among other vulnerable pollinator species.

2.6.3 Use of Synthetic Pesticides in Agricultural Lands

Synthetic agricultural pesticides may contain potent chemicals that affect both beneficial insects and plant biodiversity (Iwasa *et al.*, 2004; Pisa *et al.*, 2015; Schmitz *et al.*, 2014). For example, systemic pesticides have reported to change vegetation structure since they inhibit normal plant growth by affecting their respiration, roots and shoots elongation, nutrients uptakes as well as biological component of the soil (Ahemad & Khan, 2012; Lichtenstein *et al.*, 1962; Siddiqui & Ahmed, 2006). Pesticides can kill insect pollinators directly or by reducing their foraging efficiency and behaviour (Henry *et al.*, 2012; Kovács-Hostyánszki *et al*., 2017). Pollinators that forage around agricultural fields are more susceptible to pesticides than those whose range does not extend to cultivated area (Krupke *et al.*, 2012). For instance, extensive use of neonicotinoids and pyrethroids in commercially cultivated land has contributed so much to the loss of pollinators worldwide that they are now banned in some regions (Gill *et al.*, 2012; Stanley *et al.*, 2015;

Whitehorn *et al.*, 2012). When sprayed, pesticides contaminate both nectar and pollen grains, which are primary food source for adult pollinators and their larvae (Chauzat *et al.*, 2006; Choudhary & Sharma, 2008; Tosi *et al.*, 2018). The level of contamination is intensified when contaminated pollen grains are transported into the hive and it may wipe the whole colony (Krupke *et al*., 2012). This pesticide is highly neurotoxic and has reported to affect foraging activities of both honeybees and other wild pollinators (Van der Sluijs *et al*., 2013). Apart from bees, these pesticides are reported to repel important pollinating diptera and coleoptera species from visiting flowers of contaminated plants (Easton & Goulson, 2013). Generally, the overall body functioning of the insects are affected following exposure to neonicotinoids and thus leading to reduced pollination services (Stanley *et al*., 2015). However, high agricultural intensification has influenced application of combined pesticides which severely cause death of many pollinator species (Gill *et al*., 2012). For example, in North America and European countries, high level of pesticide application has been due to high crop production through extensive monoculture (Horrigan *et al.*, 2002). In recent years, such agricultural methods are taking over even in developing countries replacing the traditional and sustainable ways farmers used to practice in previous decades. Although the main reason is to increase yields while minimizing production costs, it does not support agricultural biodiversity and it may cause agro-ecosystem damage in a long run (Richards, 2001).

The adverse impact of agrochemicals is not only observed on pollinators' community (Brittain *et al.*, 2010; Otieno *et al.*, 2011) but also the flora component of the ecosystem. Decreased plants visitation by pollinators has found to affect plants reproduction especially pollinator dependent plants (Lundgren *et al.*, 2013). However, there are various ways to minimize or remove the effects of pesticides to agro-ecosystems. One way is to opt organic farming practice, which eliminate synthetic pesticides and encourage abundance and richness of pollinators in agro-landscapes (Kennedy *et al*., 2013). Likewise, all activities causing negative effects to the ecosystem reduce its capacity to provide natural services including pollination, erosion control, water purification, disease and pest control and storm protection (Millennium Ecosystem Assessment, 2005). Therefore, all farming practices that increase crop yield while minimizing synthetic pesticides use must be opted to maintain natural ecosystems' services. Use of botanical pesticides and biological pest control practices are among the best studied alternative methods to control pests rather than synthetic pesticides, which impoverish agro-biodiversity, particularly in Africa (Rioba & Stevenson, 2017). Although the effects of climate change on vegetation composition, and pollinators' abundance and diversity were not explored here, this study could provide baseline data for future long-term assessment of non-crop vegetation and pollinators in the study region towards climate changes.

2.7 Conservation Approaches towards Protection of Pollinators in Tropical Africa

Although the African Pollinator Initiative was established to protect and promote African pollination systems (FAO, 2007), more studies have concentrated in few countries including South Africa and Kenya (Kiatoko *et al.*, 2014; Melin *et al.*, 2014; Mwangi *et al.*, 2016; Ollerton *et al.*, 2003, 2011; Otieno *et al.*, 2011). However, these studies have focused mainly on honeybees (Asiko *et al*., 2017; Eardley *et al*., 2009; Kasina *et al*., 2009) with little attention to other wild pollinators, which also have significant impact in crop production (Larson *et al*., 2001; Winfree *et al*., 2011). Generally, management of pollinators' habitats such as hedgerow margins, sowing of flower strips, establishment of forest corridors shall be among the topmost pollinators' conservation approaches (Briggs *et al.*, 2013; Feltham *et al.*, 2015; Heath *et al.*, 2017; Kennedy *et al.*, 2013; Westphal *et al.*, 2015) in agro-landscapes of tropical Africa. In process of restoring the habitats, plant species that blooms throughout the year in farmlands that support diverse pollinator taxa should be selected (Dixon, 2009; Peters *et al.*, 2013). In areas with severe habitat destruction due to agricultural intensification, farming systems that accommodate the agro ecological principles could help to restore damaged pollinator habitats (Nicholls *et al.*, 2016; Peters *et al.*, 2013; Scheper *et al.*, 2013). The presence of suitable habitats will definitely favour many pollinator communities due to sufficient food, mating and nesting sites (Ashworth *et al*., 2009; Brosi *et al*., 2015; Kasina *et al*., 2009; Raina *et al*., 2011). It should be clear that availability of specific life requirements for specific group of pollinators could largely limit the richness and distribution of each specific group. For example, the population of hoverflies can be determined by availability of floral resources for both adult and larval food rather than nesting sites (Holzschuh *et al*., 2016) but solitary bees distribution and abundance can be limited primarily to availability of nesting sites (Steffan-Dewenter & Schiele, 2008).

Typically, when conserving pollinators' habitats, both rare and endangered pollinator species can be protected from extinction and at the same time increasing pollination for agricultural production. Policies which encourage management of pollination services are urgently needed to maximize the yield of important crops for improved food security (Dicks *et al*., 2016; Kasina *et al*., 2009).

CHAPTER THREE
MATERIALS AND METHODS

3.1 Materials

3.1.1 Description of the Study Area

The study area was located in Moshi Rural District, Kilimanjaro in northern Tanzania (3.2468 - 3.3481° S, 37.5044 - 37.5411° E) (Fig. 1). The study sites were selected and categorized into three agricultural zones based on the elevation gradient; low zone (< 1000 m), mid zone (1000 – 1500 m) and high zone (1500 – 1800 m), since agricultural management practices and land use changes from lowlands to the highlands (Pabst *et al.*, 2013; Soini, 2005). Farmers involved in this study were those who grew common beans (*Phaseolus vulgaris* L.) on the slopes of Mt Kilimanjaro either as pure stand or mixed with other crops in small-sized farms ranging between 0.10 to 1.01 hectares. The main economic activity was agriculture, but most households also kept livestock mainly cattle and goats for milk and organic manure (Hemp, 2006b).

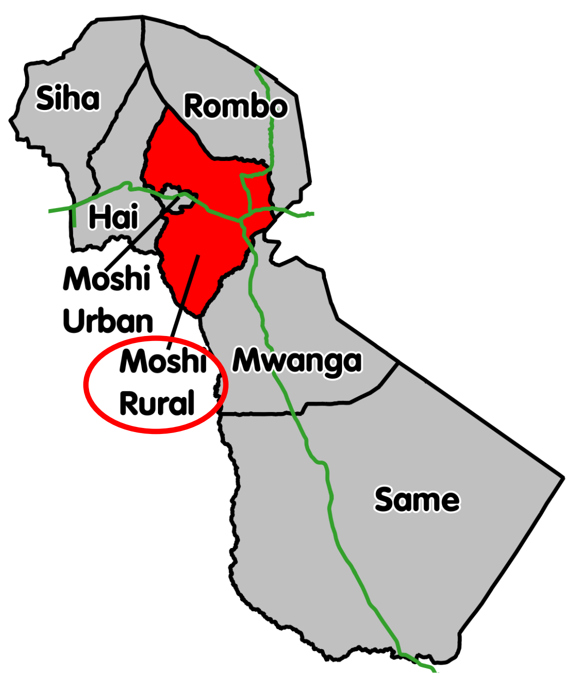

Figure 1: A map showing location of the study area

3.2 Methods

3.2.1 Evaluating the Awareness and Knowledge Gaps among Smallholder Farmers on the Importance of Pollinators in Bean Agri-systems

(i) Preparation and Designing of Household Survey

The survey involved 300 smallholder farmers growing bean crops in the study area. Names of farmers were obtained from the village offices located in each zone with the help of the local agricultural extension officer from each respective village. The survey covered three zones; Mbahe (high zone), Mieresini (mid zone) and Makuyuni (low zone) purposely to include a varied elevation area along slopes of Mt Kilimanjaro where common beans is widely cultivated. In each zone, 100 farmers who were willing to participate in this study were selected, with the principal criterion being "growing a bean crop". The number of farmers in each zone was obtained using common sample size formula calculated from list of all bean growers in the study area. Research permits were requested and granted by local government authority prior to commencement of this study. The questionnaire comprised two main sections; demographic and principal questions based on the study theme. The collected demographic information and the main questions aimed to understand farmers' knowledge and attitudes regarding pollinators and their importance in crop production, field margin management and farming practices, beneficial plants around farmland and their usage, and socio-economic importance of bean crop in improving livelihood of smallholder farmers. In general, these questions were framed purposely to enable us to understand farmers' knowledge and attitudes towards pollinators but also the overall tropical agricultural management systems that may enhance or reduce pollination services around bean fields.

To understand farmers' awareness of common pollinators found in their bean fields, both printed coloured pictures (a good resolution photograph printed on to A4 paper) and a pinned specimen of each insect guild was shown to the respondent for identification during interview. Each respondent was asked to identify every insect by either using local or Swahili name and explain its importance as far as bean production was concerned. Three pollinator specimens were collected from bean fields one week before interviews, using the specific taxa of: honeybee (Hymenoptera: Apidae:

Apis mellifera), hoverfly (Diptera: Syrphidae: *Eupeodes* spp) and solitary bee (Hymenoptera: Megachilidae: *Megachile* spp).

(ii) Training of Interviewers

A total of ten MSc students from Nelson Mandela African Institution of Science and Technology (NM-AIST), Tanzania conducted the interviews with farmers in the study area. Prior to actual data collection, all interviewers were trained by researchers for two days at NM-AIST on ethics and data collection techniques so as to obtain quality data while maintaining a good relationship with the farmers' community. After training, the interviewers undertook two days pilot session in a nearby village in order to test questionnaires, familiarise with questions but also for researcher to evaluate the ability of each interviewer to do the work.

(iii) Field Data Collection

A total number of 300 farmers (118 males and 182 females) involved in this study were interviewed between April and May 2016. After obtaining informed consent, farmers were interviewed using the pre-tested structured questionnaire using Swahili language (Tanzanian national language which all farmers spoke as either a first or second language with good fluency). Farmers were interviewed face-to-face at their home, and later the interviewers visited their bean field(s) to record and measure the size of the farm and status of the field margins. Information obtained from field observations and personal communication were also included and discussed here.

(iv) Training of Smallholder Farmers and End-line Survey

To enhance farmers' knowledge, a training component about pollinators and their importance in crop production, sustainable management of field margins and their value in supporting beneficial insects in bean agri-systems was included. To minimize the impacts to beneficial insects of current practices, alternative methods and practices to manage field margins as well as the use of non-synthetic pesticides, which are less harmful to beneficial insects and the surrounding environment were discussed. The training was done between March and April 2017; one year after baseline survey and it involved same 300 farmers who were interviewed during our baseline survey. It was a participatory training and farmers were free to share their experience and opinions during indoor and field sessions. Printed coloured picture of insects, entomological box (with insect specimens) and beneficial field margin plants were among tools used during training.

3.2.2 Assessing the Efficacy of Insect Pollination on Common Bean Yields in Bean Agri systems

To evaluate the effects of different pollination systems on bean yield, a local variety (Kariasii) of common beans (*Phaseolus vulgaris*) were planted in a randomized complete block design. Four experimental plots each of 9 m x 16 m (144 m^2) were established at each elevation zone along slopes of Mt Kilimanjaro. The experiment involved three treatments: Insect/open-pollination (open), hand-pollination (hand) and self-pollination (self). Each treatment involved 4 bean plants growing in a plot size of 2 m^2 and there were four replications per treatment. In the self-pollination treatment, bean plants were individually bagged with polyethylene net (A to Z Textile Ltd., Tanzania, mesh width: 0.4 x 0.7 mm) before the onset of flowering to allow self-pollination (Perrot *et al.*, 2018). In the hand-pollination treatment, we used a technique adopted by local plant breeders where anthers containing matured pollen were rubbed against the stigmas, but unlike in breeding processes (Drayner, 1956; Luo *et al.*, 2007), the buds were not emasculated for maximum pollination to occur. Pollen grains used to pollinate beans in hand-pollination treatment blocks were collected from bean flowers of the same variety grown outside the experimental plot. Beans were inspected every two days and all newly opened bean flowers under this treatment were pollinated. The open treatment involved random selection of same number of bean plants, but unlike the other two treatments, each bean plant was tagged and left unbagged to allow visits by insects. All sites were selected based on their management history and to avoid the effects of yield influencing factors such as soil fertility, all experimental plots were managed in the same way.

The nets were removed after pod set and when flowers had begun to wither and fall. Beans from each treatment plot were harvested after reaching senescence and the mean number of pods per plant, seeds per pod and weight of 30 representative dry seeds were calculated to determine the treatment effect. The yield data were then converted according to typical planting density to calculate yield per hectare. To obtain the average income, we visited three local markets in the study area and the average price of beans was around 1518 TSh per kg. This value was then used to calculate the differences in average income generation per hectare if beans harvested from each treatment plot would have been sold in the local markets.

3.2.3 Assessing the Movement of Flower Visitors in the Field

Fluorescent dye tracking of flower visitor movements was carried out to determine the extent to which bean pollinators interacted with field margin plants. A total of 12 sites in a small-scale bean farming area located along the slope of Mt. Kilimanjaro, were selected for this experiment, with 4 at each elevation. The non-crop vegetation along field margins comprised native and non-native plant species including herbs, shrubs and scattered trees. Most herbaceous plants and shrubs grew naturally along margins while the tree species either grew naturally or were purposely planted by the farmer/owner to offer benefits including boundary delineation, food or firewood.

Yellow fluorescent pigment (Topline Paint Pty Ltd, Lonsdale SA, Australia, supplied by SprayShop, Dry Creek SA, Australia), was applied at a rate of 1 L of dye per 100 L of water. Agricultural backpack sprayer (Taizhou Kaifeng Plastic & Steel Co., Ltd, Taizhou, China, supplied by Bajuta International Tanzania Limited, Arusha, Tanzania) was used to spray the dye on to the non-crop vegetation in the field margin. This dye remains on leaf and petal surfaces of plants in the field margin until an insect alights, at which point it rubs off on to the surface of the plant visiting insect (Rader *et al.*, 2011; Schellhorn *et al.*, 2004). The sprayed area was approximately 3 m wide along a 50 m strip during which 15 L of solution was sufficient to treat the whole designated area i.e., one margin of the field. The spraying time was between 1000 h and 1500 h when the temperature was moderate and most insects were actively interacting with flowers (Nielsen *et al.*, 2017) and the activity was carried out during the period when beans were at the 50% flowering stage. The timing was chosen to ensure there was maximum potential for interaction between pollinators and the crop when measuring their use of the field margin.

Insects were sampled from the crop using sweep-nets 24 h after spraying margins with fluorescent dye and repeated for three consecutive days. Samples were taken at four distances from the edge bordering the sprayed field margin i.e. 0 m, 10 m, 20 m, and 40 m (Perović *et al.*, 2011). At each distance, the sampling transects, 50 m long and 3 m wide ran in parallel with the control transect (i.e. field-margin edge, 0 m) were surveyed using sweep nets between 10.00 and 15:00 hrs. Insects were sampled when the weather was sunny with moderate ambient temperature of above 22 °C to avoid the effects of low temperature which reduce foraging activity of most insects (Mellanby, 1939). The collected samples were killed on site with ethanol-soaked tissue in a vial, kept in a minus 20 °C freezer and later sorted for identification in the lab. Each insect sample was inspected for pigment under UV light. The insect was considered marked (to have pigment) when a clear drop pattern of the dye observed on any part of the body while samples found to have small-scattered stains were disregarded as unmarked and were considered contaminated during sampling in sweep net (Heimoana *et al*., 2017; Schellhorn *et al*., 2004).

3.2.4 Evaluation of the Complexity and Stability of Plant-pollinator Networks in Bean Agro-systems

The study involved 24 sites located in three elevation gradients; low zone (< 1000 m), mid zone (1000 – 1500 m) and high zone (1500 – 1800 m). Since agricultural management practices, weather, vegetation composition and land use may vary from lowlands to the highlands, including wide area where beans are cultivated was necessary to understand the complexity and stability of networks in three different agro systems. Each zone had eight sites and every site was bordered by margin of herbaceous weeds, shrubs and trees. To quantify the interactions between insect pollinators and plant species across these zones, two methods were used. The first method involved systematic random sampling where 1 m^2 plots was established at the center of one of the field margins in each site to record flower-visitors' interactions. In this method, any interaction or visit within a plot was recorded for a period of one hour. Recording of plant-pollinators interactions was done during daytime between 1000 h and 1500 h because it is the time where ambient temperature is moderate and most of pollinators are active. A visit was defined to have occurred when the visitor's body came into contact with reproductive organs of the flower (Lundgren *et al*., 2013). The second method involved the establishment of walking line transects between the edge of field margin and bean field. The transect width was 2 m (1 m to the field and 1 m to the margin perpendicular to the transect line) while the length followed the size of the field. The research used human to observe and record the interaction between plants and pollinators. Data were collected in three stages (pre-ploughing, flowering and podding stages) for two seasons in two consecutive years from March, 2016 to October, 2017.

3.2.5 Assessing the Diversity and Richness of Pollinators in Association with their Host Plants across Three Zones

(i) Insects Survey and Sampling Strategy

To determine the richness and diversity of insect pollinators in three bean agro-systems; low zone (< 1000 m), mid zone (1000 – 1500 m) and high zone (1500 – 1800 m), pan trapping method was used (Westphal *et al*., 2008). Line transects were established in 24 bean farms (eight farms in each zone). At each site, two transects of 50 m long were established, one in the field margin and another in the centre of the field perpendicular to the field margin. Pan trap "kit" were placed every 10 m along transect in each site. Each pan trap kit contained bright yellow, white and blue 500 ml plastic pans and half filled with water and few drops of detergent (i.e. washing up liquid) to break the surface tension of water. The kits were placed in the afternoon and left in the field for 24 hours before first sampling. The sampling was done after every 24 hours for two consecutive days (48 hours) (Brittain *et al*., 2010). The captured insects were collected from each pan and stored into a separate labelled tube (site name, collection date, transect line name, trap number and pan colour). Unidentified specimens were collected, preserved in 70% ethanol for identification in the laboratory. Insects were sampled four times per season i.e. during pre-ploughing (before planting), seedling, flowering and podding stages.

(ii) Vegetation Survey and Sampling Strategy

To determine common flowering plants growing along field margins of bean crop in three agro-system zones; low zone (<1000 m), mid zone (1000 – 1500 m) and high zone (1500 – 1800 m), line transects of 50 m long were established in 24 bean farms (eight farms in each zone). At each 10 m measure, a quadrat (1 m^2 by size) was systematically established to assess plant community in one of the field margins of each farm. Species coverage in each quadrat was determined using Domin scale (a system describing the cover of a species in a vegetation community). Vouchers of unknown plant species were collected in duplicate and sent to National Herbarium of Tanzania, Arusha and Royal Botanic Gardens, Kew for identification.

3.3 Data Analysis

Multivariate analysis of variance (MANOVA) was performed to determine the overall effects of pollination systems on bean yields across the zones. MANOVA was used to compare between independent variables such as sites, season, zones and three treatments (open, hand and self-treatments) which were dependent variables. A univariate ANOVA was then employed to determine significant differences in means between treatments on each dependent variable. However, various tests were used where ANOVA assumption conditions were not met. The Tukey's honest significant difference (HSD) test was applied for multiple comparisons of means at 95% - confidence level to understand where those differences laid between pollination treatments. To test significant differences between farmers' responses in three zones, a Kruskal-Wallis rank sum test (KW) was performed (Sheskin, 2011). A Kruskal-Wallis was also used to determine the differences between the proportions of dye-marked versus unmarked insects by zone and sampling days. A Kruskal-Wallis rank sum test was used after the data were tested and found that they were normally distributed. To test for the effects of field margins vegetation on numbers of pollinators in the bean fields, generalized linear model with Poisson distribution was then used. Through bipartite (a package in R software), a two-dimensional matrix function (plotweb) was used to visualize the interactions between plants and flower visitors which were recorded during experiment. The ecological indices such as robustness, nestedness, degree of specialization, connectance for each zonal network were calculated using special function in R software known as network level. The network analyses were done to understand stability status of each zone networks using plant-pollinator interactions data.

Simpson's Diversity Index (D) was used to determine insect species diversity and richness across the agro-ecosystem zones.

$$\boldsymbol{D = 1 - \frac{\sum n(n-1)}{N(N-1)}}$$

Where:

D = Simpson's Diversity Index

N = The total number of organisms of all species

n = The total number of organisms of a particular species.

Shannon Diversity Index (H) was used to determine plant species diversity and richness across the agro-ecosystem zones.

$$H = - [\sum P_i \ln P_i]$$

Where:

H = the Shannon diversity index

P_i = proportion of each species in the sample

$\ln P_i$ = natural logarithm of this proportion

The species evenness (E) was also calculated using the formula

$$E = H/H_{max}$$

Where:

E = Evenness

H = Shannon Diversity Index

H_{max} (Maximum diversity possible) = ln(S)

S = number of species/species richness

Ln(S)= natural logarithm of species richness

CHAPTER FOUR
RESULTS AND DISCUSSION

4.1 Results

4.1.1 Farm Size, Gender and Age of Respondents

The survey results which involved 300 respondents of which 61% (182) were female and 39% (118) male recorded no differences in knowledge between male and female respondents with respect to the identification of the three pollinators; honeybee ($KW_1 = 2.2546$, p = 0.1332), hoverfly ($KW_1 = 0.0004$, p = 0.9837), solitary bee ($KW_1 = 0.3467$, p = 0.556). Similarly, there was no significant difference of knowledge between male and female respondents regarding the importance of pollinators in crop production: honeybee ($KW_1 = 1.9633$, p = 0.1612), hoverfly ($KW_1 = 0.2960$, p = 0.5864), solitary bee ($KW_1 = 0.0455$, p = 0.831). It was also found that the age of farmers engaged in bean cropping was evenly distributed and the knowledge of pollinators between farmers did not vary significantly by age; honeybee ($KW_{54} = 55.145$, p = 0.4311), hoverfly ($KW_{54} = 43.427$, p = 0.8478), solitary bee ($KW_{54} = 68.767$, p = 0.0851). Likewise, there was no significant difference of knowledge by age between farmers in three zones of the importance of pollinators in crop production; honeybee ($KW_{54} = 50.75$, p = 0.6005), hoverfly ($KW_{54} = 38.912$, p = 0.9393), solitary bee ($KW_{54} = 17.594$, p = 1). Most farmers in the mid and high zones (64% and 69% respectively) worked in farms of not more than 0.20 hectares whereas for farmers in the low altitude only 38% had farms of this size. The average farm size across all zones was 0.27 hectares.

Table 1: Gender and Age of Respondents in the Study Area

Variable		Zone			Statistical test
		Low	Mid	High	
Gender	Female	77	57	48	p = 0.002
	Male	23	43	52	
Age (year)	18-40	39	54	44	p = 0.431
	41-60	46	44	42	
	Above 60	15	2	15	

4.1.2 Farmers' Knowledge of Common Pollinators before and after Training

Overall, 77% of farmers identified the honeybee correctly while 5% identified it incorrectly and 18% said they did not recognise the insect at all. Only 5% of farmers were able to correctly identify hoverflies, with 15% identifying it incorrectly and 80% did not recognise the insect. About 98% of the farmers were unable to identify solitary bee by any local or Swahili name while 2% identified the insect incorrectly. Generally, there was little variation in knowledge among farmers at different altitudes although significantly more farmers in mid zone (84%) recognised the honeybee compared with those in low (66%) and high (79%) zones (KW_2 = 10.074, p = 0.0065). Also, there was no significant difference in knowledge of hoverflies (KW_2 = 2.5695, p = 0.2767) and solitary bees (KW_2 = 5.5397, p = 0.0627) between farmers at three different altitudes.

One year after training, awareness of honeybees among smallholder farmers had increased by 34%, 14% and 20% in low, mid and high zones respectively. Only 1% of farmers in the high zone identified the insect incorrectly and 2% of farmers in the mid zone were not aware of this insect. The results showed a significant increase in knowledge retention among farmers of hoverflies by 25%, 49% and 73% in low, mid and high zones respectively, compared with pre-training results. It was found that only 39%, 22% and 24% of farmers who identified the insect incorrectly while a small group of farmers failed to do so (Fig. 2). There was a significant increase of knowledge of solitary bees where more farmers in the low zone (73%) were able to identify a solitary bee by name compared with 59% in the mid and 55% in high zone. Even after training, 16%, 32% and 30% of farmers were recorded in the low, mid and high zones who identified solitary bee incorrectly while a significantly lower number of farmers said they were unaware of the insect (Fig. 2).

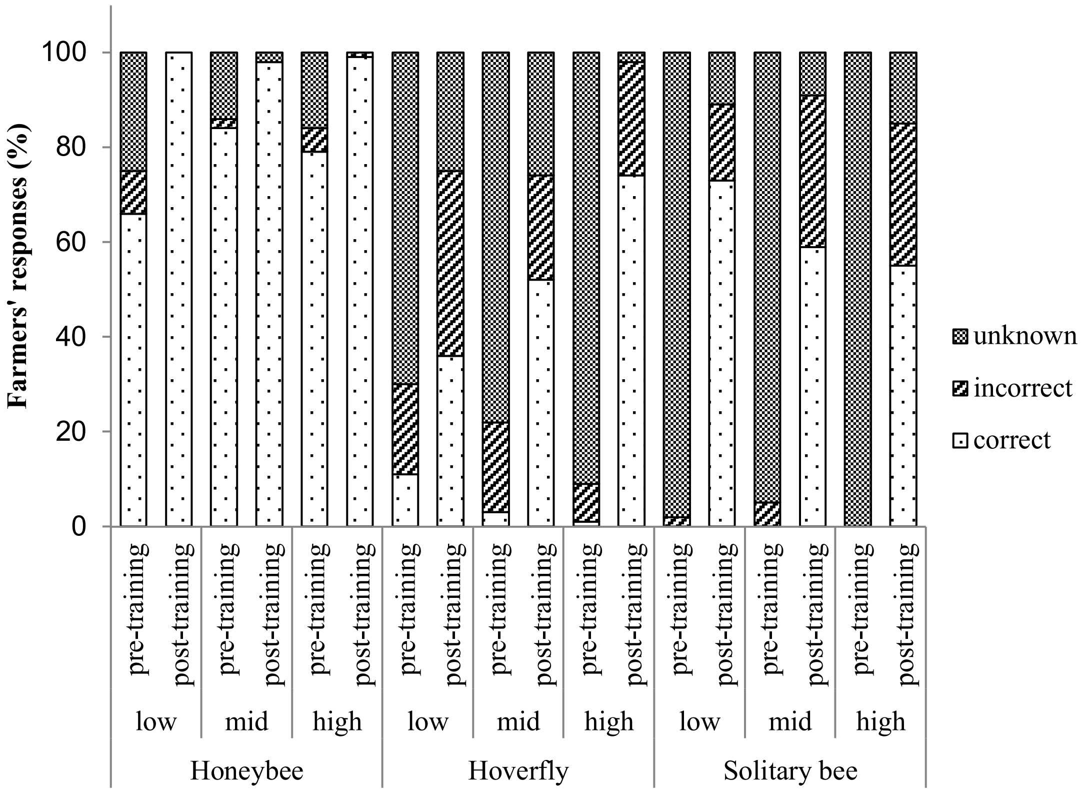

Figure 2: Farmers' ability to recognize and identify common pollinators from photographs and specimens, before and one year after training activities, presented according to the three elevation zones

4.1.3 Farmers' Knowledge of the Importance of Pollinators in Crop Production before and after Training

Surprisingly only 53%, 56% and 45%, of farmers in the low, mid and high zones respectively, expressed awareness of the importance of honeybees as a crop pollinator. However, more alarmingly a significant minority of farmers identified honeybees as a pest and some did not know the potential importance of this insect in crop production reflecting the perception that many farmers see all insects as problematic rather than beneficial. There was no significant difference in knowledge among farmers across three zones on the importance of honeybee in crop production ($KW_2 = 0.91476$, $p = 0.6329$). Knowledge among farmers in the three zones regarding the role of hoverflies in pollination differed significantly ($KW_2 = 8.1048$, $p = 0.0174$) with the majority of farmers being unaware of the insect. Only 14%, 7% and 1% of farmers in the low, mid and high zones respectively, recognised the insect as pollinators. No farmers responded to indicate any prior knowledge regarding the role of wild solitary bee species as crop pollinators while a minority identified solitary bees as crop pest (Fig. 3). There was no significant difference in knowledge between farmers in three zones regarding the importance of solitary bees as pollinators of crops ($KW_2 = 0$, $p = 1$).

One year after training, a significant increase in knowledge between farmers ($KW_1 = 27.675$, $p < 0.001$) was recorded where the majority, 95%, 92% and 98% of them in the low, mid and high zones reported understanding the importance of honeybees as crop pollinators. Variable knowledge between farmers regarding the importance of hoverflies in crop production were recorded and the majority of farmers recognised this insect as a pollinator (24% low, 18% mid and 33% high), natural enemy of pests (18% low, 12% mid and 20% high) and others recognised it as both pollinator and natural enemy (22% low, 33% mid and 27% high). Knowledge about solitary bees was also enhanced and retained post-training with the majority of farmers, 52%, 65% and 63% in the low, mid and high zones respectively, recognizing and reporting solitary bees as pollinators with only a minority of farmers still considered the insect a pest or were not aware of the insect at all (Fig. 3).

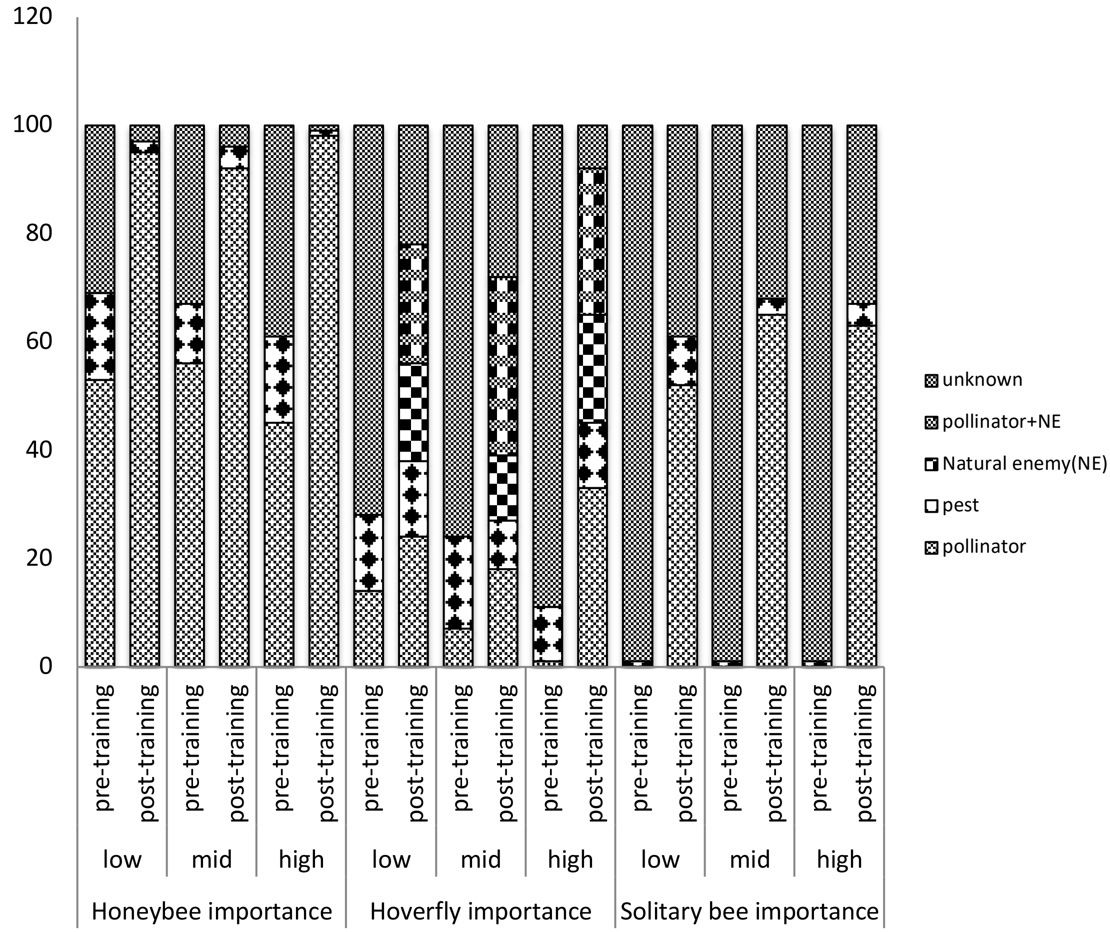

Figure 3: Farmers' ability to articulate the importance of three different pollinator groups in bean production, presented before and after training activities had taken place, and disaggregated by elevation zone. Hoverflies are also a natural enemy (NE)

4.1.4 Management of Field Margins in Bean Agri-systems

In the baseline survey, farmers reported that they frequently cleared their field margins and the most common methods were cutting and burning (Fig. 4). There was significant variation in frequency with which low zone farmers cleared their field margins more frequently compared with those in the mid and high zones ($KW_2 = 17.598$, $p < 0.001$). However, one year after training, fewer farmers, 55% and 32% in the low and high zones respectively, who cut their field margins were recorded while in the mid zone a slight increase were recorded although this was in concert with a significant reduction in the farmers burning field margins (Fig. 4). At the baseline, 8%, 33%, 5% of farmers in the low, mid and high zone respectively, reported burning their field margins, the number decreased to 4%, 9%, 3% after training. No farmers applied herbicides to manage weeds in the field margins compared with pre- training where 1% and 3% of farmers in the low and mid zones respectively, did so.

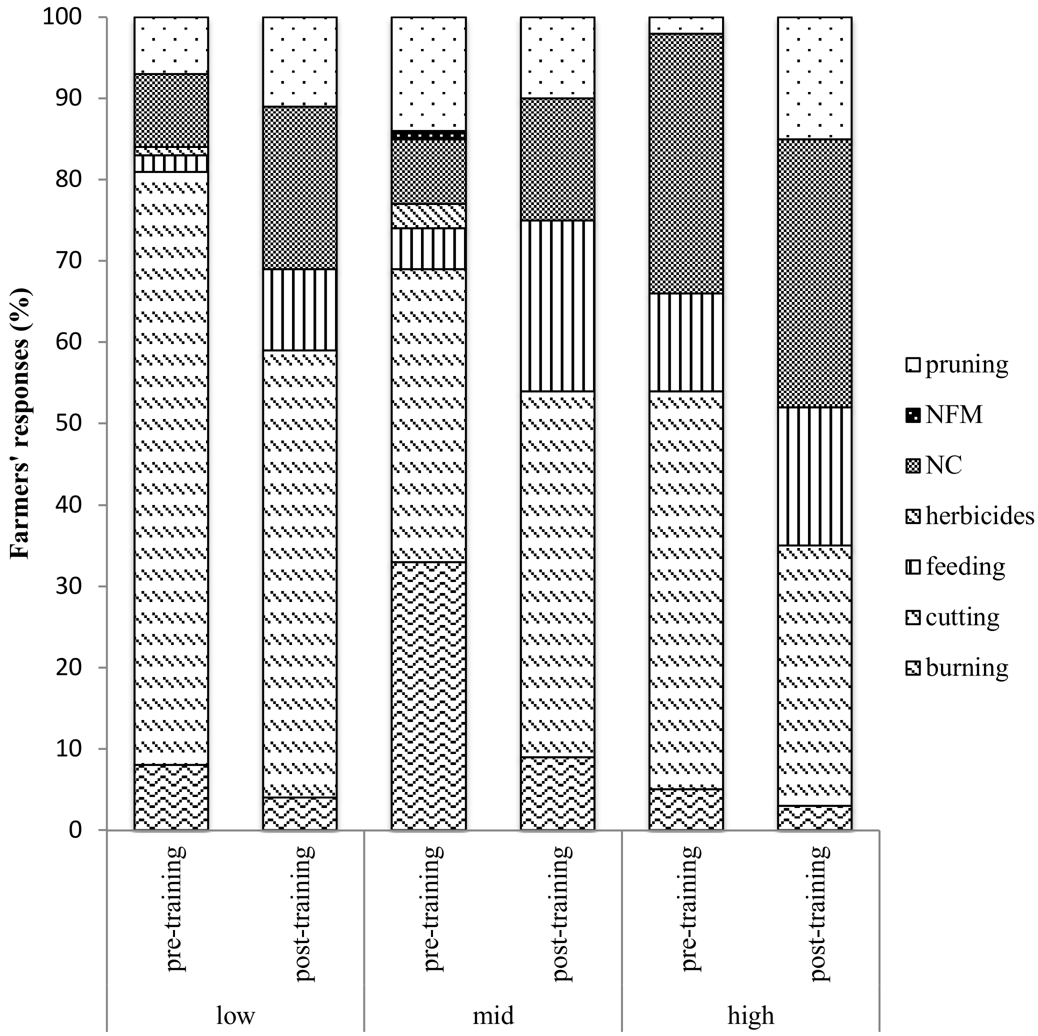

Figure 4: Farmers' responses about their preferred methods used to manage field margins in bean agro-systems. NC=No clearing of field margin, NFM=No Field Margin

4.1.5 Farmers' Knowledge of the Role of Field Margin Plants in Bean Agri-systems

It was found that 27%, 56% and 55% of farmers in the low, mid and high zones respectively, who did not mention beneficial plants as a feature of their bean cropping systems. Although various flowering plants species such as *Tithonia diversifolia*, *Ageratum conyzoides*, *Commelina foliacea*, *Neonotonia wightii, Bidens pilosa* and *Desmodium uncinatum* were recorded along margins of bean fields and they were frequently visited by insects (Table 3), 64%, 35% and 31% of farmers in the low, mid and high zones respectively, declared that their bean field margins do not include beneficial plants. However, a minority of farmers (3%) in the low zone cited flowering plants as important while 9% in the mid zone reported the presence of beneficial plants but they were not able to describe them specifically, even using local names. A small group of farmers mentioned *Thevetia peruviana*, *Acacia tortilis*, *Persea mericana*, *Azadirachta indica* and *Prunus* spp. As beneficial plants found within and along their bean fields. Coffee (*Coffea arabica*), cassava (*Manihot esclulenta*), collard greens (*Brassica* spp.) and sunflowers (*Helianthus annuus*) were also listed as beneficial plants when intercropped with beans since they increased the number of honeybees in bean field. There was a statistically significant difference between the three zones in farmers' knowledge of beneficial plants (KW_2 =30.056, $p < 0.001$), with the majority of farmers in the low zone not mentioning beneficial plants in their field margins. Across elevation zones, farmers listed various benefits of field margin plants where more farmers in the high zone reported fodder and erosion control as major benefits from margin plants compared with low and mid zone farmers (KW_2 = 27.753, $p < 0.001$). In the baseline survey, no farmers reported the importance of marginal plants in attracting pollinators. However, one year after training, between 7 and 11% of farmers who recognised the importance of these plants in promoting pollinators was recorded (Fig. 5).

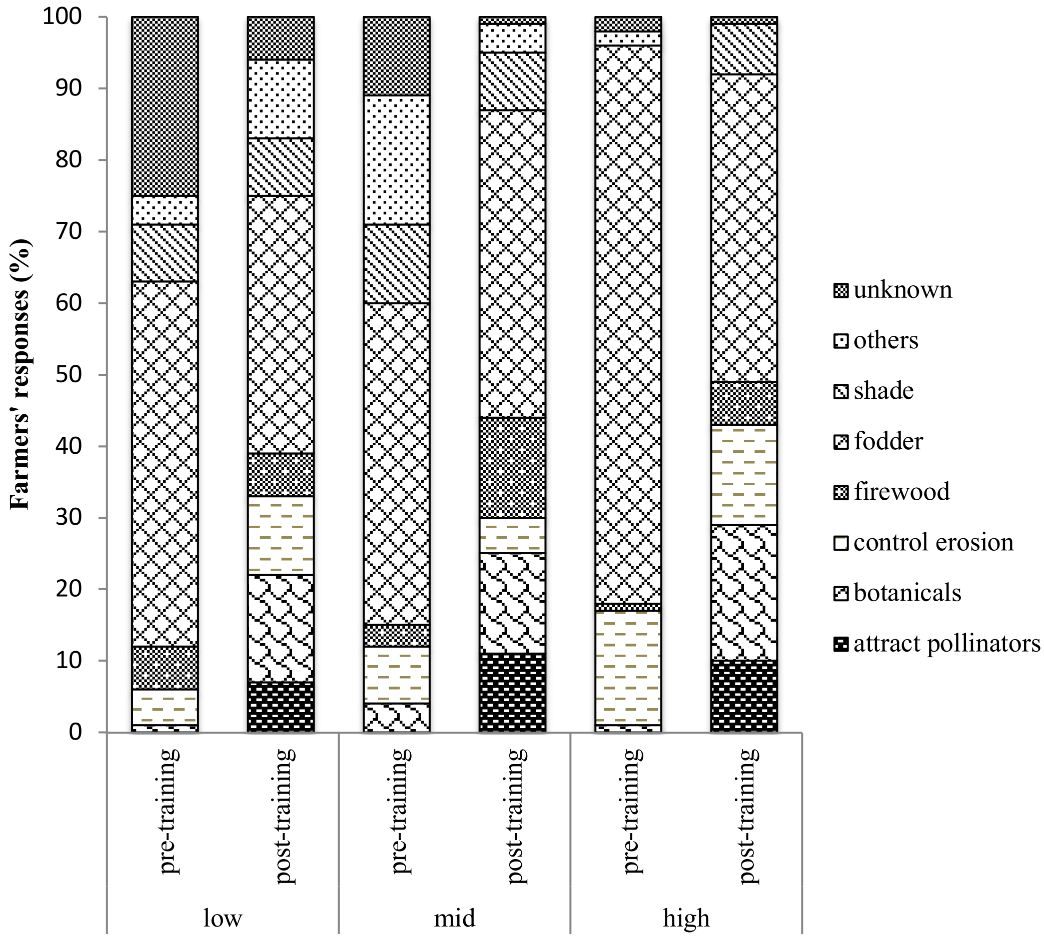

Figure 5: Farmers' responses about the roles of field margin plants in bean agro-systems, presented before and after training activities had taken place, and disaggregated by elevation zone

4.1.6 Farming Practices by Smallholder Farmers in Bean Agri-system

In the baseline survey, approximately 75% and 87% of farmers in low and mid zones respectively, reported application of synthetic pesticides, whereas in the high zone few did so (Fig. 6). The most common pesticide products were Selecron 720EC (Profenofos), Karate 5EC (Lambda-cyhalothrin-Pyrethroids) and Dursban 24ULV (Chlorpyrifos). The key advantages reported by farmers for using synthetic pesticides were not surprisingly their apparent efficacy at controlling pests but also their ease of use, while the disadvantages reported included toxicity and cost indicating that farmers were aware of the dangers of using synthetic products. A minority of farmers didn't report any drawbacks.

Although the same farmers who were interviewed during the baseline survey were trained about the effects of synthetic pesticides application to beneficial insects, the results from end-line survey (one year later) indicate many farmers still applied these chemicals to control pests. However, a change in rates of application was recorded; the number of farmers who did not apply these products increased to 41% and 52% in the low and mid zones respectively, from 25% and 13% at baseline, while less change was recorded in the high zone where little pesticide was used at the outset (Fig. 6).

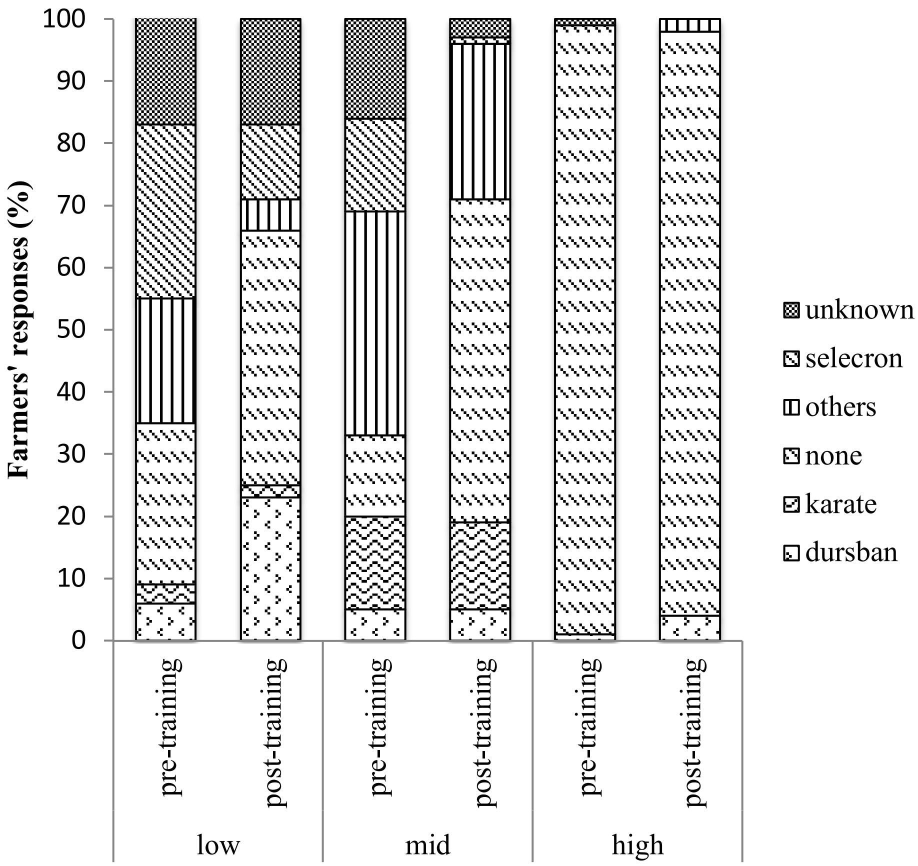

Figure 6: Farmers' responses regarding application of synthetic pesticides in bean agro-systems before and after training activities had taken place, and disaggregated by elevation zone

On the other hand, only a small number of farmers using organic and/or botanical pesticides were recorded (Fig. 7). The farmers who did use these reported that their being less toxic and affordable as major reasons for adopting them. Organic pesticides reported included ash, cattle urine and dung and botanicals made from a part of or the whole plant that has insecticidal and/or repellent properties. Farmers mentioned plants such as *Tithonia diversifolia*, *Azadirachta indica*, *Tephrosia vogelii*, *Tagetes minuta* and *Aloe vera* as common botanical pesticides in the area. One year after training, a significant increase in number of farmers who either applied botanicals, organic pesticides or a mixture of botanicals and organic pesticides to control pests were recorded (Fig. 7).

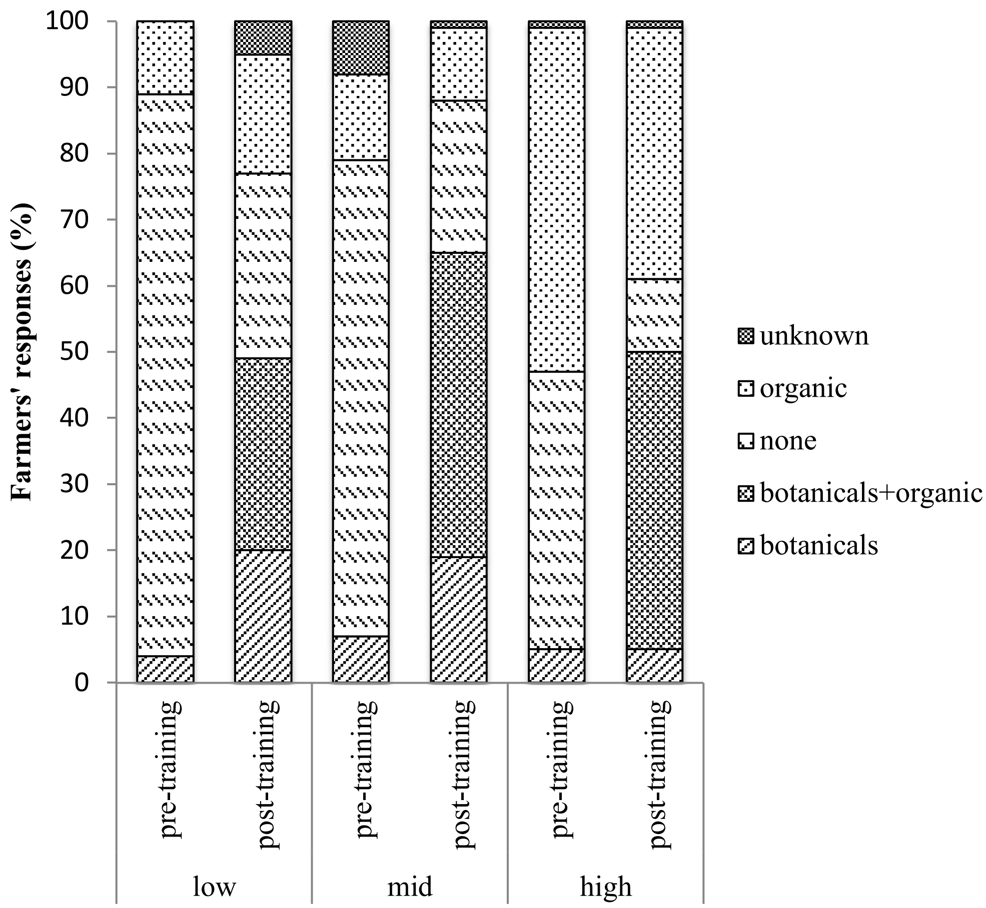

Figure 7: Farmers' responses regarding application of non-synthetic pesticides in bean agro-systems before and after training activities had taken place, and disaggregated by elevation zone

4.1.7 Socio-economic Importance of Bean Crop to Smallholder Farmers

Beans were equally popular across the zones ($KW_2 = 2.5383$, $p = 0.2811$) and were important for food security as well as income. The results showed that 51%, 60% and 21% of farmers in low, mid and high zones respectively, earned an income up to 100 USD after selling beans in the local markets during the first season of 2016. Although some farmers were earning up to 400 USD per cropping harvest, 36% of farmers in the low, 29% in the mid and 80% in high zones did not earn any income in that particular season. Consequently, only 1% and 2% of farmers in the low and mid zones respectively, earned more than 300 USD during the season. There was significant variation in income earned by farmers across three zones after selling beans during this season ($KW_2 = 49.564$, $p < 0.001$). The majority of farmers in high zone did not have enough beans to sell in the market after taking what they needed from their harvest. For those who sold beans their income was mainly spent on clothes, food, household supplies, paying school fees for their children, building or renovating their houses and medical services.

4.1.8 Effects of Pollination Service on Bean Yield in Smallholder Farming Systems

Open pollinated plants bore the highest number of pods, had the highest mean number of seeds per pod, and the weight of seeds was also highest, compared to the self-pollinated treatments (pods: $F_1 = 166.5$, $p < 0.001$; seeds: $F_1 = 101.9$, $p < 0.001$; weight: $F_1 = 38.08$, $p < 0.001$). Hand-pollinated beans did not differ significantly from the open pollinated treatment except on weight of seeds (Fig. 8). Increase in weight in open pollinated beans is an indication of improved seed quality and yield brought about by pollinating insects (Bartomeus *et al*., 2014). The highest pod count, bean/pod count and seed weight (g) overall was consistently recorded from the open-pollinated plants in the mid-zone (Fig. 9-11). Although there were significant differences among zones ($F_2 = 26.604$, $p < 0.001$), there were no significant interactions between treatments and the zones ($F_4 = 0.565$, $p = 0.8709$).

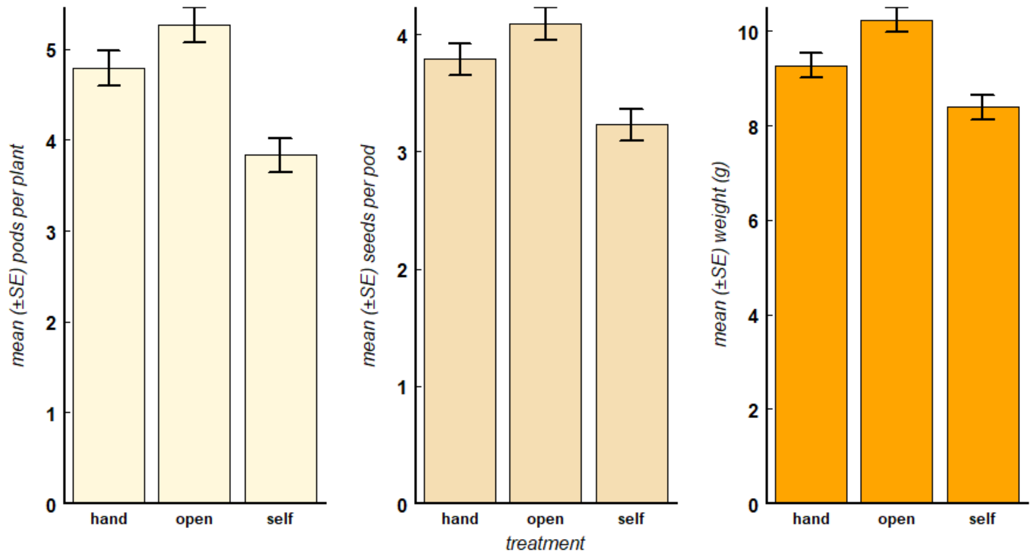

Figure 8: Bean yield parameters, means (±SE) number of pods, and number of seeds and weight of 30 seeds for each treatment. The treatments are: open-pollination (open), hand-pollination (hand) and self-pollination (self). The error bars on top of the means measure the Least Significant Difference (LSD). Pollination treatments are considered significantly different if the error bars do not overlap ($p \leq 0.05$)

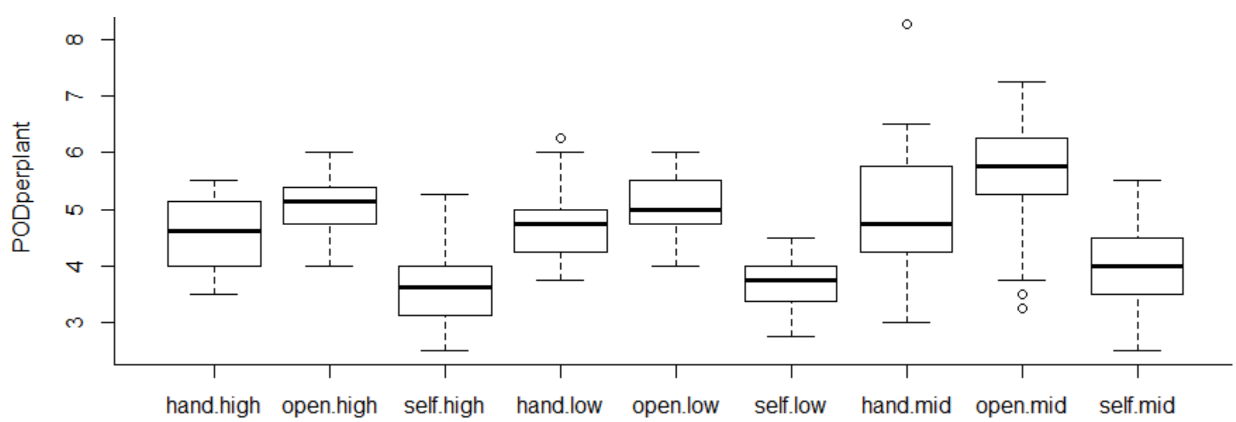

Figure 9: Box-plots comparing number of pods per plant between three pollination treatments in *P. vulgaris*: hand, open and self-pollination. Thick black lines within the boxes represent median values; the upper and lower limits of the boxes represent 1st and 3rd quartiles respectively. High, low and mid refer to agro ecological zones

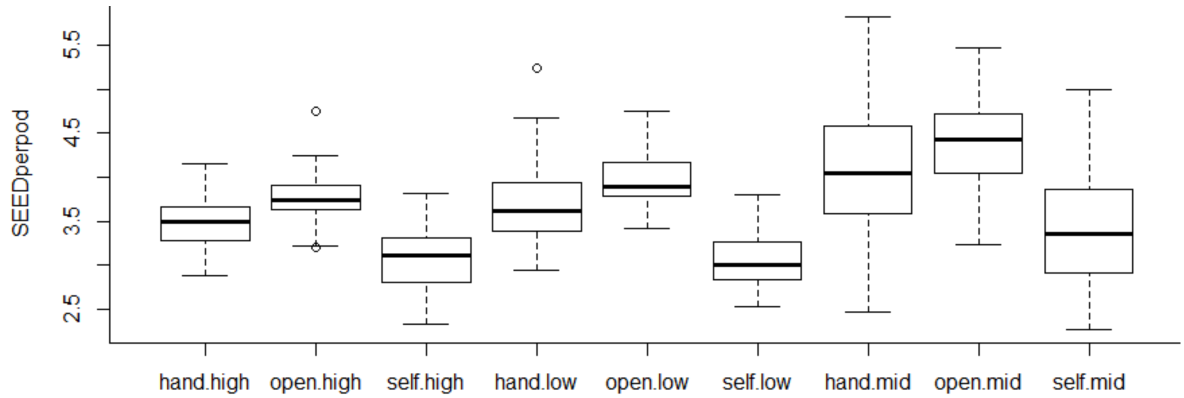

Figure 10: Box-plots comparing number of seeds per pod between three pollination treatments in *P. vulgaris*: hand, open and self-pollination. Thick black lines within the boxes represent median values; the upper and lower limits of the boxes represent 1st and 3rd quartiles respectively. High, low and mid refer to agro ecological zones

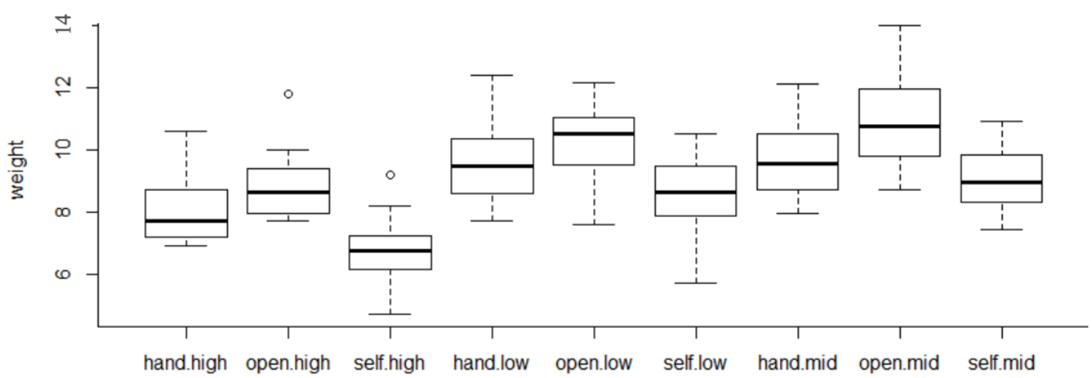

Figure 11: Box-plots comparing weight (g) of 30 seeds between three pollination treatments in *P. vulgaris*: hand, open and self-pollination. Thick black lines within the boxes represent median values; the upper and lower limits of the boxes represent 1st and 3rd quartiles respectively. High, low and mid refer to agro ecological zones

When the bean yields per plant were extrapolated to field level, the increase in kg/ha as a result of insect flower visits became particularly apparent (Table 2). There was an increase in mean yield per hectare from 681 kg in self-pollinated beans to 1478 kg in open-pollinated beans. Furthermore, the amount of beans harvested from open-pollinated treatments exceeded those in hand-pollinated treatments suggesting that while pollinators are potentially a major yield limiting parameter where they are absent that there is no pollinator deficit or pollen limitation in the study area. Due to increased bean yields following insect pollination, improved income among smallholder farmers in the study area associated with landscapes that maximise pollinator services is possible. The calculated average income per hectare was higher in open-pollinated bean plots compared with the other treatments. Overall, the results revealed that insect pollination provides a major contribution to bean yields and is an essential ecosystem service in improving bean yields and food security in bean agro-systems.

Table 2: Comparisons of average of bean yield between three treatments (open, hand and self) per hectare. The average price (1518 TSh per kg) obtained from three local markets in the study area and converted to USD. The exchange rate was 1 USD to 2200 TSh (CRDB, 2018)

Pollination treatments	Average bean yield (kg/ha)	% Increase in bean yield	Average Income ha^{-1} (USD)
Open	1478	117	1020
Hand	1131	66	780
Self	681	-	470

4.1.9 Movement of Pollinators between Field Margins and Bean Field

A total of 980 insects were sampled during the fluorescent dye assessment of which 327 were flower-visiting taxa that may be pollinators. Pollinators were observed under UV light and a total number of 203 (62%) insects tested positively (dye-marked) and 124 (38%) insects tested negatively (unmarked). Higher numbers of sampled insects (133) were recorded at the mid zone compared to the low (122) and high zone (72). However, the number of dye-marked insects did not vary significantly between the zones ($H_2 = 2.926$, p = 0.2315) similarly to the total number of sampled insects ($H_2 = 1.792$, p = 0.4082). Honeybees (*Apis mellifera*) (Plate 1) were the most frequently sampled dye-marked insects across the zones where a total of 103 (51%) individuals were collected during three days of sampling. Insects including small bees (Hymenoptera: Halictidae and Apidae) were often collected while carpenter bees (Hymenoptera: Apidae: *Xylocopa* sp.) and cuckoo wasps (Hymenoptera: Chrysididae) were the least sampled species during this assessment. Other flower visitors included Amegilla bees (Hymenoptera: Apidae: *Amegilla* sp.), bee flies (Diptera: Bombyliidae), hoverflies (Diptera: Syrphidae) butterflies

(Lepidoptera), moths (Lepidoptera) and a diversity of small solitary bees (Hymenoptera: Apoidea). The number of dye-marked insects did not vary significantly between sampling days ($KW_2 = 3.963$, p = 0.1379). However, a GLM test showed that the number of marked insects caught varied significantly by distance from the margin ($Z_{214} = -3.492$, p = 0.0005) with most marked individuals being sampled nearer to field margins (Fig. 12). The results also demonstrated that bees were the most abundant dye-marked pollinating insects than any other taxa (Fig. 13).

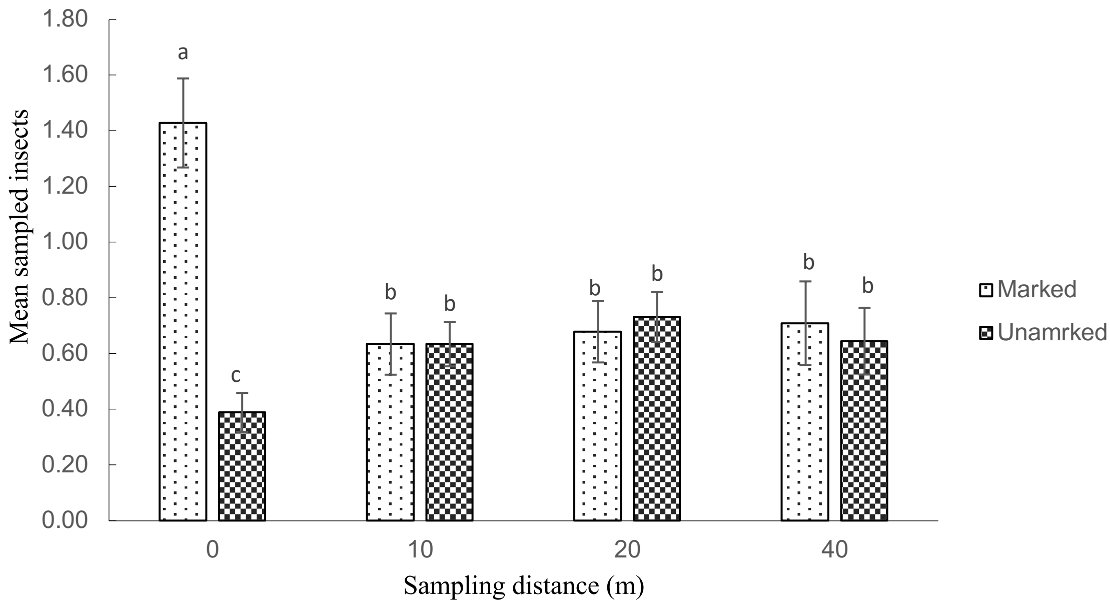

Figure 12: The effects of field margin position on numbers of flower visitors in bean field (field margin/edge indicated as 0 m)

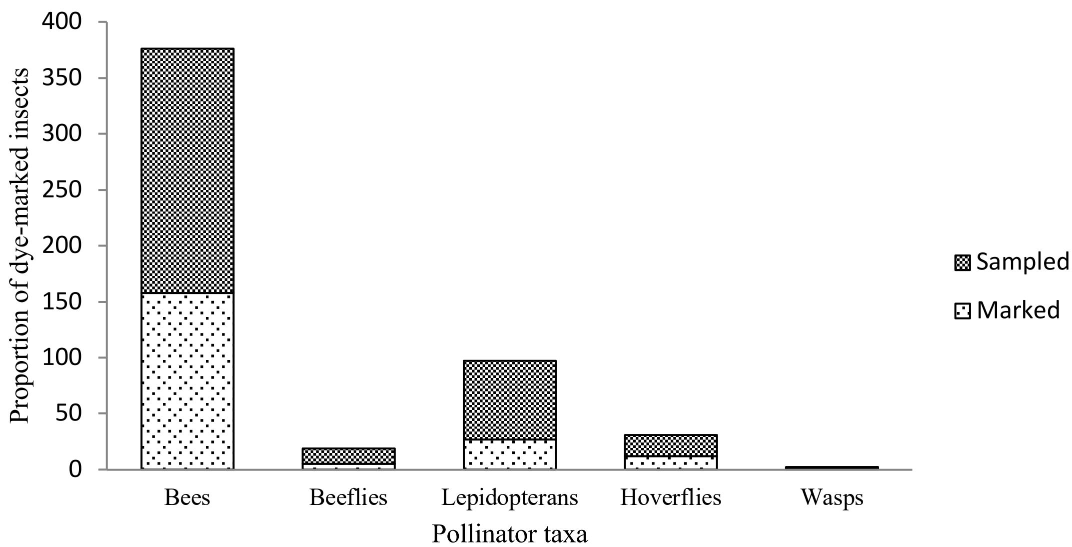

Figure 13: The proportion of dye-marked insects by functional group collected during fluorescent-dye experiment in bean agro-systems

4.1.10 Richness and Diversity Common Flower Visitors in Bean Agri-systems

With trapping method, a total number of 3830 individual insects were recorded during the entire sampling period in bean agro-systems. Wasps (Hymenoptera) (38.19%) were the most abundant flower visitors followed by small bees (Hymenoptera: Halictidae and Apidae) (30.08%), moths (Lepidoptera) (9.69%), bee flies (Diptera: Bombyliidae) (8.88%), solitary bees (Hymenoptera: Megachilidae: *Megachile* sp.) (4.91%), honeybees (Hymenoptera: Apidae: *Apis mellifera*) (3.45%), carpenter bees (Hymenoptera: Apidae: *Xylocopa* sp.) (1.96%), hoverflies (Diptera: Syrphidae) (1.49%), butterflies (Lepidoptera)) (0.78%), amegilla bees (Hymenoptera: Apidae: *Amegilla* sp.) (0.34%) and cuckoo bees (Hymenoptera: Halictidae) (0.23%). There was a significant difference in number of insects collected between three pan colours ($KW_2 = 172.23$, $p < 0.001$) where most insects were recorded from yellow pans (44.43%) followed by white (33.42%) and blue (22.15%). Wasps, small bees, moths, bee flies, solitary bees were mostly attracted by yellow colour while white colour attracted most honeybees, butterflies and hoverflies.

There was a significant difference in the number of insects sampled between three elevation zones ($KW_2 = 10.017$, $p = 0.0066$) with a higher number of insects recorded in the high zone (38.39%)

followed by the low zone (34.44%) and lastly the mid zone (27.17%). Also, the number of insects collected between margins and bean fields varied significantly (KW_1= 14.002, p = 0.0002) whereas more insects were collected in the margins (55.25%) than in bean field (44.75%). However, there was no significant difference in number of insects collected between traps established along field margins of each zone; low zone (KW_4= 2.5814, p = 0.6301), mid zone (KW_4 = 2.1435, p = 0.7094) and high zone (KW_4= 1.8584, p = 0.7618). However, all three zones had high insect diversity with the highest Simpson's diversity (*D*) value being seen in the mid zone (*D* = 0.7724) compared to the low (*D* = 0.7275) and high zone (*D* = 0.7065).

As far as the vegetation analysis was concerned, the Shannon diversity index showed that the high zone had high plant diversity (*H*), high richness (*S*) and high species evenness (*E*) (*H* = 3.44, *S* = 42, *E* = 0.92) compared with the mid zone (*H* = 2.99, *S* = 39, *E* = 0.82) and low zone (*H* = 2.76, *S* = 37, *E* = 0.76). However, plant species dominance varied between zones whereas *Sida rhombifolia* (Family: Malvaceae) dominated the low zone while *Asystasia mysorensis* (Family: Acanthaceae) was dominant in the mid zone and *Ageratum conyzoides* (Family: Asteraceae) in the high zone. Other common flowering plants recorded during botany survey are presented in Table 3.

Table 3: Common flowering plants sampled during botanical survey along field margins of bean fields. The plant species presented here grew naturally in bean agro-system except *Morus australis* Poir. which was planted purposely for fruits Plant species

Family	Voucher number		Ecosystem benefits	References
Acacia tortilis (Forssk.) Hayne	Fabaceae		Pollinator food resource, boundary's mark.	Dino (2004)
Ageratum conyzoides L.	Asteraceae	FE20	Pollinator food resource, pesticidal.	Rioba and Stevenson (2017)
Amaranthus hybridus L.	Amaranthaceae		Vegetable.	Bvenura and Afolayan (2015)
Bidens pilosa L.	Asteraceae	FE08	Pollinator food resource, vegetable, pesticidal,	Mkindi *et al.* (2017)
Commelina foliacea Chiov. Subsp.	Commelinaceae	FE14	Vemegdiectianballe., fodder, pollinator food	Addis *et al.* (2013)
Commiphora spp	Burseraceae		resource. Pollinators' nesting resource, medicinal.	Martins *et al.* (2014)
Conyza bonariensis (L.) Cronquist	Asteraceae	FE04	Pollinator food resource, medicinal.	Thabit *et al*., (2015)
Desmodium intortum (Mill.) Urb.	Leguminosae	FE26	Fodder, N-Fixation, control striga weed. Fodder,	Midega *et al.* (2018)
Desmodium uncinatum (Jacq.) DC.	Leguminosae		N-Fixation, control fall armyworm. Pollinator	Midega *et al.* (2017)
Galinsoga parviflora Cav.	Asteraceae		food resource, vegetable.	Jaca and Kambizi (2011)
Cleome gynandra L.	Cleomaceae		Vegetable, medicinal.	Van Jaarsveld *et al*. (2014)
Hyptis suaveolens (L.) Poit.	Lamiaceae		Pollinator food resource, pesticidal, medicinal.	Pavunraj *et al*. (2014)
Launaea cornuta (Oliv. & Hiern)	Asteraceae	PM14	Vegetable, medicinal.	Sreeramulu *et al.* (1983)
Leucas martinicensis (Jacq.) R.Br.	Lamiaceae		Pollinator food resource, medicinal.	Ramalingam *et al.* (2013)
Morus australis Poir.	Moraceae	FE17	Pollinator food resource, fruits, fodder, medicinal.	Hussain *et al.* (2017)
Neonotonia wightii (Wight & Arn.)	Leguminosae	FE16	Fodder, food, pollinator food resource. Pollinator	Viswanathan *et al.* (2001)
Ocimum gratissimum L.	Lamiaceae		food resource, medicinal.	Braga *et al*. (2011)
Oxalis 41orniculate L.	Oxalidaceae		Medicinal, pollinator food resource.	Hebbar *et al.* (2004)
Richardia scabra L.	Rubiaceae	PM15	Pollinator food resource, medicinal.	Poonkodi and Ravi (2016)
Solanum nigrum L.	Solanaceae		Vegetable.	Ashagre *et al*. (2016)
Tagetes minuta L.	Asteraceae		Pollinator food resource, pesticidal.	Phoofolo *et al*. (2013)
Tridax procumbens L.	Asteraceae	PM09	Pollinator food resource, medicinal.	Christudas *et al.* (2012)

4.1.11 Complexity and Stability of Pollinator Networks in Bean Agri-systems

The networks composed of 37 plant species and 14 flower visitors in the low zone (Fig. 14), 38 and 18 in the mid zone (Fig. 15) and, 26 and 18 in the high zone (Fig. 16) respectively. The data showed that *Ageratum conyzoides*, *Bidens pilosa and Richardia scabra* were the most visited plants as they interacted with many insects compared with other plant species in the networks (Fig. 14-16). Other core plant species in the networks were *Glycine wightii*, *Commelina benghalensis* and *Tridax procumbens*. Honeybees and small bees were the most abundant and core visitors of many plants in the networks across all three zones. Other species such as hoverflies, bee flies, wasps and butterflies were also found to interact with many plant species in all three networks. In all three zones, each network composed of four major insect groups whereas Hymenoptera had higher number of individuals while Coleoptera had the least. It was also observed that the number of pollinators positively correlated with the number of plant taxa in the network (Fig. 17). There was significant difference in robustness (*R*) between pollination networks from three zones (F_2 = 4.672, p = 0.0598) whereas the low zone network was slightly more robust (*R* = 0.8290) compared to the mid (*R* = 0.8117) and high zone (*R* = 0.7840) networks. However, the robustness of the three networks did not vary significantly between farming stages (F_2 = 1.644, p = 0.27). Also, the connectance (*C*) did not vary significantly between the zones (F_2 = 0.853, p = 0.4720) but varied significantly between farming stages (F_2 = 6.321, p = 0.0333) with greater value being observed in the flowering stage compared to pre-ploughing and podding stages. Although there were no significant differences in nestedness between the networks in the three zones (F_2 = 4.286, p = 0.0698), the high zone network was slightly more nested compared to the mid and low zone networks (Fig. 18). Similarly, the three networks did not show significant variation in nestedness between farming stages (F_2 = 0.849, p = 0.473) but slightly increased during flowering stages compared to the rest of the stages (Fig. 18). Generally, the bean agro-systems were found to have high insects' diversity because all networks had Shannon diversity (H) value of greater than 3.50, low zone (*H* = 4.1663), mid zone (*H* = 4.0720) and high zone (*H* = 4.1347), however, their differences did not vary significantly (F_2 = 0.539, p = 0.609). Moreover, all three networks were highly generalized, with the high zone being slightly specialized (H'_2 = 0.1839) than other two zones (Table 4).

Table 4: Network-level metrics for three mutualistic networks constructed based on plant-flower visitors' interactions from three elevation zones of smallholder bean agro-system

Network-level metrics	**Zone**		
	Low	**Mid**	**High**
Connectance	0.3872	0.2564	0.3056
Degree of specialisation (H'_2)	0.1616	0.1285	0.1839
Interaction evenness	0.6638	0.6213	0.6572
Linkage density	8.5010	8.3763	7.2907
Nestedness	14.2871	11.1663	16.7273
Robustness	0.8290	0.7765	0.7877
Shannon diversity	4.1663	4.0720	4.1347

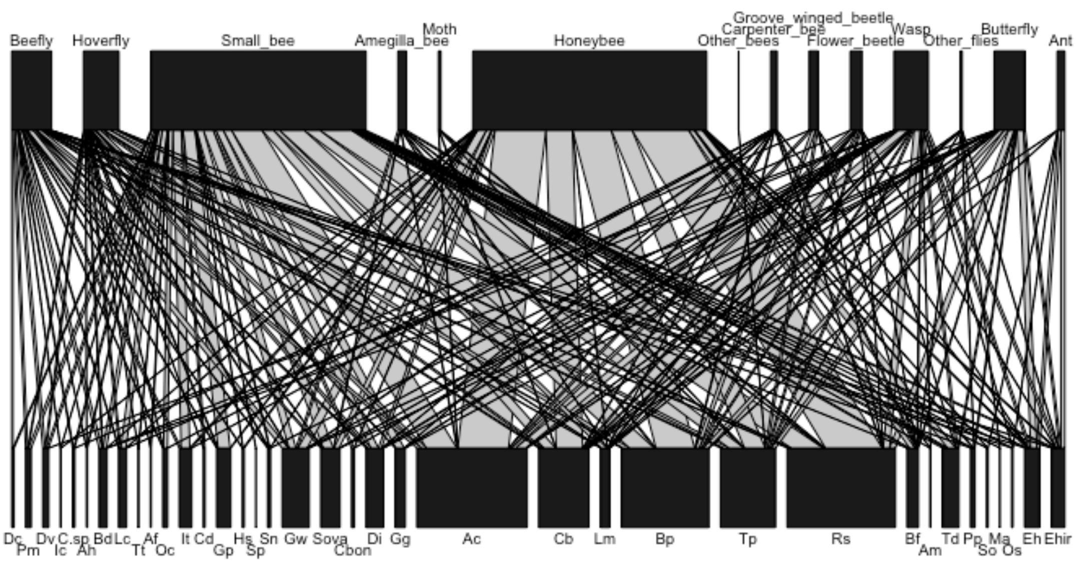

Figure 14: A network showing interactions between flower visitors (full names) represented by black boxes in the upper level and field margin plants in the lower level. The box size is proportional to the total number of visits recorded, and the link size to the frequency of this particular link

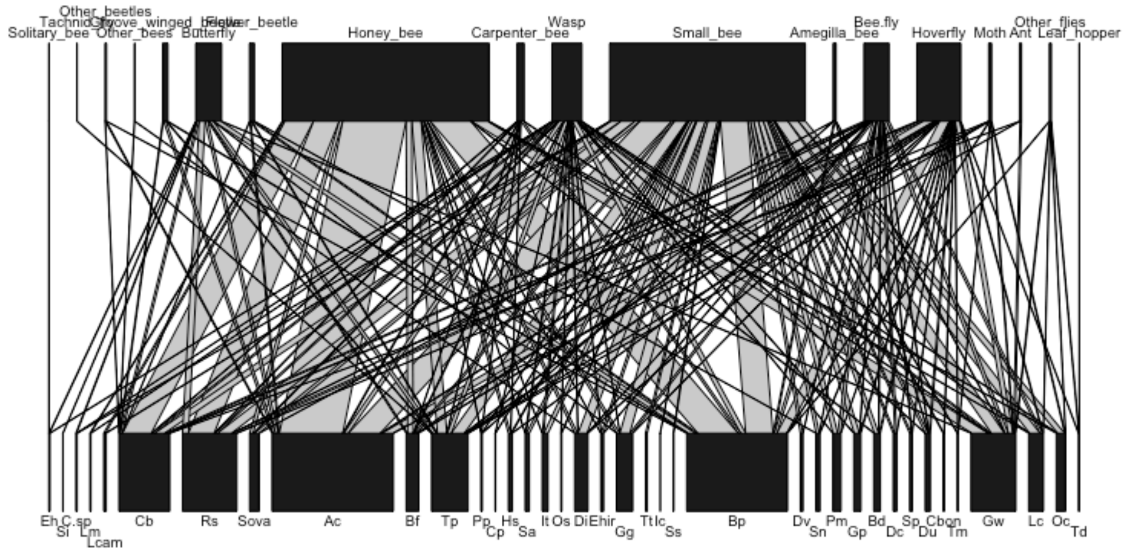

Figure 15: A network showing interactions between flower visitors (full names) represented by black boxes in the upper level and field margin plants in the lower level. The box size is proportional to the total number of visits recorded, and the link size to the frequency of this particular link

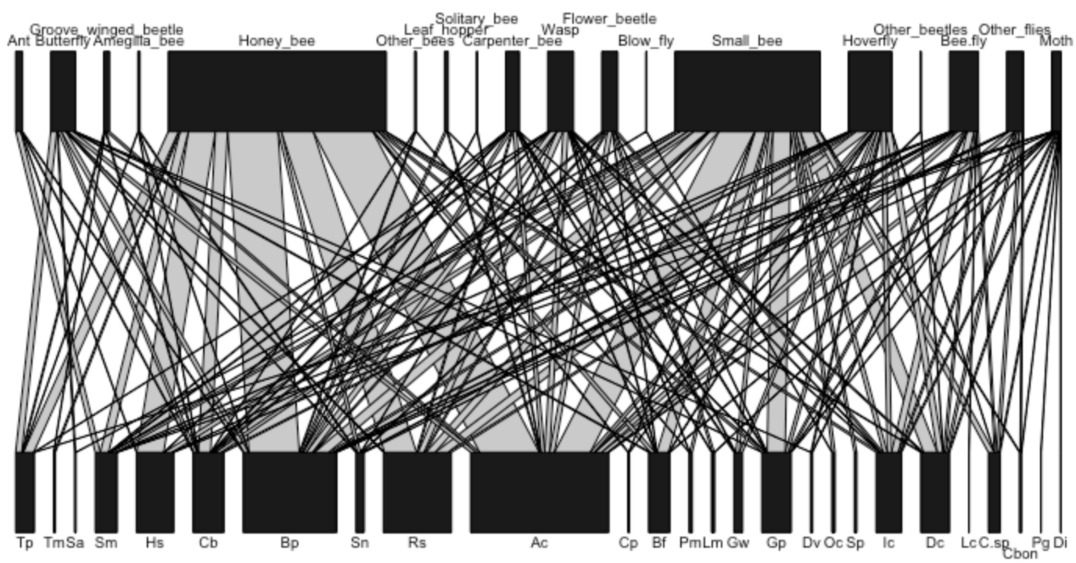

Figure 16: A network showing interactions between flower visitors (full names) represented by black boxes in the upper level and field margin plants in the lower level. The box size is proportional to the total number of visits recorded, and the link size to the frequency of this particular link

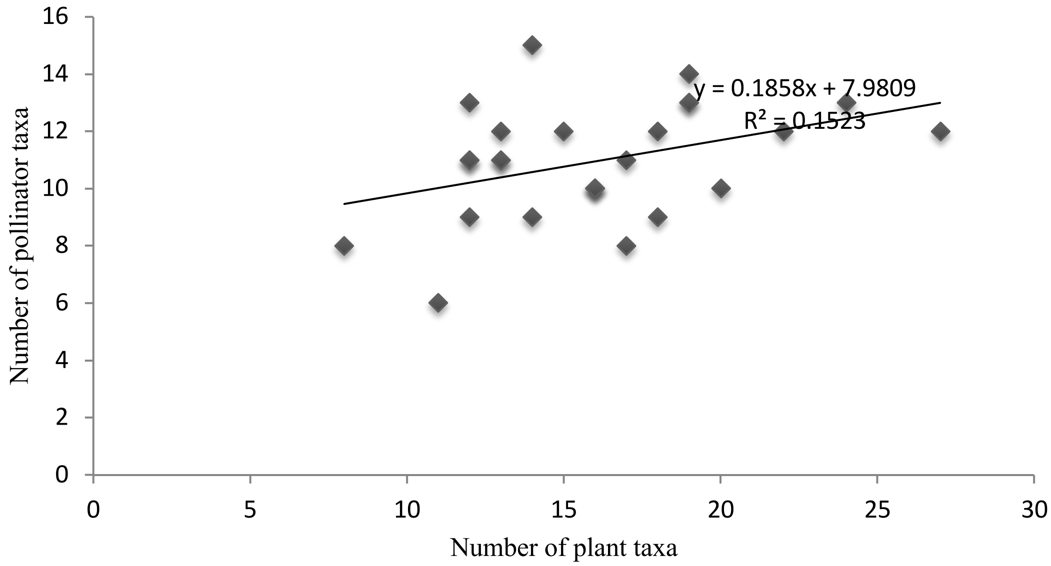

Figure 17: Number of pollinator taxa recorded visiting wild plants species in bean agro-systems for two cropping seasons between 2016 and 2017, measured in 1m² plots placed along margins of bean fields. Each data point represents total number of pollinator taxa recorded during sampling period

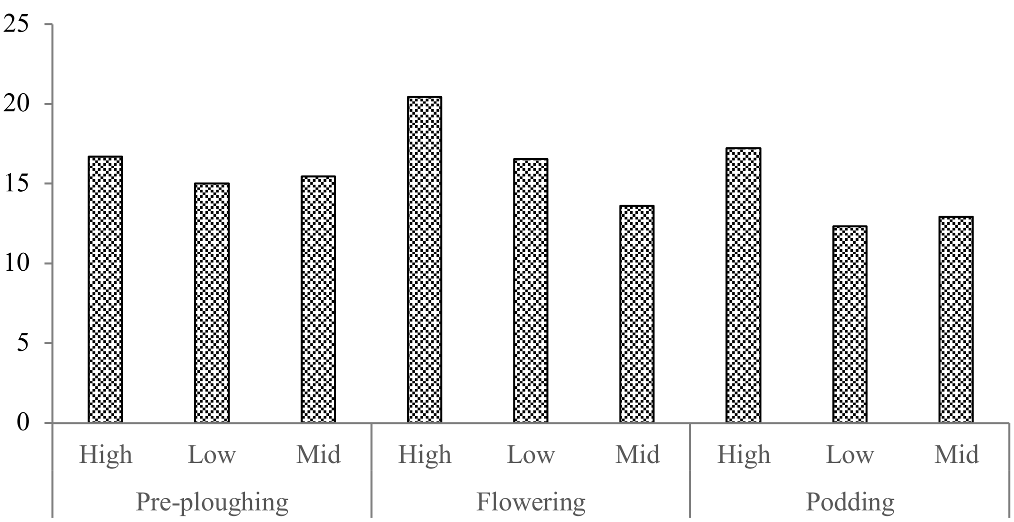

Figure 18: The nestedness of three pollinator networks measured from three elevation zones during beans-farming stages; pre-ploughing, flowering and podding

4.2 Discussion

4.2.1 Farmers' Knowledge of Common Pollinators and their Importance in Bean Production, before and after Training

The majority of farmers in this region lack knowledge about pollinators and their importance in improving crop yield, but it is not linked to age or gender. Most farmers were unable to identify hoverflies and solitary bees and surprisingly few identified honeybees. Smith *et al*. (2017) also reported that farmers who grow a variety of pollinator dependent and non-dependent crops in India were not able to recognise solitary bees and this may highlight an important knowledge gap since wild pollinators invariably contribute to yield benefits in most pollinator dependent crops whereas honeybees do not always do so (Garibaldi *et al*., 2013). Similarly, Kasina *et al*. (2009) reported farmers being aware of honeybees but less so for other pollinators. It may be that honey bee keeping is widely practised around farmlands in the surveyed areas primarily for their honey and wax and associated income, with their importance to crop yield being less well understood. Alternatively, farmers in this study may have obtained the knowledge from previous agricultural extension work around beekeeping programs(Lyver *et al.*, 2015; Soini, 2005). Although we still recorded some famers who were unable to identify honeybees, hoverflies and solitary bees correctly one year after training, the awareness significantly increased compared to pre-testing results indicating that knowledge gaps can be closed through education.

While some farmers were able to recognise these insects, particularly honeybees, most of them categorised the insects as pests and some did not recognise the insects at all, let alone their potential role in crop production. This has been a well-recognised challenge in Africa due to the unfavourable perceptions that farmers have of insects as a result of little knowledge of their economic importance (Frimpong-Anin *et al.*, 2013; Munyuli, 2011; Otieno *et al.*, 2011). The study observed that honeybees were recognised by most farmers in the surveyed area while lacking information on hoverflies and solitary bees. Since we have observed some differences in the knowledge about pollinators among farmers in three zones, further investigation was needed to determine how farmers access agricultural information and identify the best approaches for wider scale knowledge transfer about pollinators to farmers and how training can support this.

The responses of farmers surveyed one year after training changed significantly indicating that farmers acquired and retained knowledge and even changed perceptions about landscape and land management practice. For example, significantly more farmers reported being aware of the importance of honeybees, hoverflies and solitary bees as pollinators of crops compared with the responses recorded during the pre-training survey. Although in the baseline the majority of farmers had little knowledge of pollinators and their importance, training strengthened their knowledge and even one year later after training, many were still able to recognize the insects and their function. The overall results suggest that training is an essential and effective tool to change farmers' knowledge and perceptions and to change their agricultural practices. Increased understanding about pollinators and their importance in crop pollination is necessary for smallholder farmers to recognise the connection between these insects and agricultural productivity; therefore, such events should be encouraged. The knowledge changes reported here suggest that smallholder farmers in this area would have continued to hold the same negative view they had beforehand if they had not received training. More studies should also focus on barriers and constraints faced by farmers when they need to access agricultural information that would help to improve production.

4.2.2 Importance of Field Margins in Bean Agro-systems

Field margin management is an important consideration in agro-ecological intensification (AEI) since it can affect the pollinator populations in cropping landscapes while their diversity and abundance is influenced by the availability of specific floral forage resources and nesting sites in non-crop habitats when the crop is not in flower (Blaauw & Isaacs, 2014; Morandin & Kremen, 2013; Nicholls & Altieri, 2013). In the baseline survey, some farmers reported that they cleared their field margins more often and the most common methods were cutting and burning which can simultaneously decimate above-ground nesting species (Brown *et al.*, 2017; Ne'eman *et al.*, 2000). This practice may negatively affect pollinator populations with consequences for crop yields since frequent mowing of vegetation is known to reduce habitat and food resources (Buri *et al.*, 2014; Halbritter *et al.*, 2015; Kennedy *et al.*, 2013; Potts *et al.*, 2003). On the other hand, timely and planned burning of forestlands can boost some pollinating guilds but due to its complexity, adopting this in bean farming would need to be implemented with much more consideration to avoid the negative impacts (Campbell *et al.*, 2007; Potts *et al.*, 2005).

One year after training, fewer farmers cut or burned their field margins and no farmers applied herbicides to manage weeds in the field margins compared with pre- training results. The results suggest that changing farm management among farmers through knowledge enhancement may help to conserve beneficial plants in bean agro-systems and support agro ecological intensification.

4.2.3 Farmers' Knowledge of the Role of Field Margin Plants in Bean Agri-systems

The majority of farmers did not recognise the importance of field margin plants in supporting beneficial insects in bean agro-systems, and some declared that their bean field margins do not include beneficial plants. This suggests that most farmers may lack knowledge about farming practices that enhance pollinators, and where they do identify potentially beneficial plant species, they fail to link agricultural practices, pollination services and crop production. The study found differences in knowledge of beneficial plants among farmers by zones, and this may be due to differences in vegetation composition including species diversity in field margins that varies by altitude (Hemp, 2006a), which may also affect farmers' knowledge. Where margin plants were reported to offer benefits to smallholder farmers, the most common benefits reported were livestock fodder and erosion control but varied with zones. More farmers in the high zone reported fodder and erosion control as major benefits from margin plants compared with low and mid zone farmers. This zonal variation may be explained because most farmers in this agro-system keep livestock in stalls so require fodder daily for them (Hemp, 2006b). These farmers may also benefit more from the value of non-crop vegetation to control soil erosion since their farms are located in high altitudes (above 1500 m) where rain can wash away soil. The use of plants to mitigate against soil erosion is a common practice in many highland areas (Angima *et al.*, 2000; Zuazo & Pleguezuelo, 2008). Although non-crop vegetation nearby crop fields has been reported to support pollinators and other beneficial insects (Kennedy *et al.*, 2013; Öckinger & Smith, 2007; Otieno *et al.*, 2015; Paredes *et al.*, 2013), farmers did not mention this benefit at the start of this study, suggesting that they lack knowledge. However, one year after training, some farmers were able to recognise the importance of these plants in supporting pollinators.

During the botanical survey, some fields had wide and richer margins while some had narrow margins with fewer plants species which may determine insect diversity and local abundance (Kohler *et al.*, 2008; Rundlöf *et al.*, 2018). This study argues that farmers' fields with lower flower richness could opt to enrich their field margins by sowing native flowering plants to promote pollination services (Feltham *et al.*, 2015; Korpela *et al.*, 2013; Sidhu & Joshi, 2016). However, the context and options available to smallholders must be established to understand the scope to support them to move towards pollinator conservation. Although it may take time to maximize pollination services, farmers are likely to change their farming practices if they are assured through demonstration that higher diversity and richness of pollinators enhances crop yields. Along with supporting pollinators, added benefits of field margin vegetation if implemented more widely include carbon sequestration; nourishment (food products), firewood and fibers; air quality and climate regulation; soil quality improvement; weed, pest and disease control; water purification; and cultural services (Moonen & Bàrberi, 2008; Mudavanhu *et al.*, 2017; Richardson, 2010; Swift *et al.*, 2004).

4.2.4 Farming Practices by Smallholder Farmers in Bean Agri-system

Most farmers, particularly in the high zone, practiced mixed cropping, a typical system practiced by Chagga tribe people, the dominant ethnic group in the study area (Hemp, 2006b; O'kting'ati *et al.*, 1984; Soini, 2005). Although farmers use synthetic pesticides to control insect pests, they are broad spectrum and so can have deleterious impacts on pollinators (Brittain *et al.*, 2010; Henry *et al.*, 2012; James & Xu, 2012; Melisie & Damte, 2017). They reduce pollinator species abundance and diversity by killing them directly or affecting their foraging behaviour and physiological activities (Brandt *et al.*, 2016; Fischer *et al.*, 2014; Gill *et al.*, 2012; Gill & Raine, 2014). Although the same farmers who were interviewed during the baseline survey were trained about the effects of synthetic pesticides application to beneficial insects, the results from the end-line survey indicate many farmers still applied these chemicals to control pests. This study argues that continuous training about the effect of these chemicals to the environment, and intensive demonstration on the use of less harmful bio pesticides may help to reduce the number of farmers who uses synthetic pesticides in this region.

Although organic and botanical pesticides can be effective at controlling pests and cause less harm to beneficial insects, human health and the surrounding environment (Amoabeng *et al.*, 2013; Campos *et al.*, 2016; Mkenda *et al.*, 2015; Stevenson *et al.*, 2017), only a small numbers of farmers were using these pest management options. Although some farmers mentioned a few plant species used as botanical pesticides in the area, none were aware of the potential of field margin species such as *A. conyzoides* as a botanical insecticide (Amoabeng *et al.*, 2014; Rioba & Stevenson, 2017). Recent studies conducted in the same agricultural landscape, also reported high performance of *T. diversifolia* and *T. vogelii* extracts in controlling pests of *P. vulgaris* with lower negative impacts on beneficial arthropods (Mkindi *et al.*, 2017; Tembo *et al.*, 2018).

Since a small group of farmers were using non-synthetic pesticides, the training also aimed at building farmers' capacity on various non-synthetic pesticides, which may be used as alternatives to synthetic pesticides to avoid deleterious effects to beneficial insects. The significant changes recorded one year after training suggest that farmers were willing to reduce the use of synthetic pesticides if they were assured through demonstration of the effectiveness of alternatives. The experience shows that farmers rely on synthetic pesticides in the absence of knowledge and guidance on alternative methods to control pests (Williamson *et al.*, 2008).

4.2.5 Socio-economic Importance of Bean Crop to Smallholder Farmers

Beans were reported to be an important dietary component, consumed around three times a week for the majority of farmers and daily for a minority which corroborates previous reports of its importance in most areas of Tanzania (Hillocks *et al.*, 2006). They were important for food security as well as income, often replacing coffee (Maghimbi, 2007). Since beans were found to be importance in improving the livelihood of people in this region, intervention to increase its production is justified. Living standards and food security is likely to be improved among poor households in this region if bean production increases.

4.2.6 Potential Value of Insect Pollination Service in Bean Production in Bean Agri-systems

It is often assumed that common beans are largely autogamous and that, consequently, the role of pollinators is trivial (Ibarra-Perez *et al.*, 1997; Papa & Gepts, 2003). This study showed that pollination could make a substantial and financially significant contribution to yield. Indeed, the calculations indicated that the value of insect pollination was relatively high and farmers could face a potential loss of up to USD 500 of their income per hectare if natural pollination services were lost. In a country where the Gross National Income per capita in 2017 was below USD 1000 (World Bank, 2018) for a farm of around 1 ha in size this is a major loss to household income and food and nutritional security, thus pollination services and landscape management to conserve pollinating insects should be a major consideration in drafting agricultural policy to enhance food and nutritional security in bean farming systems. More information is needed on which species are the most important and which specific field margin plants are important in supporting them.

Open pollination increased bean yield and quality through seed weight, seed number per pod, and pod number per plant. No trade-offs related to open pollination with respect to yield was recorded. The result accords with other studies such as Nayak *et al*. (2015), who reported a yield benefit of more than 100% in open-pollinated Faba beans, and more modest benefits recorded by Free (1966) in common beans visited by honeybees. The role of honeybees versus wild bees is likely to be key to understanding which flower visiting species are important to yield in these cases: increasing evidence indicates that honeybees are not always efficient pollinators (Garibaldi *et al*., 2013; Grass *et al*., 2018), including in legume crops where they are among the most frequent flower visitors (Marzinzig *et al*., 2018). Expectedly, honeybees (51%) were the most frequently sampled insects in this study. Other comparable studies in other parts of East Africa have also reported *A*. *mellifera* being among abundant pollinators in cropping systems (Kasina *et al*., 2009b; Otieno *et al*., 2011). Other insects collected included *Amegilla* sp. (2%), bee flies (2%), carpenter bees (3%), hoverflies (6%) and miscellaneous Lepidoptera (13%), all of which could play a role in pollination. Other work on pollination in legume systems has indicated that short-tongued bees rob heavily, whereas long-tongued species are more effective pollinators (Marzinzig *et al*., 2018) although apparent evidence of robbery as indicated by holes chewed into corollas is not necessarily indicative of a major impact on fertilization as robbery events are reported to be much less frequent than pollinating visits (Barlow *et al*., 2017). In East Africa, long-tongued bumblebees (*Bombus* sp.) are not present but carpenter bees fill a similar niche and are highly effective as bean pollinators (Masiga *et al*., 2014). This study would recommend further work in the system to investigate the efficacy of pollination services offered by specific flower visitors and those that interacted with common beans during sampling.

The exclusion experiments demonstrated that open-pollinated plants yielded more than self-pollinating plants. Low yield in self-pollinated beans could be due to strong inbreeding depression which may have lowered the fitness of seeds (Barrett, 2002) contrary to open-pollinated beans which received pollen from flowers from different plots. Another explanation could be that leguminous flowers do not activate well without insect visits therefore very few pollen grains contacted stigmas of self-pollinated flowers for fertilization. However, I also obtained the unexpected result that the hand-pollinated plants produced lower yield than the open-pollinated plants. Hand pollination typically represents that maximum pollination service so this result was surprising. However, this may be explained by the approach taken of bagging the hand-pollinated plants; it is likely that the experimentally applied single pollination event was insufficient to maximise yield and this may have affected fruit setting among plants (Otieno *et al*., 2011). More typical is to leave the plants in hand-pollination treatments uncovered (Birkin & Goulson, 2015; Grass *et al.*, 2018). While this means it was therefore not possible to evaluate whether this system is pollinator-limited, it does provide some information about the pollination processes in this crop and variety, specifically that (a) a single event (including a single insect visit) may be insufficient for effective pollination, and therefore if pollinator numbers are low yield will be limited and (b) insect pollination is more effective than a single hand pollination event in the current system, indicating that hand pollination is not a viable alternative for farmers of this crop in areas lacking pollinators. Farmers should therefore be supported to manage their farms to conserve and augment numbers of pollinators to reduce yield gaps and income loss due to sub optimal pollination.

Based on the finding that pollination is important and valuable, I also evaluated whether potential pollinators in the crop were making use of natural and semi-natural vegetation around field margins, as this is a key target for management interventions to promote pollinator species (Dicks *et al*., 2016; Potts *et al*., 2016). Capturing various dye-marked insects from within the crop is therefore evidence that the insect has previously visited the margin either for feed or refuge before moving into the crop. Although other non-pollinating species including pests were also found during collection, they were disregarded in the analysis since the target was pollinating insects. Although record of visits to field margins and beans is an indication that has some value to these beneficial insects, further studies should explore whether these insects are using field margin vegetation as a resting, nesting, food resource sites or both. In the case of potential pollinators, this can be associated with feeding behaviours in both the margin and crop.

A high proportion of the insects collected from the crop contained dye traces, which indicated extensive movement between crop margin and crop in a distant-dependent fashion with more margin-users found very close to the margin. This demonstrated that firstly, not all margin insects remained in the margin, so the margin can be a donor of ecosystem services into the crop. Secondly, penetration of these services into the crop has the potential to reach the centre of the field but will be most marked around the edges, close to the margin unless alternative management techniques such as intercropping or sowing of flower strips within the field are used to enhance movement around the fields (Korpela *et al.*, 2013; Pereira *et al.*, 2015). However, there was no significant difference between the proportions of marked potential-pollinators at 10, 20, 30, or 40 m, implying two behavioural syndromes among margin-users in the crop, those that strayed only a short distance (<10 m) into the crop, or those who moved off margins and into the crop and then foraged more widely among the crop plants. For instance, dye-marked insects such as honeybees were sampled at all distance, 0 m (50%), 10 m (13%), 30 m (21%) and 40 m (16%), suggesting that honeybees can forage up to over 40 m and there was no evidence of distance-dependent effect recorded for this insect over 10 m. Woodcock *et al*. (2016) also reported no declining effect in honeybees' visitation rates into the oilseed rape field even at a distance of 200 m from the field edge. This is contrary to other insects such as hoverflies, small bees and butterflies where their abundance declined with increasing distance from field margin.

Surprisingly, marked bee flies were not sampled at any distance in the bean field and instead all marked individuals were collected at field margin (0 m). The explanation could be that bee flies are not visitors of common beans and so have no purpose to enter the crops or fly a large distance into the field to forage. As the fields are small, it is unsurprising that flying insects that are able to cover large distances of 100 m or more in a short time, including carpenter bees (Pasquet *et al*.,

2008) and honeybees (Beekman & Ratnieks, 2000; Hagler *et al.*, 2011; Perrot *et al.*, 2018), used the majority of the field fairly evenly; this contrasts to work on coffee plantations that are very large, in which there was a strong distance-dependent effects moving away from semi-natural habitat at the edges of fields, especially for small bees (Klein *et al.*, 2003) and large fields of temperate oilseed rape, where similarly the number of bees towards the field centre were very low (Bailey *et al*., 2014). This work suggests that future studies should also consider the effect of field size and landscape patterns on the abundance and richness of pollinators in smallholders' bean fields. However, it is important to note that this study did not focus on monitoring absolute abundances of potential pollinators at different distances, but on the eventual destinations of field margin users, and the sweep netting technique did not discriminate pollinators from nectar thieves or transient insects not using the flowers.

For farmers these data show that those with small fields may reap more benefit from the field margin plants than those with larger fields, as margin-using insects were less frequently recorded further (> 20 m) from the margin. However, as nearly 50% of potential pollinating species sampled even from the centre of the field showed fluorescent dye marks consistent with use of the margins, the study highlights that the margin vegetation is providing benefits to these insects. Although other studies have reported that presence of diverse and floral rich margins can enhance pollinator species in the neighbouring crop field (Garratt *et al.*, 2017; Morandin & Kremen, 2013), further work should focus on characterising the nature of insect-plant interactions in the margin and crop to indicate which plants are most important for promoting specific pollinator abundance and movement into the crop. This study suggests further studies also to focus on comparing how different types and management of field margins can affect stability and persistence of pollination services in this agro-system.

4.2.7 Pollinator Richness and Diversity in Bean Agri-systems

The high zone area had high richness of flower visitors compared to the low and mid zones and the differences could be due to high plants diversity and richness recorded in this zone compared to other two zones. Various studies have reported that areas that are rich in floral resources attracts high number of flower visitors than those with poor floral resources (Ghazoul, 2006; Klein, 2009; Wu *et al.*, 2018). This could be due to availability of necessary living requirements particularly foods (Garratt *et al.*, 2017; Nicholls & Altieri, 2013). Although higher numbers of individual wasps were recorded during this study, bees were the most abundant taxa in the area suggesting that they may also be the most important pollinator group providing pollination services to many plants and key crops grown in the study area. With exception to few known species of wasps which pollinate some specialized plants (Shuttleworth & Johnson, 2009; Van Noort *et al.*, 2013; Weiblen, 2001), few studies have reported the importance of wasps as effective pollinators of crops but rather as regulators of pests (De Lange *et al.*, 2018; Gurr *et al.*, 2003). Although wasps may not be as well reported for pollination service as bees, some plants have very specialised pollination mechanism that can only be accomplished by specific pollinating wasps (Weiblen, 2001; Wiebes, 1979) suggesting that all groups of pollinators are important and they require conservation. For example, Agoanine wasps (Family: Agaonidae) are among eminent wasp groups specialised in pollinating various species of fig trees (Family: Moraceae) (Da Costa & Graciolli, 2010; Schiffler, 2002). In some pollination systems, the interaction is obligate meaning that either of the partners cannot survive in absence of the other (Weiblen, 2001). This study argues that high abundance of wasps recorded may suggest good status of natural enemies necessary for biological pest control in the study area. However, their population might have been enhanced by presence of herbaceous habitats in the field margins that provides necessary resources for the insects to reside (Bianchi *et al.*, 2006; Gillespie *et al.*, 2016). Both predatory and parasitic wasps have been reported as among effective regulators of crop pests in many agricultural ecosystems (Mackauer & Völkl, 1993; Yang *et al.*, 2017). Therefore, conservation plans in this area should also consider this group of beneficial insects for improved natural pest management which may help to reduce application of synthetic pesticides in the area.

Unlike for wasps, both managed and wild bees have revealed the highest levels of effectiveness in pollinating large number of cultivated crops (Ballantyne *et al.*, 2017; Biesmeijer *et al.*, 2006) whereas wild bees being the most reliable pollinators (Kremen *et al.*, 2004). However, pollination by wild bees seems to favour this type of agro-system since the highest level of their effectiveness have been observed mostly in small farms (Isaacs & Kirk, 2010) which is the case for this study area. Being reported as the most important and abundant pollinator taxa in the world (Smith & Mayfield, 2018), this study also recorded higher number of bees occupying more than 50% of the total collected insects where small bees dominated the group compared to larger bees. This also conforms to other comparable studies regarding pollinator richness in agro landscapes of tropical region (Ramalho, 2004; Smith & Mayfield, 2018) where this group has been reported to be a major pollinator (Masiga *et al*., 2014). The current study in northern Tanzania by Ojija *et al*. (2019) also reported bees being the most frequent group visiting both invasive and native wild plant species.

Because sampling was done in smallholder bean farming systems, high records of large bees such as carpenter bees (Family: Anthophoridae) were expected as they are among major visitors of legume crops (Bohart, 1960; Masiga *et al*., 2014) but surprisingly it was not the case. One of the reasons could be sampling method which might be unsuitable in capturing carpenter bees or low richness/abundance due to either lack of woody shrub or tree vegetation and/or abundant floral resources, which are important requirements for carpenter bees to reside (Raju & Rao, 2006; Watmough, 1974). For example, field margins with bamboo trees, dead branches of trees, decaying logs and pithy stems could be a suitable environment for both large and small carpenter bees to build their nests (Keasar, 2010; Raju & Rao, 2006). Being among larger long-tongued pollinators, carpenter bees are also capable of buzz pollination that favours fertilization process of most legumes (Ballantyne *et al*., 2017; Keasar, 2010; Marzinzig *et al*., 2018). A study conducted in similar agricultural systems reported higher yields among French beans following high visitation by carpenter bees (Masiga *et al.*, 2014) signifying the importance of these insects in bean production. As such, food resources and nesting sites enhancement in the bean agro-systems may be necessary to promote their population for improved pollination services (Keasar, 2010). This may also support other pollen vectors of legumes recorded in the study area including honeybees (Family: Apidae) (Milfont *et al.*, 2013; Stoddard, 1991) and solitary bees (Family: Anthophoridae and Megachilidae) (Aouar-sadli *et al.*, 2014; Bond & Kirby, 1999). These insects are mostly attracted by multiple flowering plants that produce large quantities of pollen and with higher nectar sugar concentration than those with low food resources (Abrol, 2006, 2007; Ghazoul, 2006). Therefore, enriching the farms with pollen and nectar-rich plants may create conducive environment for the pollinators to reside and continue to forage throughout the year (Korpela *et al.*, 2013; Nicholls & Altieri, 2013; Wratten *et al.*, 2012).

Other small pollinators such as stingless bees grouped under small bees in this study were also abundant in the area. Although they may not be effective pollinators of beans (Heard, 1999), various studies have reported that they are main visitors of many wild plants and crops in tropical agro ecosystems (Klein *et al.*, 2002; Liow *et al.*, 2001; Ramalho, 2004). Being non-stinging and easy to keep in hives, it has been reported that stingless bees can be used for commercial pollination of high value crops in greenhouses (Heard, 1999; Slaa *et al.*, 2006). However, like other pollinators, human disturbance has continued to be a major threat for their richness and existence in various ecosystems (Brown & Albrecht, 2001; Ramírez *et al.*, 2013; Samejima *et al.*, 2004). To ensure protection of these insects, farmers should improve and manage their field margins because pollinator abundance and diversity is mostly dependent on the quality and quantity of the surrounding semi-natural habitats (Blaauw & Isaacs, 2014; Heard, 1999; Krimmer *et al.*, 2019). For example, augmenting the field margins with generalist plants may attract higher number of pollinators and thus maintaining the stability and complex structure of the plant-pollinator interactions in the ecosystem (Biella *et al*., 2019). Since there is little information regarding status of pollinators and their importance in Eastern Africa farming systems (Kasina *et al*., 2009; Munyuli, 2011; Otieno *et al*., 2011), this study has highlighted key pollinator species in smallholder bean-farming systems in northern Tanzania which offers pollination services to various plants and cultivated crops. Also, it has highlighted the richness and diversity status of both major flower visitors and their associated host plants in the area. The baseline information generated by this study may be a good foundation for future studies particularly those focusing on pollinators and pollination systems in similar agricultural systems.

However, further studies in this area should focus on specific requirements such as food resources and nesting sites of potential pollinator groups as some of the species such as Amegilla and Cuckoo bees were infrequently recorded in the study area. Understanding of this component may help toward conservation of these species in this smallholder farming system.

4.2.8 Complexity and Stability of Plant-pollinator Networks in Bean Agri-systems

Because the loss of species is among the various factors that affect pollination networks in an ecosystem (Kaiser-Bunbury *et al.*, 2010; Memmott *et al.*, 2004), understanding the interactions between plants and pollinators is important for planning conservation measures in smallholder agro-systems. However, through understanding of the key species building up the networks, predicting the effect of species extinction in plant-pollinator community is possible and necessary (Memmott *et al.*, 2004). The results of the network analyses indicated that *A. conyzoides*, *B. pilosa* and *R. scabra* were the most visited plant species while honeybees and small bees were the most linked pollinators in all three networks. *Ageratum conyzoides* and *B. pilosa* were identified as the most generalist plants in the network implying that their loss could lead to decrease in pollinator richness in the study area and thus effecting the whole pollination system (Biella *et al*., 2019). As such, these species play major role in bean agro systems and they should receive special management and conservation attention to keep their interactions persisting because the health of the pollination systems depends on them (Valiente-Banuet *et al*., 2014). Apart from providing food to many flower visitors in the system, species such as *A. conyzoides* and *B. pilosa* have been used to control pests and diseases of key crops in similar agro-ecosystems (Mkindi *et al.*, 2017; Rioba & Stevenson, 2017). Although some of these plants may be invasive in the area and their effects on native plant-pollinator network have been reported (Burghardt *et al.*, 2010; Lopezaraiza-Mikel *et al.*, 2007), other studies have shown that these species may be important food providers to number of pollinators (Bartomeus *et al.*, 2008; Drossart *et al.*, 2017) particularly when native plant species are less abundant or not available. Also, they may facilitate pollination of native plant species by drawing a wide number of pollinator species into a plant community (Bartomeus *et al.*, 2008; Lopezaraiza-Mikel *et al.*, 2007; Stout & Morales, 2009). Therefore, this study argues that maintaining key network species in farmlands may guarantee survival of many pollinator taxa and thus strengthening the complexity and stability of pollination networks (Carvalheiro *et al.*, 2010). Although the results have shown high robustness and high species diversity in bean agro-system pollination networks, loss of core plant species may lower both stability and strength of these networks (Kaiser-Bunbury *et al.*, 2010) as a result of pollinators decline due to loss of food resources (Kells *et al.*, 2001; Potts, Biesmeijer *et al.*, 2010; Roulston & Goodell, 2011). Also, it may cause loss of less generalised pollinators and/or force other species to change their foraging behaviour and preferences (Goldstein & Zych, 2016). Although all the networks showed low level of specialization suggesting that they are likely to be tolerant to loss of species from the community (Dormann *et al.*, 2009), conservation of both potential pollinators and their associated plants is necessary to maintain resilient plant-pollinator interactions for improved pollination services in this farming system. It has been reported that there is a limit point where even the very generalized and nested networks may collapse following severe interruption (Fortuna & Bascompte, 2006; Memmott *et al.*, 2004; Biesmeijer *et al.*, 2010). This signifies that the mutualistic interactions i.e., between plants and pollinators in agro landscapes, should be carefully managed and protected because their loss may lead to failure of ecosystem functions (Valiente-Banuet *et al*., 2014). Because farmers play a major role in the management of non-crop vegetation around their farms, they should therefore be informed about appropriate conservation strategies to ensure stable pollination networks. It has also been reported that planting of flowering plants along field edges can enhance the stability of the pollination networks in the community due to increased pollinator abundance (Feltham *et al.*, 2015; Sidhu & Joshi, 2016). Kremen *et al*. (2004) also reported an increase in the stability of pollination services as the natural habitat areas increased.

Therefore, farmers should augment their field margins and increase their dimensions for guaranteed pollination services in the adjacent crop fields (Blaauw & Isaacs, 2014; Westphal *et al.*, 2015). This study is the first to establish the structure of pollination systems based on elevation gradient and highlighted the core plants and pollinator species which need conservation attention to safeguard the ecosystem functioning in smallholder bean-farming systems in Tanzania. However, future studies should also focus on stability of the pollination network in this agro-system towards changing climate and other anthropogenic factors and predict their overall effects on complexity, strength and stability of the networks if any of the core plants or pollinator species such as *A. conyzoides* and honeybees respectively, disappear from this ecosystem. This piece of information will be important for understanding the trend of pollination networks in smallholder farming systems but also may encourage management and conservation of agro-ecosystems and their associated services in the near future.

CHAPTER FIVE
CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This study has revealed that insect pollination offers a significant benefit to increased yield in common beans in smallholder farming systems. Following this evidence, I argue that biotic pollination is as important as other agricultural inputs to improve crop productivity and food security since it provided a yield boost of 117% relative to beans from which insects were excluded. This is similar to (or exceeds) the impact of many recent interventions reported in agriculture in low-income systems (Koskey *et al.*, 2017; Pretty *et al.*, 2006). However, the need for farmers to understand such services is necessary for them to recognize the importance of managing agricultural biodiversity in their farmlands and this is currently a limiting factor as many farmers are knowledge poor about beneficial invertebrates (Elisante *et al.*, 2019). The study has also revealed that training could help to bridge the knowledge gaps among farmers and enable them to better understand the relationship between farm management activities and agro-biodiversity in crop production. However, there is also a need for farmers to be equipped with knowledge and tools to enable them to make informed decisions about their management practices and be empowered with information about better alternatives for food production that they can adopt.

Also, the study found that a high proportion of insects captured in the crop had previously visited the margin, suggesting that field margin plants can act as refuge or food reserve for pollinators and can promote their populations into neighbouring crop fields. This use of margins indicates the need for sustainable management interventions that protect natural vegetation, in order to augment pollinator abundance and pollination services in agrarian landscapes (Boreux *et al.*, 2013). During the off-season and when beans are not blooming, these plants can support pollinators by providing food and nesting sites and thus keeping their population at natural state (Morrison *et al.*, 2017; Nicholls & Altieri, 2013).

This study has highlighted the need for agro-ecological programs, workshops, seminars and training events to increase smallholders' knowledge of beneficial invertebrates and the value of field margin plants in supporting agricultural biodiversity (Elisante *et al*., 2019). Elevating people's knowledge on pollination ecology and other ecosystem services may be a good foundation towards enhancing of crop and plant diversity in the tropical agro-systems. However, the context and options available to smallholders must be established to understand the scope to support them to move towards pollinator conservation. Although it may take time to maximize pollination services, farmers are likely to change their farming practices if they are assured through demonstration that higher diversity and richness of pollinators enhances crop yields.

Future studies in tropical Africa should focus on missing information on both rare and endangered pollinator species and the findings should be incorporated in the conservation policies and programs. However, understanding pollinators distribution may also be important, as it will help conservationists and stakeholders to identify areas that need immediate conservation intervention. Further studies on pollination ecology of common beans may also need to look at two important aspects; pollinator-specificity and effectiveness, to determine which insect species is the most effective pollinator of this crop.

5.2 Recommendations

This study recommends multi stakeholder involvement to help farmers adopt appropriate ecologically based systems to increase crop production in smallholder farming systems without compromising the wellbeing of agro-biodiversity and the environment. Farming practices that threatens agricultural biodiversity in bean farming systems, such as removal or burning of field margin vegetation, should be discouraged and instead, farmers with fields that have low flower richness could opt to enrich their field margins by sowing native flowering plants to promote pollination services (Feltham *et al.*, 2015; Korpela *et al.*, 2013; Sidhu & Joshi, 2016).

Plant species such as *A. conyzoides*, *B. pilosa* and *R. scabra*, which have been reported to offer multiple benefits in the agro ecosystem, should be maintained along field margins as potential food resources for pollinators and not always considered as bad plants (weeds). Although afforestation and reforestation has been given attention mainly to combat climate change, it could also be practiced purposely to restore highly degraded areas and rejuvenate pollinators' semi-natural habitats.

Moreover, farmers are encouraged to use alternative pest control methods instead of synthetic pesticides which have detrimental impacts on beneficial insects.

Formulation of participatory policies (Maderson & Wynne-Jones, 2016) that encourage protection and conservation of agro-biodiversity for improved pollination services are urgently required to maximize the yield potential of beans and other key crops in smallholder farming systems. Optimising pollination services should be a major priority in policy setting for improved food security and livelihood of smallholders in the study area.

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APPENDICES

Appendix 1: Questionnaire on Assessing Farmers Knowledge on Pollination Service

Baseline Survey Questionnaire

Introduction

Good morning/afternoon. My name is XXX. Thank you for sparing time to come and meet with us today. We are a team of researchers from the Nelson Mandela African Institution of Science and Technology. We are running studies and experiments in efforts to improve the quality of beans from farms in selected households in Moshi district. We are requesting to interview you for 2 hours in order to obtain information which will help us to come up with lessons and strategies for improving bean yield in the targeted farms.

- Do you consent for us to continue with this interview? Yes ( ) No ( ).

Farmer's personal profile

- Name of farmer:
- Age: Sex:
- Number of persons residing in farmer's household:
- Titles of persons residing in farmer's household: Father ( ) Mother ( ) Boy child(ren) ( ) Girl child(ren) ( )
- District: Ward: Village

Note: All questions in this questionnaire pertain to the beans farm selected for the study.

Objective	Main survey indicator	Questions
General background information	Background information	1) What is the approximate size of your farm which has been designated for this study? 2) What is planted in this farm? 3) What variety of beans do you grow in this farm? 3.1 Uyole njano ( ) 3.2 Lyamungo 90 ( ) 3.3 Kijivu local variety ( ) 3.4 Mke mwema ( ) 3.5 Kriasii ( ) 3.6 Jesca ( ) 3.7 Rose coco ( ) 3.8 Soya ( ) 3.9 Others, list: 4) What is the approximate area which is cultivated with beans?
To assess extents to which changes in knowledge and attitudes can lead to improved farm practices	% of targeted farmers who demonstrate changes in knowledge and attitudes that can lead to improved farm practices	*Beans varieties* 5) Which varieties of beans harbor the natural enemies and the insect pests? 5.1 Uyole njano ( ) 5.2 Lyamungo 90 ( ) 5.3 Kijivu local variety ( ) 5.4 Mke mwema ( ) 5.5 Kriasii ( ) 5.6 Jesca ( )

		5.7 Rose coco ( ) 5.8 Soya ( ) 5.9 I don't know ( ) 5.10 Others, list: *Insects* 6) What insect is this shown to you in a picture? For every insect, assess the response and tick appropriately: 6.1 Right answer ( ) 6.2 Wrong answer ( ) 6.3 I don't know 6.4 ( ) List the wrong answer: 7) What is the significance or implication of the insect on the picture insect for your beans farming? 7.1 Pollinator ( ) 7.2 Pest ( ) 7.3 Natural enemy ( ) 7.4 I don't know ( ) *Pesticides* 8) Please mention the varieties of synthetic pesticides that you know: 1.1 Actellic ( ) 1.2 Bamethrine ( ) 1.3 Karate ( ) 1.4 Selecron ( ) 1.5 Diazinon ( ) 1.6 I don't know ( ) 1.7 List others: 9) Please mention the varieties of organic pesticides that you know: 9.1 Ashes ( ) 9.2 Cattle urine ( ) 9.3 Cow dung ( ) 9.4 I don't know 9.5 ( ) List others: 10) Please mention the varieties of plant pesticides that you know: 10.1 Leaves of neem tree ( ) 10.2 Leaves of wild sunflower ( ) 10.3 I don't know ( ) 10.4 List others: *Perceived advantages and disadvantages of plant pesticides* 11) What do you perceive as is the advantage of using plant pesticides to improve your beans farming? 11.1 Affordable ( ) 11.2 Easy to obtain ( )

		11.3 Effective to eradicate pests quickly ( ) 11.4 Non-toxic 11.5 ( ) I don't know 11.6 ( ) List other advantages: 12) What do you perceive as the disadvantages of using plant pesticides to improve your beans farming? 12.1 Hard to process or prepare ( ) 12.2 Difficult to obtain ( ) 12.3 I don't know ( ) 12.4 List other disadvantages: *Perceived advantages and disadvantages of synthetic pesticides* 13) What do you perceive as is the advantage of using synthetic pesticides to improve your beans farming? 13.1 Easy to obtain ( ) 13.2 Easy to use ( ) 13.3 Effective to eradicate pests quickly ( ) 13.4 I don't know ( ) 13.5 List other advantages: 14) What do you perceive as the disadvantages of using synthetic pesticides to improve your beans farming? 14.1 Toxic ( ) 14.2 Expensive ( ) 14.3 Difficult to obtain ( ) 14.4 I don't know ( ) 14.5 List other disadvantages:
To assess extent to which improved farm management leads to increased yield	% of targeted farmers who adopt improved farm management practices in their bean farms	*Plants* 15) Which beneficial plants are found in your beans farm? 16) How do you attract or retain these plants to your beans farm? *Field margins* 17) How often do you clear your field margins? 17.1 Monthly ( ) 17.2 Quarterly ( ) 17.3 Half yearly ( ) 17.4 Annually ( ) 17.5 I don't clear field margins ( ) 18) What method do you use for field margin clearance? 18.1 Burning ( ) 18.2 Cutting or digging ( ) 18.3 Feeding animals ( ) 18.4 List others ( ) 18.5 I don't clear field margins ( ) 19) What do you use your field margin plants for? 19.1 Pesticides ( ) 19.2 Controlling erosion ( )

		19.3 Planting animal feeds ( ) 19.4 Others ( ) 19.5 I don't use field margin plants ( ) 20) List any plan species that you purposely leave when you clear your field margins? 21) For each of the species you mentioned above, why do you retain them? *Pesticides* 22) Please provide a list of pesticides that you use to improve your beans farming: 22.1 Actellic ( ) 22.2 Bamethrine ( ) 22.3 Karate ( ) 22.4 Selecron ( ) 22.5 Diazinon ( ) 22.6 Ashes ( ) 22.7 Cattle urine ( ) 22.8 Cow dung ( ) 22.9 Leaves of neem tree ( ) 22.10 Leaves of wild sunflower ( ) 22.11 I don't use pesticides ( ) 23) For each pesticide that you mention, please explain the reason why you use them? *Agricultural inputs* 24) Which agricultural inputs do you use to improve your beans farming? 25) For each input that you mention, please explain why you use these inputs? *Mixed/Mono cropping* 26) What type of cropping do you practice? 26.1 Mixed cropping ( ) 26.2 Mono cropping ( ) 27) Please explain why you practice the said type of cropping in your beans farm?
	% of farmers who improve farm management practices and report increased yield	28) In the most recent harvest of XX month of XX year, how many kilogrammes of beans did you harvest from your beans farm under this study?
	% of farmers who improve farm management practices and report improved quality of beans	29) In the most recent harvest of XX month of XX year around what proportion of beans harvested from your farm did you: 29.1 Sell ( ) 29.2 Consume at home ( )

	produced	29.3 Feed animals with ( ) 29.4 Throw away because of bad quality ( ) 30) In the most recent harvest of XX month of XX year, approximately what proportion of the harvested beans did you feel were of highest first grade quality in terms of weight, texture, color and being free of disease and infestation, like in the picture being shown to you? 30.1 None ( ) 30.2 More than none to one quarter ( ) 30.3 More than one quarter to half ( ) 30.4 More than half to three quarters ( ) 30.5 More than three quarters to 100% ( ) 31) In the most recent harvest of XX month of XX year, approximately what proportion of the harvested beans did you throw away or give to animals after feeling they were of poor quality, like in the picture being shown to you? 31.1 None ( ) 31.2 More than none to one quarter ( ) 31.3 More than one quarter to half ( ) 31.4 More than half to three quarters ( ) 31.5 More than three quarters to 100% ( ) 32) Please randomly select and provide me around 20 bean seeds to look at from your recent harvest. 32.1 Proportion of seeds perceived by enumerator to be of good quality (/20) 32.2 Proportion of bean seeds perceived by enumerator to be of average quality (/20) 32.3 Proportion of bean seeds perceived by enumerator to be of bad quality (/20)
To assess extent to which improved yield and quality translates into improved livelihoods, welfare and living standards for the farmers and their families	% of farmers who report increased income from selling beans from the targeted farms	33) In the most recent harvest of XX month of XX year, at what average price did you sell one kilogramme of beans from your farm? 33.1 Prices per kilogramme in Tshs ( ) 33.2 I did not sell any ( ) 34) In the most recent harvest of XX month of XX year, around how much income did you get from selling beans from your farm? 34.1 Total amount earned in Tshs ( ) 34.2 I did not sell any or earn any income( ) 35) Did the beans income you earned from the most recent harvest increase as compared to previous harvests? 35.1 Yes ( ) 35.2 No ( ) 36) Please explain what could have led to the situation in your response above
	% of farmers who	37) In the most recent harvest of XX month of XX year, within

	report increased frequency of household beans consumption as a results of harvesting from the targeted farms	the month of the harvest, averagely around how many times in a week did your family consume beans from your farm?
	% of households who reported beans income leading to improved access to basic needs	38) How did you use the income earned in selling beans from your farm in the in the most recent harvest of XX month of XX year: 38.1 To buy food ( ) 38.2 To buy other household goods and supplies ( ) 38.3 To buy clothing ( ) 38.4 To construct or improve housing or shelter ( ) 38.5 For medical treatment ( ) 38.6 To pay for education related costs ( ) 38.7 I did not earn any income from beans ( ) 38.8 List other uses:
	% of households who report gender equality in use and decision making on resources related to beans farming	39) In the most recent harvest of XX month of XX year, who in your household took the final decision on how the beans harvested from the farm could be used? 39.1 Father ( ) 39.2 Mother ( ) 39.3 Both Father and Mother ( ) 39.4 Boy child ( ) 39.5 Girl child ( ) 39.6 List others: 40) Who in your household took the final decision on how the income from the selling beans from your farm could be spent? 40.1 Father ( ) 40.2 Mother ( ) 40.3 Both Father and Mother ( ) 40.4 Boy child ( ) 40.5 Girl child ( ) 40.6 List others: 41) On which of your household members was the income from selling beans sales directly spent? 41.1 Father ( ) 41.2 Mother ( ) 41.3 Boy child ( ) 41.4 Girl child ( ) 41.5 I don't know ( ) 41.6 List others: