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DEPARTMENT OF ZOOLOGY, ENTOMOLOGY, & FISHERIES SCIENCES

BEES AND THEIR CONTRIBUTION TO THE YIELD OF ROBUSTA COFFEE AND PUMPKINS IN SELECTED DISTRICTS OF CENTRAL UGANDA

BY

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To my family, they made many sacrifices during the course of this study.

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LIST OF ACRONYMS

ANOVA	Analysis of Variance
GDP	Gross Domestic Product
IBM	International Business Machines Cooperation
PAST	Paleontological Statistics
SPSS	Statistical Package for Social Sciences
UBOS	Uganda Bureau of Statistics
UCDA	Uganda Coffee Development Authority

GENERAL ABSTRACT OF THE STUDY

Bees play a vital role in enhancing the yields of flowering crops like Robusta coffee and pumpkins through pollination. This study investigated how cultivation practices influence bee diversity, abundance, and their contribution to the yields of Robusta coffee and pumpkins in the southern Kyoga basin district of Kayunga and central Lake Victoria Crescent districts of Luwero and Nakaseke. The research was conducted between July 2020 and April 2022. The study focused on Robusta coffee grown under shaded and open sun conditions, as well as pumpkin plots located at distances of ≤ 3 km and > 3 km from potential natural or semi-natural bee habitats. Bee diversity and abundance were assessed twice between December 2020 and October 2021 using pan trans and sweep nets across 100 m^2 plots established on each study site for the respective crops. Pollination exclusion treatments were undertaken to assess the impact of pollination on fruit set and yield. Statistical analysis using one-way ANOVA and logistic regression revealed that shaded Robusta coffee plots and pumpkin plots ≤ 3 km had significantly higher bee diversity, abundance, and crop yield. *Hypotrigona* sp. and *Lasioglossum* sp., were more prevalent in shaded conditions. Pumpkin plots ≤ 3 km exhibited higher fruit set, larger fruit mass, and greater seed counts than those > 3 km. In contrast, completely bagged flowers resulted in the complete absence of fruit production, underscoring the absolute dependence of pumpkins on insect pollination. The findings emphasize the critical role of agroforestry systems and the proximity of crops to pollinator habitats in enhancing pollination services and optimizing crop yields and hence the promotion of sustainable agriculture in Uganda.

CHAPTER ONE: INTRODUCTION

1.1 Background

Pollination is the transfer of viable pollen grains from the anthers to receptive and compatible stigmas of flowering plants and when followed by fertilization, usually results in fruit and seed production (Potts et al., 2016). Pollination is an ecosystem function that is fundamental to plant reproduction, agricultural production and the maintenance of global biodiversity (Schmeller et al., 2017). It links agro-biodiversity to agriculture and about 75% of the leading global food crops and 35% of global production volumes from crops are dependent upon animal pollination (Klein et al., 2007; Ollerton et al., 2011). Insect pollination contributes an estimate of €153 billion annually to global economic contribution which is equivalent to 9.5% of the total value of global agricultural production hence illustrating its vital role in food security (Gallai et al., 2009). According to Potts et al. (2016), crops dependent on pollination have a higher per ton market value compared to those not dependant on pollination showing its direct economic importance.

Pollinators include water and wind vectors; animal pollinators especially insects lead pollination in both cultivated and wild ecosystems (Khalifa et al., 2021). Among insets, bees are the most important pollinator, servicing a wide range of fruits, vegetables and seed crops (Garibaldi et al., 2013). Wild pollinators including solitary bees and non-*Apis* species promote fruit set better than honey bees and hence contribute in improving yield (Garibaldi et al., 2013). Although Robusta coffee (*Coffea canephora*), is self-compatible, it benefits a lot from insect pollination; bees increase fruit set, bean weight and uniformity of ripening (Klein et al., 2003; Munyuli, 2011). Similarly, pumpkins (*Cucurbita* spp.) depend to a large extent on insect pollinators most especially honey bees for the transfer of pollen from male to female flowers (Stanghellini et al., 1998). In pumpkins, inadequate pollinator visitation leads to low fruit set and poor yield (Hurd et al., 1971). Other than food provisioning, pollinators provide other benefits since they contribute directly to medicines, biofuels, fibers, construction materials, musical instruments, arts and crafts and also act as sources of inspiration for art, music, literature, religion, and technology (Potts et al., 2016). Specifically, bees also play a big role in the ecosystem architecture as high-end “recycling centers” by redistributing high-value material like pollen (rich in protein) and nectar (rich in energy) within the ecosystem (Roubik, 1994). Stingless bees alone redistribute 10% of the total annual energy production from primary production in a given square kilometer of tropical forest annually, into their hives (Roubik, 1994). The trash and waste from stingless bee hives, itself rich in nutrients, amounts to about 1,800 kg/year/square hectares (Potts et al., 2016).

Nevertheless, pollination is one of 15 ecosystem services identified as declining by the Millennium Ecosystem Assessment (2005). Populations of bees especially honey bees and wild bees pollinators have declined globally with the strongest evidence coming from Europe and North America Potts et al., 2010; Garibaldi et al., 2013; Potts et al., 2016). Threats that are driving the decline of pollinators including bee species (~50% since 1950) are pesticides and diseases (Potts et al., 2010). Besides, there is growing global demand for a diverse and nutritious diet (Klein et al., 2007; Eilers et al., 2011), This is resulting in habitat destruction due to more land being cultivated to satisfy global needs for food (Foley et al., 2011; Tilman et al., 2011). These is causing loss of nesting and foraging resources for pollinators, and ultimately leads to a decline in pollinator activity, with potential serious consequences to crop production (Kremen et al., 2002). In areas where bees have declined, crops are not pollinated sufficiently leading to yield reduction and reduced supply of nutritious food (Eilers et al., 2011). In Africa, knowledge gaps persist, but similar drivers of pollinator decline exist (Kasina et al., 2009; Munyuli, 2011). In Uganda, earlier surveys confirm high bee diversity and the role of bees in coffee and other crops (Munyuli, 2011).

Monitoring of pollinators in sub–Saharan Africa has been limited leaving these regions ecologically vulnerable to pollinator decline and with limited information about its extent and implications. In Uganda in particular, information on the value of insect pollinators and bee pollinators, in particular, is unknown because of insufficient studies (Munyuli, 2011). This study, therefore, seeks to get information on the diversity of bee pollinators and demonstrate their contribution to crop yield using Robusta coffee and pumpkins as model crops. The findings will provide experimental evidence for developing policies that recognize the role of biodiversity conservation in improving productivity and crop yield.

1.2 Statement of the problem

Global agriculture is now twice as pollinator dependent compared to five decades ago, a trend that has been accelerating since the early 1990s (Potts et al., 2016). However, the global decline in pollinators including bees is posing a threat to biodiversity conservation, agricultural productivity, and rural livelihoods hence undermining ecosystem services, food security and economic stability on communities that are depend on pollinator dependent crops (Sadafale et al., 2025; Food and Agriculture Organization [FAO], 2019). Previous research in central Uganda by Munyuli (2010) showed that bees contributed to coffee fruit set and yield, but knowledge gaps on bee diversity in other agricultural systems and how this diversity contributed to crop yield under smallholder practices exist (Munyuli, 2010; Klein et al., 2007).). In Uganda, farmers have limited awareness regarding the role of pollinators in enhancing crop yield (Munyuli, 2011). The insufficient information constraints evidence-based policy formulations on biodiversity conservation and its role in improving crop yield. In the absence of empirical data, drivers of pollinator decline including bees will continue hence affecting pollination services thereby threatening food insecurity, household livelihoods and reduced foreign exchange due to poor yields from pollinator crops. There is therefore urgent need to generate evidence-based information on bee diversity and demonstrate their contribution to the yield of cash and food crops. In the current study, Robusta coffee and pumpkins here used as model crops. *Coffea* and Cucurbits are popular plant families for plant - pollination studies because their floral biology and bee-pollinator interactions are key to crop yield (Beer et al., 2011; Knapp et al., 2019). Besides, both crops are cultivated in most parts of the study area and have local economic value both as a source of nutrients and income to farmers.

1.3 Objectives

1.3.1 General objectives

To examine the diversity and contribution of bees to yield of Robusta coffee and pumpkin to support formulation of pollinator-friendly policies for sustainable agriculture.

1.3.2 Specific objectives

1. To determine the diversity of bees in Robusta coffee and pumpkin farms under different cultivation practices in selected districts of central of Uganda.
2. To assess the contribution of bees to the yield of Robusta coffee and pumpkins under different cultivation practices in selected districts of central of Uganda.

1.4 Hypotheses

1. The diversity of bees in Robusta coffee and pumpkins does not vary under different cultivation practices.
2. The yields of Robusta coffee and pumpkins are not increased by bees under different cultivation practices.

1.5 Justification for the study

The 2030 Agenda for Sustainable Development and its 17 Sustainable Development Goals place food security, improved nutrition, sustainable terrestrial ecosystems and biodiversity conservation at the core of national development planning. Therefore, pollinators especially bees will be vital in achieving the SDGs because 87 out of 115 leading global food crops consumed by humans rely to varying degrees upon animal mediated pollination (Klein et al., 2007; IPBES, 2016; Potts et al., 2021; FAO, 2023). In Uganda, agriculture contributes about

24 % of GDP and accounted for 33 % of its export earnings during the FY 2021/22 (International Trade Administration, 2022). Besides, the Uganda Vision 2040 currently aims to transform the Ugandan society from a peasant to a modern and prosperous society by increasing household incomes and improving the quality of life of Ugandans (National Planning Authority (NPA). (2020). To meet these national goals as well as international biodiversity commitments like the Convention on Biology Diversity (CBD), it's important to understand the diversity and contribution of bee pollinators to crop yield. However, there is limited farmer awareness regarding pollinator-diversity and its effect on crop yield (Klein et al., 2007). Data on pollination biology including on bee-pollinator dependent crops in Uganda is limited. Hence, it's necessary to generate information on bee diversity and their contribution to crop yield using Robusta coffee and pumpkins as model crops since these crops offer well-studied pollination systems (Magrach et al., 2019). This information is required by stakeholders in sustainable production of pollinator dependent crops and also in creating awareness on the importance of agro-biodiversity in crop production and productivity.

CHAPTER TWO: LITERATURE REVIEW

2.1 Bees and pollination

Bees belong to the Order Hymenoptera, sub-Order Apocrita, and super-family Apoidae. There are about 20,900 species of bees in seven families, though many are undescribed and the actual number is probably higher. Out of the seven bee families known globally, six occur in Africa namely; Apidae, Megachilidae, Melitidae, Andrenidae, Colletidae and Halictidae (Michener, 2000). Bees are found on every continent except Antarctica, in every habitat on the planet that contains insect pollinated flowering plants. Bees range in size from tiny stingless bee species *Trigona minima*, whose workers are less than 2 millimeters long, to large species of leafcutter bee *Megachile pluto*, whose females can attain a length of 39 millimeters (Grüter, 2020; Michener, 2000; Ascher et al., 2008). Bees feed on nectar and pollen, the former primarily as an energy source and the latter primarily for protein and other nutrients. Most pollen is used as food for their larvae.

Most bees are generalist in that they collect pollen from a range of flowering plants while some are specialists, gathering pollen from one or a few species or genera of closely related plants (Klinkhamer, 2006). Specialist pollinators also include bee species which gather floral oils instead of pollen, and male orchid bees, which gather aromatic compounds from orchids (one of the few cases where male bees are effective pollinators). Bees are able to sense the presence of desirable flowers through ultraviolet patterning on flowers, floral odors and electromagnetic fields (Dafini et al., 2012). Very few plant species are effectively pollinated by a single bee species, and some plants are endangered at least in part because their pollinator is also threatened. But there is a tendency for oligolectic bees to be associated with common, widespread plants visited by multiple pollinator species (Michener, 2000; Ascher et al., 2008). Some bee species including honey bees and stingless bees are eusocial or partially social living in colonies but over 90% of bee species (mason bees, carpenter bees, leafcutter bees, and sweat bees) are solitary.

Bees play an important role in pollinating flowering plants, and are the major type of pollinator in many ecosystems that contain flowering plants. It is estimated that they pollinate about one-third of food consumed by humans, increase the biodiversity of plant species, maintain genetic diversity within plant populations and increase fruit yields (Batra, 1995). The managed honey bee, *A. mellifera*, is the dominant visitor to more than half of the world's animal-pollinated crops (Klein et al., 2007; Kleijn et al., 2015). Bee pollination has direct effects on the profitability and productivity of a substantial amount of global crop varieties, including most vegetables, seeds, and nuts, and some high-value agricultural products, such as coffee (Khalifa et al., 2021).

However, observations over the last half decade indicate global decline in the species richness of wild bees and other pollinators. This is due mainly from the effects of climate change and human activities including land fragmentation, alteration of habitats, change in land use patterns, agricultural intensification, and misuse of agrochemicals (Kearns et al., 1998). High temperatures, and humidity due to climate change, affects the growth, reproduction, and survival of bees thereby reducing not only the biodiversity of bees and other pollinators but also agricultural production (Ma et al., 2019).

The conversion of natural habitats to agricultural land causes the loss of nesting and foraging resources for pollinators, especially bees, and ultimately leads to a decline in pollinator activity with potentially serious consequences for crop production (Kremen et al., 2002). The decline in the diversity and abundance of bee pollinators and a reduction in yield of the crops they pollinate have been reported in many continents, including North America (Williams et al., 2001) and Europe (Cane and Tepedino, 2001; Goulson et al., 2008). In 2014 the Intergovernmental Panel on Climate Change report warned that bees faced an increased risk of extinction because of global warming (Gosden, 2014).

2.2 Diversity of bees in Robusta coffee and pumpkins

Coffea canephora and all other self-incompatible *Coffea* species were previously believed to be mainly wind pollinated because *Coffea* species have light and dry pollen (Free, 1993). However, *C. canephora* is now regarded as an entomophilous crop with bees being the primary pollinator while other insects such as ants, butterflies and beetles make only a small contribution (Willmer and Stone, 1989). Bees and other insects frequently visit *C. canephora* flowers because their flowers are much bigger with much more intense smell and their coffee shrubs produce more flowers than highland coffee (Klein et al., 2003a). Fruit set in *C. canephora* is higher following bee visits and during massive synchronous flowering events, *Apis* spp., stingless bee species, the leaf-cutter bee *Megachile frontalis*, *Trigona*, *Creightonella*, and *Amegilla* are the main and frequent flower visitors in Papua New Guinea (Willmer and Stone, 1989). Synchronous flowerings attract social bees, but because of the high concentration and density of flowers, bee movement between plants is rather limited and the potential for out-crossing is poor (Willmer and Stone, 1989).

Fruit set therefore in *C. canephora* depends on cross-pollination by bees and the absence or inadequate pollination leads to a high frequency of misshapen low quality fruits known as "peaberries" and hence reduced yield (Ricketts et al., 2004; Roubik, 2002). According to Klein et al. (2003a), pollination by bees increase fruit set in *C. canephora* by 25% compared with the control (wind pollination and autogamy combined. Members of the species-rich solitary bees lead to higher fruit set in Robusta coffee, they are more efficient as pollinators of Robusta coffee than social bee species even though the visitation rates of social bees to coffee flowers are higher (Klein et al., 2003b; Willmer and Stone, 1989).

The higher pollination efficiency of solitary bees could be due to the following findings: (1) solitary bees switch between plants more often than social bees, thereby offering a higher enhance of cross pollination (Willmer and Stone, 1989). (2) Social bees collect less pollen and more nectar than solitary bees and contact the stigma less often (Freitas and Paxton, 1998). (3) Most solitary bees have longer tongues and therefore make contact with the stigma more often (Corbet, 1996). (4) Social, stingless bees often damage flowers, so fruit set may be reduced (Maloof and Inouye, 2000; Irwin, Brody and Waser, 2001). The number of species and number of individuals in the bee community is important for overall pollination success in Robusta coffee (Klein et al., 2003b). Stingless bees play a prime and critical role in the delivery of pollination services to coffee in Uganda and in Kenya (Karanja et al., 2010). After pollination, the fruits of *C. canephora* take approximately 2 months longer to mature (i.e., 9 –11 months) than those of C. *arabica* (De Castro and Marraccini, 2006).

Generally, bee-mediated pollination increases coffee fruit weight, give rise to improved fruit shape, and also leads to uniform ripening of coffee berries thus no field losses (Roubik, 2002a; Ricketts et al., 2004). Increased fruit set and quality of coffee is ascribed to outcrossing effects by bee pollinators depositing pollen grains from different coffee plants to coffee flowers and a higher efficiency of pollen deposition (Olschewski et al., 2006). Coffee berry size is enhanced by the fruit set and the more successful the fruit set is the larger the berry size and the higher the yields (Roubik, 2001). Meanwhile, the absence of pollinators especially bees not only affects the total harvest but also the quality of yield through misshapen fruits and unusually small fruits of inferior biological qualities associated with pollinator failure (Karanja et al., 2013).

Insect pollination is essential in pumpkins because all *Cucurbita* species are monoecious plants with yellow showy pistillate and staminate flowers occurring singly in the axils of the leaves (Free, 1993). They have sticky pollen requiring pollen transfer to stigma for fruit set (Hurd et al., 1971). Pumpkins are dependent on bee-mediated pollination to produce fruit, and an increase in bee visits to female pumpkin flowers results in larger fruit (Pfister, 2017;

Haider et al., 2025). Because insect pollination is a generally indirect effect of foraging behavior, entomophilous plants such as cucurbits have evolved adaptations that influence pollinating insects for rapid and effective pollinator visits and therefore maximum yields. The adaptations include; possession of bright yellow flowers, providing large quantities of nectar and pollen as floral rewards, developing nectar guides to help direct pollinator movement, and placing the rewards so that the pollinator must contact the stamens or stigma (Proctor et al., 1996). Honey bees have a high search ability for flower resources, foraging optimally in terms of energy and time efficiency (Seeley, 1995), and visit only one species of flower in a bout. When honey bees do visit *Cucurbita* spp. flowers, they show a strong preference for female flowers and do not as frequently collect pollen compared to other native bees (Tepedino, 1981).

Honey bees are common visitors in pumpkin fields but crop visitation is shared with a wide range of wild bees whose composition varies with landscape context and floral resource availability in surrounding habitats (Skinner & Lovett, 1992; Winfree et al., 2007; Artz & Nault, 2011). Hence, pumpkin pollination depends on many bee species and conservation of nearby natural and semi-natural habitats and the maintenance of diverse floral resources are important for sustaining pollination services and stable yields of *C. pepo*. Fruits have been shown to abort in the absence of pollination in *Cucurbita pepo* (Martínez et al., 2014). But there are several other varieties of *Cucurbita pepo* that have been observed to set fruit in the absence of fertilisation via parthenocarpy (Robinson and Reiners, 1999; Kurtar, 2003; Martínez et al., 2013). These parthenocarpic varieties still produce a greater quantity and quality of fruits, including a higher sugar content (Shin et al., 2007), when they are pollinated by insects (Martínez et al., 2013; Nicodemo et al., 2013). In *C. pepo* however, presence of already pollinated fruits has been shown to significantly decrease the number of pistillate flowers and increase the likelihood of new fruit aborting (Stanghellini et al., 1998).

2.3 Effects of cultivation practices on bee diversity in Robusta coffee and pumpkins

Certain cultivation practices encourage and promote the existence of pollinators and hence pollination of Robusta coffee thereafter increasing their yield (Munyuli, 2014). Bee species richness in coffee can be encouraged through growing them in shade, pruning trees to increase sunlight and by increasing the availability of nesting sites for solitary bees (Klein et al., 2003c). Robusta coffee grown with diverse shade trees and in agroforestry systems supports higher bee abundance and species richness than open-sun monocultures because shade trees provide floral resources, nesting sites and microclimate buffering that favour many wild bees (Munyuli, 2011). Shade trees reduce the stress of *Coffea* spp. by ameliorating adverse climatic conditions, nutritional imbalances, modify microclimate by reducing temperatures and reducing water loss through both lower soil evaporation and crop transpiration (Gomes et al., 2020; Jha et al., 2014; Lin, 2010). Shade trees also reduce hydric stress by increasing relative humidity, favouring growth and the development of soil microorganisms (Partelli et al., 2014). Extensive monocultures are associated with a limited pollinator supply and reduced pollination, whereas agricultural diversification supports wild bees by providing nesting and foraging resources (Kovács-Hostyánszki et al., 2017). Robusta coffee gardens that are intensely managed with too much weeding, frequent tillage, and widespread use of agrochemicals have fewer floral resources and nesting areas with reduced bee diversity (Munyuli, 2011). Nesting sites of solitary bees can be encouraged through minimum tillage. Bee diversity in robusta coffee depends not only on on-farm practices but also on nearby semi-natural habitats, farms nearer to remnant vegetation or with connected habitat patches host more pollinators including bees (Jonas et al., 2024). Hence, maintaining shade-trees and adopting low-intensity cultivation practices increase pollinator diversity, which translates into improved fruit set, berry weight, and long-term yield stability in Robusta coffee systems (Jonas et al., 2024).

Much as Robusta coffee agroforestry systems have benefits, trees that are alternate hosts to the black coffee twig borer e.g., Avocado and *Albizia chinensis,* should be avoided or must be carefully managed because they can act as reservoirs or attractants for pests (Egonyu et al., 2017). According to UCDA (n.d.), trees that have leaves that take very long to decompose e.g., eucalyptus, pine tree; trees that produce thorns e.g., *Erythrina abyssinica* should be avoided in coffee plantations. Shade tree selection and management is important in coffee agroforestry systems because increased shade may again increase the incidence of some pests and diseases such as *Phythphora palmivora* and *Mycena citricolor* and decrease the incidence of others such as *Colletotrichum gloeosporioides* and *Cercospora coffeicola.* (Avelino et al., 2004; Jaramillo et al., 2011). Smaller holder pumpkin farming systems in Uganda and East Africa at large show that cultivation practices which maintain natural or semi-natural vegetation near fields contribute positively to bee diversity and thus pollination potential (Nang'oni et al., 2025). A study by Nang'oni et al. (2025) found that pumpkin farms located in landscapes with higher vegetation cover supported *Apis mellifera* colonies that collected pollen from a broader array of plant families compared to farms in low vegetation cover landscapes. Additionally, landscapes with few natural habitats or floral resources limit the diversity of pollen sources and therefore may reduce the diversity of bee taxa visiting pumpkin flowers. Hence, cultivation practices such as preserving hedgerows, maintaining semi-natural patches or mixed vegetation around pumpkin fields, and reducing habitat simplification can be crucial for sustaining a diverse bee community in pumpkin agroecosystems (Waithaka et al., 2023)

Cultivation practices that most directly influence the life cycle of wild bees include tillage, which can destroy or reduce the survival of immature bees in soil or plant debris; crop diversity, which affects the availability of continuous food resources such as pollen and nectar throughout the season; and pesticide use, which can have direct lethal or sublethal effects on adult bees and foraging behavior (Cane and Neff, 2024; Kline and Joshi, 2024). Maintaining low-disturbance soil areas, a diversity of flowering crops, and minimizing pesticide exposure are therefore critical for supporting healthy wild bee populations in agroecosystems.

Naturally occurring wild flowers such as agricultural weeds and hedgerow flowers provide floral resources to pollinators (Bretagnolle and Gaba, 2015). *Apis mellifera* has been observed to visit *Cucurbita pepo* flowers more often than wild flowers in the morning when *Cucurbita pepo* flowers were open, before 'switching' to wild flowers after *C. pepo* senescence (Knapp et al., 2018). Non tillage allows areas to remain undisturbed for nesting and hibernation. Large areas of mass-flowering crops, including the cucurbit crop itself, may dilute pollinator densities or, if the area is small, concentrate pollinator densities (Holzschuh et al., 2016). This is pronounced if additional food and nesting sites are not provided, hence pollinators move transiently between available forage rather than increasing their population size (Holzschuh et al., 2016).

Bees require food resources and undisturbed nesting substrates during their developmental period in order to sustain their populations (Cane and Neff, 2024; Kline and Joshi, 2024). However, the current intensification of agriculture systems to improve yields involves greater use of modern agricultural technologies and agrochemicals that are harming pollinator populations including those that cucurbit pollinators (Brittain et al., 2010; Goulson et al., 2015). Fragmentation and habitat destruction add to the rate of genetic erosion by reducing gene flow between locally interbreeding group within a geographic population, and increases the likelihood that populations and species will become extinct including pollinators like bees. Wild pollinators need undisturbed habitat for nesting, roosting and foraging; therefore, they are very susceptible to habitat degradation and fragmentation.

Generally, cucurbit yield can increase if a crop is surrounded by more diverse habitats where increased species richness and abundance of wild pollinators can improve pollination services (Hoehn et al., 2008; Garibaldi et al., 2011) and provide insurance against any pollinator loss

(Shuler et al., 2005). Improving the quantity and quality of pollen and nectar resources available for pollinators, and allowing areas to remain undisturbed for the insects to nest, mate, and hibernate benefits pollinator populations and therefore reduce pollination deficits (Bommarco et al., 2013).

2.4 Other factors that affect bee pollination services of Robusta coffee and pumpkins

Changes in land use such as the conversion of native forests into cultivated areas causes loss of sources of pollen, nectar and oil, as well as varied nesting sites, hence a major cause of loss of pollinator species including bees (Kremen et al., 2002). Pollinators, especially bees need natural plant remnant habitats for foraging purposes, nesting or oviposition, source of water, mating and roosting caves (Roubik, 1995; Ricketts, 2004). In coffee, pollinator diversity and visitation rate declines with increasing isolation from patches of native habitats, and this decline affects yields (Kremen et al., 2002; Ricketts, 2004). Hence, natural forests and forest fragments should be preserved (< 500 m) so that forest-nesting social bees can travel easily to the coffee fields to pollinate (Klein et al., 2003a). The number of social bees decreases with distance to forest while number of solitary bees increased with light intensity and greater quantities of blossoms (Klein et al., 2003a). Generally, habitat loss and land use changes can alter floral and nesting resources of bees (Flores et al., 2018; Happe et al., 2018) which in turn affects bee behavior and bee community composition (Mullally et al., 2019).

Besides the natural factors affecting bee pollination, the use of pesticides, such as acetamiprid and ergosterol-inhibiting fungicides, threaten pollinator diversity and hence pollination services (Han et al., 2019). Through providing crops with essential nutrients, protecting the crops from pests and diseases, weed control, agrochemicals help farmers achieve higher yields and hence play a key role in increasing agricultural productivity. However, they have been used indiscriminately rising concerns over their usage. Agrochemicals used that have effect on bee diversity and abundance are insecticides and herbicides. Spraying agrochemicals such as fungicides, insecticides, and pesticides cause contamination, toxicity, and declines in the quality and quantity of nutrients in the pollen and nectar, leading to poor colony health and hence threatening the survival of bees (Tosi et al., 2017; Tome et al., 2017). Agrochemicals may affect larval stages of pollinators including bees, nesting sites, foraging sites for adults and even mating sites of some pollinators. Besides, residues of pesticides and other synthetic products remain in the nectar and pollen collected by bees, leading to neurotoxicity, immune deficiency, behavioral changes, chronic ailments, and death (Christen et al., 2018; Arce et al., 2018). These will ultimately reduce the pollination efficiency of pollinators including bees and hence affecting crop yield. Nevertheless, agrochemicals are indispensable in agriculture to maintain productivity as the population is exponentially increasing and so is the demand for food there is therefore a need to encourage their judicious use.

2.5 Evaluating pollination in pumpkins and Robusta coffee

Pollination can generally be quantified and hence evaluated directly or indirectly in two ways. First by directly estimating pollinator performance through pollinator behaviour and / or pollen deposition on stigmas. In this method of quantifying pollination, pollinator visitation to crop flowers, abundance at crop flowers, and pollen deposition (whilst stigmas are receptive) are all considered to be measures of pollinator performance (King et al., 2013; Munyuli, 2011). Pollinator performance is the relative measure of pollinator effectiveness, based on pollinator behaviour (visitation (rate and/or timing), single visit pollen deposition) or contribution to yield (fruit weight, fruit number, seed set (Ne′eman et al., 2010; King et al., 2013). Pollen deposition is the number of pollen grains deposited on stigmas following visitation by individual bee species or all bee species combined, for multiple visits. Direct method of quantifying pollination also involves actual counting of pollen grains placed on the stigma with a light microscope (Ne′eman et al., 2010; Syarrudin et al., 2021).

However, certain species have arrangements of stigmatic papillae, or copious quantities of stigmatic exudate, which makes counting of pollen difficult (Dafni, Kevan and Husband, 2005). There is also a chance of counting pollen grains on the stigma that do not belong to the species represented by the pistil. Besides, it may not be possible to observe the entire stigma when mounted on a microscope slide (Kearns and Inouye, 1993) The counting of pollen tubes at the style base in plant species that are self-compatible is another technique used to measure pollination directly and accurately (Williams and Rouse, 1990). Each viable pollen grain, properly placed on a receptive stigma of the same species, sends down one pollen tube to deliver the sperm cell nuclei necessary for fertilization to occur. Pollen tubes within the centre of the style are relatively protected, and are therefore not nearly as susceptible to loss from the style as pollen grains might be from the stigma, during tissue processing (Matsumoto et al., 2021).

The other method of quantifying pollination is by indirectly estimating pollinators' contribution to yield usually measured as fruit set, seed set, fruit weight, fruit weight per plant, fruit number, fruit size, seed number and percentage fruit or seed set ((Ne′eman et al., 2010; Klein et al., 2021)). Percentage fruit set is the number of fruits / number of flowers X 100. However, measures of yield are usually influenced by environmental factors that affect fruit production e.g., soil type, resource availability and cultivation practices (Garibaldi et al., 2020). When environmental factors that affect yield are constant, a single visit pollen deposition is the most direct measure of pollination success (Kremen et al., 2004). Unfortunately, these are poor estimators of pollination because fruit production which is a measure of flower fertilization can only be an indirect measure of pollination or the placement of pollen grains on the stigma. The problem with counting fruit is that pollination can be grossly underestimated in plants that undergo abortion of developing fruits (fruit drop), which usually occurs when relatively low nutritive resources are available to the plant (Ne′eman et al., 2010). Another hindrance to determining pollination from seed or fruit yield can occur in plant species that have a low ovule number per flower relative to the number of pollen grains placed on the stigma. In such cases, the potential number of ovules fertilized cannot be known by fruit counts, and hence pollination will again be underestimated (Herrera, 2020). However, for plants that develop fruits parthenocarpically in the complete absence of pollination, pollination can be overestimated if it were measured by fruit count in such plant species (Aizen and Harder, 2007). For plant species that are self-incompatible, a zero-fruit count may not truly indicate lack of pollination (Ashman et al., 2004). In those cases, crop pollination services can be valued as the difference between crop profits when wild pollinators provide services, and crop profits with diminished pollinator availability due to habitat loss (Klein et al., 2007; Gallai et al., 2009; Munyuli, 2011).

Evaluating pollinators' contribution to yield in cucurbits can be indirectly measured as seed set or fruit weight (Ne′eman et al., 2010). Fruit number and percentage fruit set reflect the number of flowers pollinated, while seed set, and average fruit weight reflect the quantity of pollen that a flower receives hence affecting the number of seeds per fruit or the fruit size (Ne′eman et al. 2010). Number of seeds and fruit set of *Cucurbita pepo* are positively correlated with the number of pollinator visits that each flower receives. (Roldán-Serrano and Guerra-Sanz 2005; Vidal et al., 2010)

Coffee fruits are "drupes" (fleshy fruits that have a hard nut) De Castro and Marraccini (2006) and normally develop with two ovules (Klein et al., 2003b). Reduced pollination leads to low fruit set in *C. canephora* and formation of "peaberries" (Klein, Steffan-Dewenter and Tscharnkte, 2003a). "Pea berries" form during coffee fruit development when only one ovule matures and one is aborted, resulting in one seed instead of two (Free, 1993). Pea berries are normally undesirable since they are deformed or misshapen beans (Ricketts et al., 2004; Muschler, 2001). Therefore, besides percentage fruit set, number of coffee fruits and peaberries can be used to evaluate pollinator's contribution.

CHAPTER THREE: GENERAL MATERIALS AND METHODS

3.1 Study area

The study was carried out from July 2020 to April 2022 in the Southern Kyoga Basin district of Kayunga, the Central Lake Victoria Crescent districts of Luwero and Nakaseke all in Central Uganda (figure 3.1). Kayunga district lies 00°42 09 North and 32°53 20 East and is approximately 74 km by road from Kampala, Uganda's Capital City. Kayunga District covers a land area of approximately 1,587.8 km² and with a population density of about 227 persons per km², which is higher than Uganda's national average population density of 224 persons per km² (Uganda Bureau of Statistics, UBOS, 2024). The vegetation cover of the study area is very much influenced by River Ssezibwe, Musaamya wetland system, River Nile and Mabira forest since it is surrounded by them. Agriculture is the main economic activity in Kayunga district employing about 90% of the population due to the fertile soils, good climate and adequate rainfall.

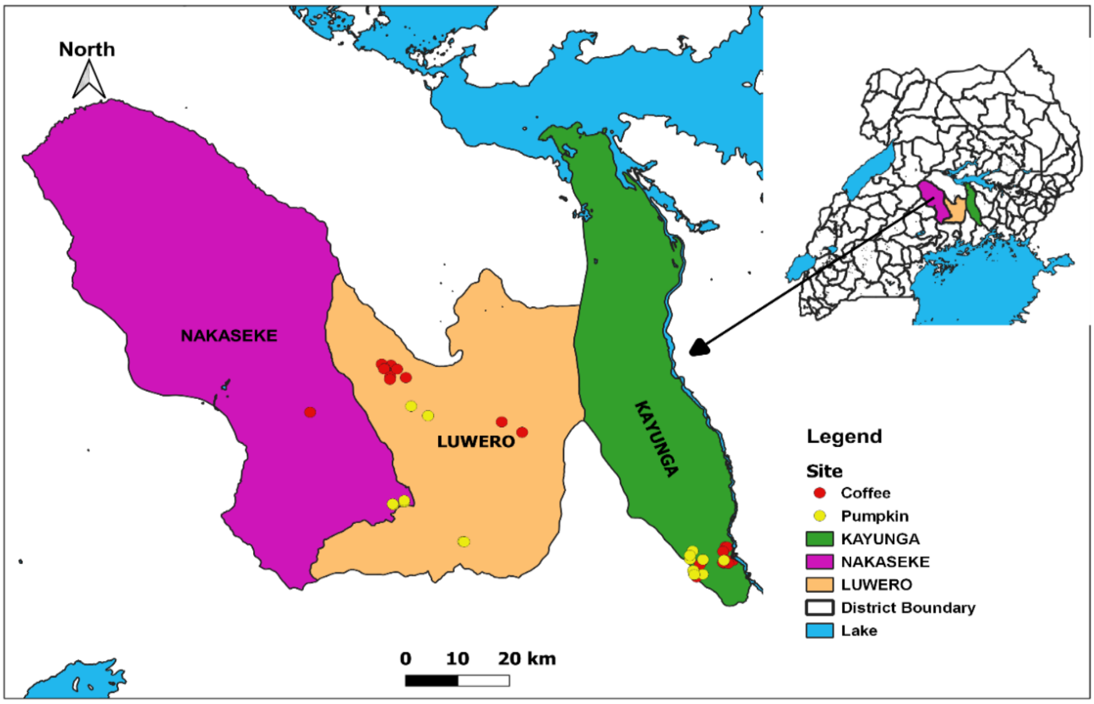

Figure 3.1: Location of Nakaseke, Luwero and Kayunga districts in Uganda

Luwero district lies 00° 50 North, 32° 30 East and approximately 75 km by road, North of Kampala with a total land area of approximately 2217.6 km^2 and a population density of 277 persons/km^2 which is also higher than the national average (UBOS, 2024). The southern part of Luwero district (sub-counties of Makulubita, Kalagala, Bamunanika, Zirobwe) is relatively fertile and supports all kinds of crops but the northern area (Kamira, Butuntumula and parts of Kikyusa sub-counties) is semi-arid. Cattle keeping is the main dominant occupation though crops like Robusta coffee, pineapples, bananas and pumpkins are also grown.

Meanwhile, Nakaseke district is located between 00°44 North and 32°25 East. It covers a total area of 3,477.3 km^2 with a very low population density of 54.9 persons/km^2 (UBOS, 2017). Cattle keeping is the main economic activity of people of this district since much of the district is semi-arid but subsistence production of Robusta coffee, maize, beans, pumpkins, sweet potatoes, tomatoes, egg plants, cassava, pineapples, mangoes take place.

This study was conducted in these districts of Central Uganda because Robusta coffee is the main cash crop (UBOS, 2014). Pumpkins, bananas, pineapples, maize, beans, watermelons too are planted in all this districts for household consumption and for sell to Kampala the capital city of Uganda where there is ready market from the urban population in the city since these districts are nearer to Kampala. The study area has a mosaic landscape with "islands" of natural habitats like forest fragments, forest reserves, wetlands, and woodlands. It also has different vegetation cover, different land use types, different farm management systems comprising of mostly Robusta coffee, bananas, pineapples, pumpkins, beans of differing management intensities. Open grasslands with low tree cover, wooded landscapes are found scattered within agricultural matrices dominated by linear and nonlinear features of semi-natural habitats (fallows, hedgerows, grasslands, forest plantations, and rangelands) that are displayed as field boundaries of diverse small-scale fields. The study area was also characterized by high demographic pressure, limited access to arable and fertile lands, intensive (continuous) crop cultivation, over exploited lands and massive use of agrochemicals especially in Kayunga (UBOS, 2014). Besides, Kayunga is more humid than Luwero and Nakaseke hence these districts represented well central Uganda.

3.2 Site selection

For Robusta coffee, a total of 24 study sites were sampled; 12 from Kayunga, 11 from Luwero and 01 Nakaseke districts during the first trial. The same sites were used for the second trial but only 10 sites were sampled from Luwero district therefore a total of 23 sites were sampled during the second trial. The one (01) site in Luwero district was lost after the owner sold the land and the new owners cut off all the coffee plants that were in it. The study sites were selected based on the following cultivation practices; 1) Shaded coffee garden (12 study sites of Robusta coffee with heavy shades intercropped with trees and or bananas), 2) Open sun coffee gardens (12 study sites of pure stands coffee, not intercropped with trees and or with bananas or if any very scattered trees or banana plants with no influence of shade on the coffee plants). The selected study sites contained Robusta coffee plants of the same variety and age range (10 – 15 years).

For pumpkins, 16 different study sites were sampled; Eight (08) from Kayunga, four (04) from Luwero and four (04) Nakaseke districts. The sampling was done during wet and dry seasons. The study sites were selected depending on the distance of the site from a natural or semi natural pollinator habitat. A natural or semi-natural pollinator habitat included fallows, hedgerows, field margins, grasslands, roadsides, woodlands, woodlots, track-sides, stream-edges. In the two seasons, eight study sites ≤ 3 km from potential natural or semi-natural bee habitat and eight sites > 3 km were sampled. The sampled study sites were separated from each other by a distance of at least 1 km, to reduce the possibility of sampling the same populations of bees.

3.3 Data collection

Generally, bee sampling in Robusta coffee and pumpkin farms was carried out between December 2020 and October 2021. In Robusta coffee, bees were sampled twice when substantial flush of flowers occurred while in pumpkin farms, sampling was carried out during two different pumpkin growing seasons. Pan traps and sweep nets were used to capture bees in 100 m^2plots established at each study site of the respective crops.

Pollination exclusion experiments were carried out to estimate the contribution of bees to the yield of Robusta coffee and pumpkins under different shade levels and different distances from potential natural or semi-natural bee habitats for coffee and pumpkin plots respectively. These was carried out during two periods when there was substantial flush of flowering of Robusta coffee and two growing seasons of pumpkins. The pollination exclusion experiments included: Spontaneous Self-Pollination (SS), Manual Self-Pollination (SP), Manual Cross-Pollination (CP) Open Pollination (OP), Wind Pollination (WP) and Single Bee Visit (SBV).

Details on data collection for each of the objectives are in sections 4.1.3 and 5.1.3.

3.4 Data analysis

Data management and analysis was performed using a number of tools; Microsoft Excel 2016, Relative abundance of bees across the different cultivation practices was determined using Excel, while bee diversity was analysed with PAST software. Shapiro–Wilk and Levene’s tests were used prior to analysis in testing the data for normality and homogeneity of variance respectively. Bee abundance data (expressed as counts) was log transformed to stabilise variances since it violated the assumption of normality. Bee diversity was assessed using the Shannon–Wiener (H’) and Simpson (1–D) diversity indices. An independent samples t-test was performed to identify significant differences in bee diversity and abundance in the cultivation practices of the respective crops

A one-way analysis of variance (ANOVA) was also conducted to evaluate significant differences in the mean mass of harvested Robusta coffee and pumpkin fruits, and the mean percentage mass of coffee berries and pumpkin fruits. Where significant variations were detected, a post hoc Tukey test was used to identify the sources of these differences.

Details on data analysis for each of the objectives are in sections 4.1.4 and 5.1.4.

CHAPTER FOUR: DIVERSITY OF BEES IN ROBUSTA COFFEE AND PUMPKIN FARMS UNDER DIFFERENT CULTIVATION PRACTICES IN SELECTED DISTRICTS OF CENTRAL UGANDA

Abstract

This study examines the diversity, abundance, and distribution of bees under varying cultivation practices of Robusta coffee and pumpkins. Shaded versus open sun Robusta coffee plots and pumpkin plots ≤ 3 km and > 3 km from potential natural or semi-natural bee habitats. The study was conducted from July 2020 to October 2021 in the districts of Nakaseke, Luwero, and Kayunga all located in central Uganda. Bee sampling was done using pan traps and sweep nets across 100 m^2 plots established on each study site of the respective crops. Bee samples were collected and identified at Makerere University, while data analysis was performed using Microsoft Excel, PAST software, and R software. Diversity was assessed using Shannon and Simpson diversity indices, while independent t-tests compared variations in bee diversity and abundance across the different cultivation practices. The results revealed that shaded coffee plots supported significantly higher bee diversity and abundance, with *Hypotrigona* sp. and *Lasioglossum* sp. being more prevalent in shaded Robusta coffee plots. Similarly, pumpkin plots ≤ 3km recorded higher bee diversity and abundance compared to those located >3km. These findings underscore the ecological importance of shaded coffee agroforestry systems and the proximity of pumpkin fields to natural habitats in sustaining pollinator diversity. The study highlights the value of agroecological farming practices in promoting pollinator conservation, enhancing ecosystem services, and supporting sustainable production of key crops like Robusta coffee and pumpkins in Uganda.

4.0 Introduction

In agricultural landscapes, pollination service depends on the movement of pollinators from nesting habitats (such as forests) to foraging habitats (such as farms) (Ricketts et al., 2008). In these landscapes, forest fragments mostly serve as nesting habitats for bees, especially above-ground nesting species. About 30% of the more than 20,000 known bee species in the world are above-ground nesting (Frankie et al., 2009). For example, honeybees, and stingless bees are eusocial and are among the above-ground nesting bees (Bennett and Lovell, 2019). Stingless bees are the most diverse social bees, and many of them depend on natural cavities to form colonies (Silva et al., 2014). In natural environments such as forests, they nest in tree hollows.

Bees require a place to construct nests and flowers to forage on. Kasina et al. (2007) reported that bees also require plants for other uses such as getting nest materials, hiding, mating or just as resting sites. Undisturbed habitats provide the best home for different bees as they provide mud, resins, pebbles or plant materials for nest construction or an area for ground nesting bees to construct nests (O'Toole, 1993). The nest and flower habitats need to be close enough so that the bees can fly between them. The small bees may fly more than 200 to 300 yards while large bees may fly a mile or more from the nest to foraging area. If the flight distance is very long, the bees may find somewhere else to nest or become exhausted and die (Michener, 2007). All pollinators including bees require undisturbed habitats for provision of floral resources, nesting place and materials and refugee area during harsh environmental conditions (Kasina et al., 2007). If bees are isolated through habitat loss, it is harder for them to find mates, have enough nesting sites and eat enough food within a limited area (Kremen et al., 2002). Bees that experience habitat losses suffer from nutritional stress as it is more difficult for them to locate valuable food sources (Kremen et al., 2002).

For effect of distance from potential natural or semi-natural bee habitats to bee diversity in pumpkin plots, 67% of studies have reported that distance has a positive effect on the bee richness, abundance, and visiting rate (Rahimi et al., 2022). Bee species require food resources throughout their active period and undisturbed nesting substrate during their developmental period. Nesting substrates vary, but most bee species are either cavity nesters hence occupying existing structures such as hollow plant stems (Frankie et al., 1998) or ground nesters that excavate tunnel systems in earthen banks or bare patches of soil (Chapman et al., 1990). Nesting of ground-nesting bees in arable fields is not associated with tillage system per se, but with distance to field edge, crop cover, soil and landscape context (Tschanz et al., 2023).

The survival of offspring within planting areas depends on nests not being disturbed during development. The presence of nesting habitats and floral resources is of great importance for bees (Olsson et al., 2015; Ricketts et al., 2008). Moreover, the proximity of these habitats to each other provides favorable conditions for pollinators because they spend less energy to find food and take it to the nest (Kline and Joshi, 2020).

Coffee has experienced a 67.9 % surge in demand in the last 26 years alone, and is now considered one of the world's most economically important traded commodities, with the global coffee industry worth around US$60 billion as of 2022 (Pancsira, 2022; Torga and Spers, 2020). In order to keep up with increasing demand, the shade cover often provided in traditional, smallholder coffee farms have been sacrificed to allow for agricultural intensification, such as mechanization and yield optimization (Jha et al., 2014). These practices have led to habitat degradation, pest resistance, and loss of biodiversity (IPBES, 2022; Syafrudin et al., 2021; Zhou and Li, 2021). Coffee grown under a canopy of shade trees supports a relatively high insect biodiversity compared with unshaded monocultures (Perfecto and Snelling 1995; Moguel and Toledo 1999; Conservation International 2000; Greenberg et al. 2000). Hence, coffee producers are being encouraged to maintain a variety of shade trees in their agroforestry systems (Soto-Pinto et al. 2000). Shade coffee is the practice of growing coffee under varying levels of canopy cover to produce optimal climatic conditions for coffee growth, whilst also providing habitats for a diverse array of species (Philpott et al., 2008). Shade cover is one aspect of a strategy for conserving species within farms referred to as land-sharing (Campera et al., 2021a). Thus, biodiversity conservation is achieved through provision of habitat for wildlife. Finally, shade bolsters ecosystem service provision through the presence of wildlife within and around coffee farms, including natural pest control, pollination and soil fertility, assisting farmers with yield and, in turn, income (De Beenhouwer et al., 2013a). However, the ability of shaded farms to provide viable habitat is contested, with researchers debating the quality of this habitat, and whether or not this habitat replicates natural forest to the extent required for species, particularly those of conservation importance (Bedoya-Duran ´ et al., 2023; Ong'ondo et al., 2022). Shade has been found to increase pollinator diversity and visitation time (Manson et al., 2022).

In coffee farms, shade system does not affect bee abundance but low shade farms have a significantly higher bee species diversity than in high shade farms (Berecha et al., 2015). The preference for open sun coffee farms could be due to a seasonal lack of floral resources in forested areas when coffee is blooming, meaning there is a seasonal attraction to sun coffee farms due to the higher density and concentration of floristic resources (Vogel et al., 2021). Additionally, bee visitation rate and time has been shown to increase with increasing temperature, showing a preference for open sun farms (Manson et al., 2022). This is further supported by Classen et al. (2014), who found that honey bee visitation rate was higher in low shade farms and open sun farms when compared to higher shade treatments.

Therefore, the distance between nesting habitat and foraging site has a significant effect on the presence of pollinators in a land landscape (Ekroos et al., 2013; Ricketts et al., 2008). The arrangement of suitable nesting patches and the ability of pollinators to move from these patches to surrounding farms affect the pollination rate in agricultural landscapes (Mitchell et al., 2013). In addition to nesting habitat, adequate floral resources should be available to pollinators in a landscape (Kline and Joshi, 2020).

In Kenya, most flowering crops rely on wild pollinators from nearby habitats for pollination (Kasina et al., 2007). However, the ability of these habitats to continuously support pollinators has been interfered with by human activities. Natural and semi natural ecosystems have been continuously destroyed to avail land for farming, infrastructure and human settlements. Rapid human population growth coupled with increasing demand for food has led to land fragmentation and agricultural intensification, which are the most serious threats to the biodiversity of bees in agro-ecosystems (Benton et al., 2003). The afore mentioned anthropogenic activities have led to the replacement of indigenous plants that provide good forage for bees with exotic trees. Indigenous plants have co-evolved with native bee pollinators for a long time (Schaab and Lung, 2006). In addition, farming systems that encourage shifts from intensive to large-scale monocultures, soil compaction, burning crop litter and loss of hedgerows end up destroying food resources and nesting sites for ground nesting bees (Kinuthia and Njoroge, 2007). Large implements such as mowers and ploughs destroy ground nests of bees and floral resources (Potts et al., 2010; Tschanz et al., 2023).

Human mediated environmental change is now a constant process and modifications in land use, especially agricultural expansion, are among the most damaging to wild bee communities, as former habitat and nesting resources are converted to pasture and farm land (Williams and Kremen, 2007). However, reactions of the different bee communities to the mixed landscape modification varied indicating that wild bees are responding to landscape level changes in local resources (Morandin and Winston, 2005; Potts et al., 2010). Furthermore, these varied reactions are largely dictated by biological traits (Biesmeijer et al., 2006) and certain traits for nesting and behavior constrain certain bee guilds to specific environments (Tscharntke et al., 1998).

4.1 Materials and Methods

4.1.1 Study area

The detailed description of the study area is provided in Chapter Three, Section 3.1.

4.1.2 Site selection

The detailed description of the site selection is provided in Chapter Three, Section 3.2.

4.1.3 Data collection on diversity of bees in Robusta coffee and pumpkin plots

Data collection of bees in Robusta coffee farms was conducted twice in December 2020 to January 2021 and June to July 2021, in which periods substantial flush of flowers occurred. For pumpkins, field work was conducted during two pumpkin growing seasons of July to December 2020 and April to October 2021 depending on when the respective pumpkin gardens flowered. A plot of 100 m^2 was established on each study site and then five sub-plots of 20 m^2 each were set at each corner and center of the plot (Figure 4.1). The three pan traps of different colours (yellow, white and blue) were randomly placed in each sub-plot at a distance of 5 m apart to avoid competition between traps (Droege et al., 2010).

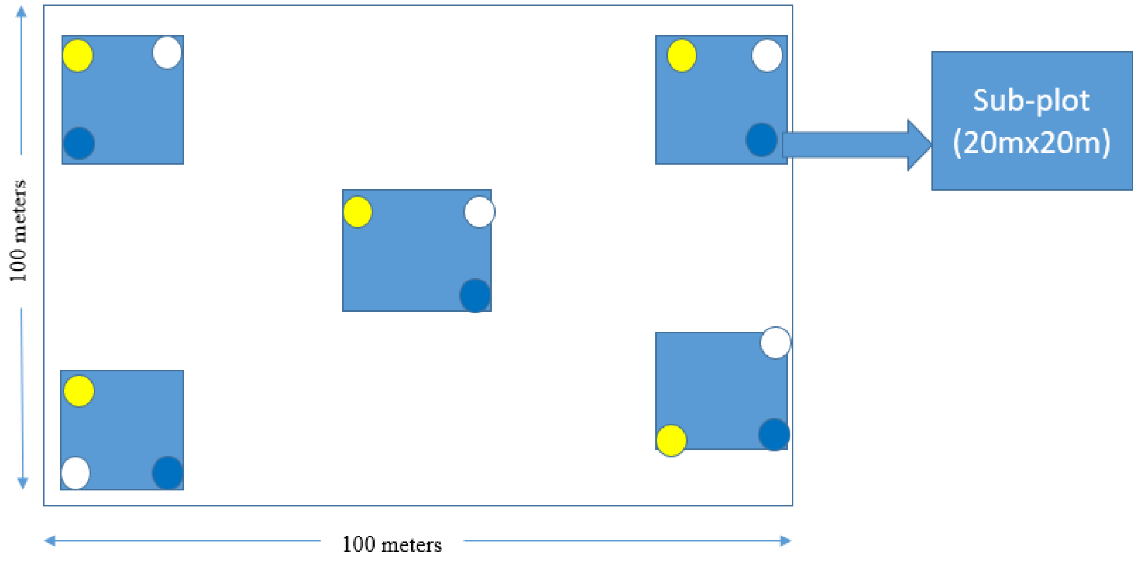

Figure 4.1: A plot of 100 m^2 in the study site with the five sub-plots showing the distribution of the pan traps in the plot.

Different species are attracted to different colours and the colours that were used in the study were identified as the most effective at capturing bees (Tolar, Trdan and Škerget, 2005). A total of 15 pan traps (5 blue, 5 white and 5 yellow) were set per plot. The pan traps were sprayed with fluorescent spray prior to their deployment and left to dry to increase their visibility to insects. Each pan trap was placed on a wooden stake of approximately 50 cm above the ground and partially filled with plain water to which a few drops of scentless liquid soap had been added to reduce on surface tension (Droege, 2015). The pan traps were left and recovered 24 hours later. The captured bees in the pan traps of the same colour were pooled and individually collected using a pair of flathead forceps. A sweep net was also used to capture foraging bees along two 1m x 20m transects for 20 minutes during each of the periods of massive flowering of Robusta coffee and pumpkins when the study was carried out.

The captured bees from pan traps and sweep net were separately preserved in 70% ethanol, labelled appropriately with date, time of capture, method of capture and plot code for transportation to Makerere University laboratory. Bee collections for each day were preserved using the same procedure. At Makerere University laboratory, the collected bees were pinned on stainless steel insect pins of variable sizes (#0, #1, #2 or #3) depending on the bee size. Bees which were smaller (3 mm or less) were glued to pinned card mounts for easy identification.

Data was recorded on; number of bee species captured per plot, bee abundance (number of individual bees captured per species) per plot.

4.1.4 Data Analysis

Data management and storage were conducted using Microsoft Excel 2016. The relative abundance of bees across different cultivation practices was determined using Excel, while bee diversity was analysed with PAST software version 4.03. Prior to analysis, data were tested for normality and homogeneity of variance using the Shapiro–Wilk and Levene's tests, respectively, in PAST. Since bee abundance data (expressed as counts) violated the assumption of normality, they were log-transformed to stabilise variances. Bee diversity assessed using the Shannon–Wiener (H') and Simpson (1–D) diversity indices. These indices were both applied due to their complementary nature: Shannon emphasizes species richness and evenness, while Simpson highlights species dominance. An independent samples t-test was performed in R software version 4.3.1 (R Development Core Team, 2017) to identify significant differences in bee diversity and abundance between open-sun and shaded plots for Robusta coffee, as well as between pumpkin plots located at different distances (≤3 km and >3 km) from potential natural or semi-natural bee habitats.

4.2 Results

4.2.1 Bee diversity in Robusta coffee plots

A total of 853 bee individuals were captured in both shaded and open sun Robusta coffee plots in the study area. The captured bees belonged to three families; Apidae, Halictidae and Megachilidae (Figure 4.2). Open sun plots had a total of 400 bee individuals where family Apidae accounted for 52.7% of its bee population. Additionally, *Hypotrigona* sp. was the most predominant species, with abundance of 52 individuals in the open sun coffee plots. *Lasioglossum atricrum* come second position with 30 individuals, while *Lasioglossum* sp. ranked third with 28 individuals. *Apis mellifera* had a population of 27 individuals. On the other hand, the bee population in shaded Robusta coffee plots was slightly higher with a total of 453 individuals. *Apis mellifera* had 26 individuals while *Megachile rufipennis* followed suit with 16 individuals. Conversely, *Hypotrigona* sp. remained prevalent with 45 individuals, maintaining its dominance in shaded coffee plots. Meanwhile, other bee species like *Lasioglossum* sp. and *Patellapis* sp. were found to contribute 36 and 22 individuals, respectively. Open sun Robusta coffee plots had 10 bee species, 14 bee species in shaded and 45 bee species were present both open and shaded Robusta coffee plots.

The number of bee taxa in shaded and open sun Robusta coffee plots was 59 and 55 bee species respectively (Table 4.1). Shaded coffee plots had a higher number of individuals

(453) compared to open sun plots (400). The number of bee individuals in shaded Robusta coffee plots was higher than in open-sun plots, with a significant difference in the number of individuals (t = 3.2, p = 0.012). Similarly, the Shannon diversity index of bee species in shaded coffee plots was significantly higher than in open-sun coffee plots (t =1.98, p = 0.04). Both plots (shaded and open sun) had the same low dominance index of 0.05. The Simpson's Index of Diversity was 0.95 for both habitats, indicating high and similar levels of diversity. Evenness in the shaded plots and open sun plots were comparable (t = 0.23, p = 0.82).

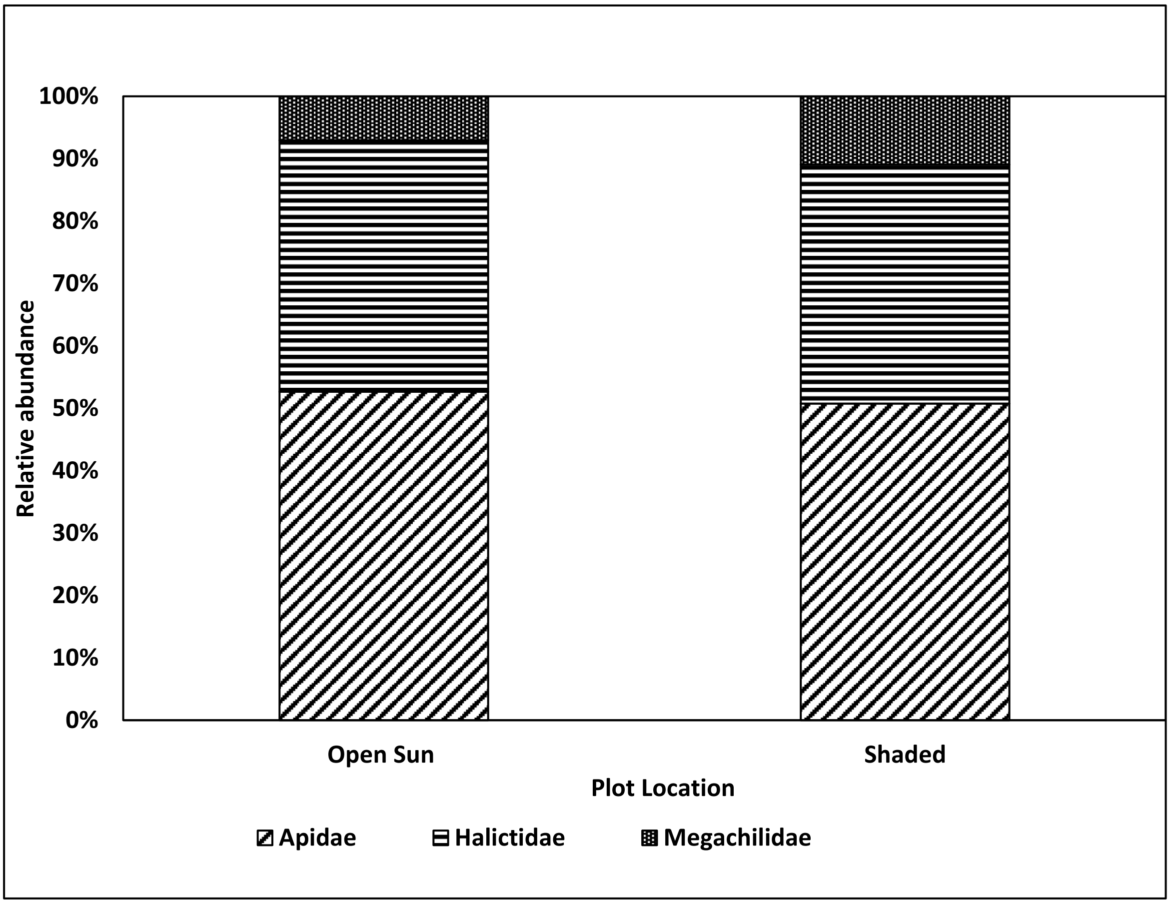

Figure 4.2: Relative abundance of the different families of bees in Robusta coffee under different levels of exposure of the coffee plots to sunlight.

Table 4.1: Diversity of bees in Robusta coffee under different levels of exposure of the coffee plots to sunlight.

Species	Open sun plots	Shaded plots
Taxa_S (Species)	55	59
Individuals	400	453
Dominance_D	0.05	0.05
Simpson_1-D	0.95	0.95
Shannon_H	3.31	3.43
Evenness_e^H/S	0.50	0.52

4.2.2 Diversity of bees in pumpkin plots

A total of 299 individual bees from four families; Apidae, Colletidae, Halictidae, and Megachilidae was captured in all the pumpkin plots (Figure 4.3). The number of individual bees from pumpkin plots ≤ 3 km and > 3 km from potential natural or semi-natural bee habitats were 153 and 146 bees respectively). For pumpkin plots > 3 km from potential natural or semi-natural bee habitats 146 bee individuals were captured during the study period, with *Apis mellifera* and *Hypotrigona* sp. as common species, with 27 and 17 individuals respectively. Other species included *Ceratina* sp., *Braunsapis* sp., and *Ctenoplectra* sp., with 12, 10, and 5 individuals respectively. Conversely, pumpkin plots ≤ 3 km had a slightly higher total of 153 bee individuals. *Apis mellifera* was the most abundant species with 17 individuals, followed by *Ctenoplectra* sp. and *Hypotrigona* sp., both with 15 and 14 individuals respectively. *Patellapis* sp. and *Braunsapis* sp. also exhibited notable presence in these plots with 10 and 8-individuals respectively. The remaining bee species occurred with abundances fewer than 8-individuals. Pumpkin plots ≤ 3 km from potential natural or semi-natural bee habitat had 17 bee species, 16 bee species in pumpkin plots > 3 km while 25 bee species were present in both distances.

The number of bee taxa in pumpkins plots ≤3-km and > 3-km from potential natural or semi natural bee habitats was 43 and 42 bee species respectively (Table 4.2). Pumpkin plots ≤ 3 km from potential natural or semi natural bee habitat had a significantly higher abundance of bees than those > 3 km ($t = 8.5$, $p = 0.01$). Additionally, the Shannon diversity index of bees in pumpkin plots ≤ 3 km, was significantly higher than those > 3 km ($t = 7.02$, $p = 0.02$).

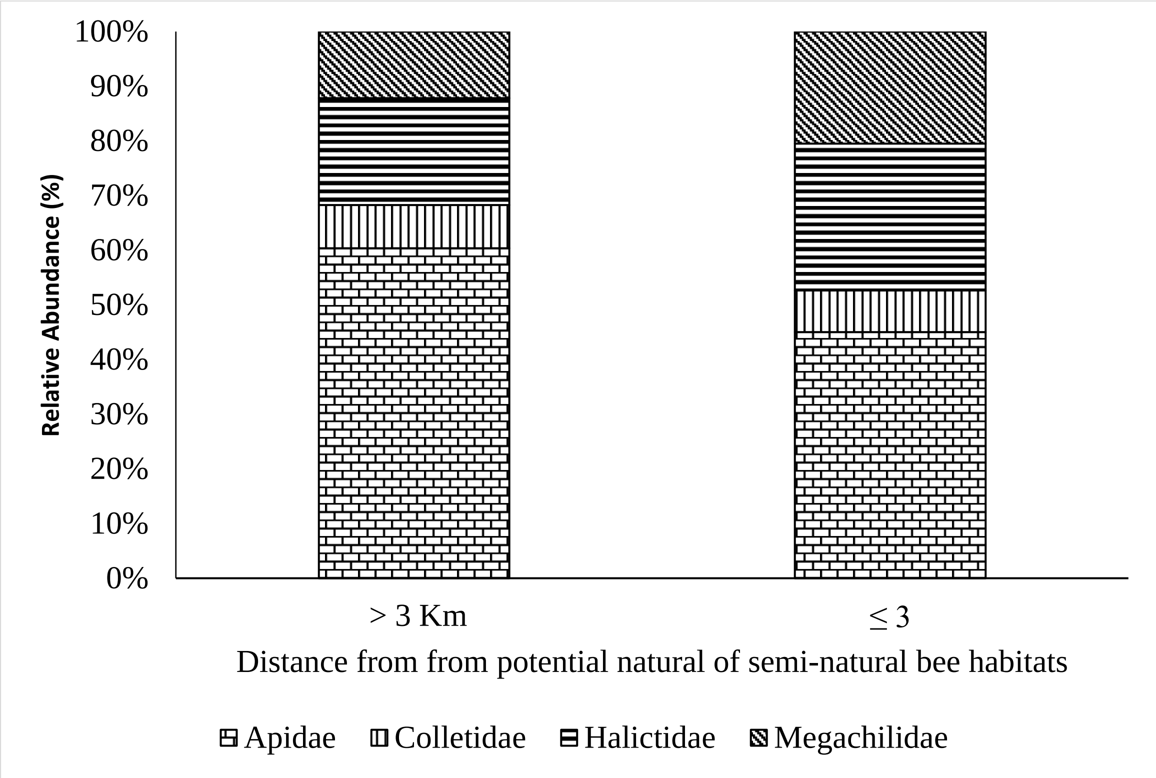

Figure 4.3: Relative abundance of different bee families in pumpkin plots under different distances of the pumpkin plots from potential natural or semi-natural bee habitats.

Table 4.2: Diversity of bees in pumpkin plots under different distances from potential natural or semi natural bee habitats

Index	> 3 Km	≤ 3 Km
Taxa_S (Species)	42	43
Individuals	146	153
Dominance_D	0.27	0.26
Simpson_1-D	0.73	0.74
Shannon_H	1.87	2.33
Evenness_e^H/S	0.23	0.24

4.3 Discussion

4.3.1 Diversity of bees in Robusta coffee plots

This study underscores the critical influence of sunlight exposure on bee diversity and abundance in Robusta coffee plots. Shaded coffee plots supported higher bee diversity and abundance compared to open sun plots. Shade provides favorable microclimatic conditions, such as cooler temperatures and higher humidity, which enhance bee foraging and nesting activity (Jha and Dick, 2010; Classen et al., 2014). These conditions are particularly important in tropical agroecosystems, where high temperatures can limit bee activity This aligns with studies conducted in Uganda and Kenya, where shade-grown coffee systems have been shown to enhance pollinator diversity and contribute to more sustainable agricultural practices (Kasina et al., 2009; Munyuli, 2011). The dominance of *Hypotrigona* sp. in both shaded and open sun plots reflects its adaptability to a variety of environmental conditions, though it exhibited a slight preference for shaded habitats. This finding is consistent with previous studies in Uganda and other tropical regions (Kasina et al., 2009; Otieno et al., 2011). While *Apis mellifera* was observed in both habitat types, its lower abundance could be attributed to the limited floral resources and nesting sites in open sun plots (Klein et al., 2003b).

Shaded Robusta coffee plots harbored a higher number of bee species compared to open sun plots and had a larger number of individual bees. The species unique to shaded Robusta coffee plots likely prefer cooler, humid conditions provided by shade, as observed in other studies (e.g., Winfree et al., 2009; Senapathi et al., 2017). Conversely, species exclusive to open sun plots may have adaptations that allow them to tolerate higher temperatures and greater sunlight exposure. This is consistent to studies that showed that certain bee species are better adapted to open, sunlit environments hence can exploit floral resources that may not be available in shaded areas (Kasina et al., 2009); Otieno et al., 2011). The presence of species unique to each habitat suggests that both shaded and open sun coffee systems are important for maintain overall bee diversity which is important for the complimentary pollination services of coffee and other crops that enhance crop yields and quality (Klein et al., 2003a; Perfecto et al., 2007).

Shaded Robusta coffee plots exhibited a higher Shannon diversity index than open sun plots, indicating that shaded Robusta coffee systems support a more diverse bee community. This is consistent with other studies that highlighted the role of agroforestry, such as maintaining shade trees in coffee plantations in enhancing biodiversity (biodiversity (Perfecto et al., 2007; Ricketts et al., 2004) The Simpson diversity index (1-D) was also higher in shaded plots compared to open sun plots, indicating a more balanced distribution of species abundance. Evenness of bee species was comparable between shaded and open sun plots, suggesting a relatively even distribution of individuals among species across both cultivation practices.

A t-test revealed a significant difference in bee abundance between shaded and open sun plots, suggests the positive role of shaded conditions in promoting bee abundance in Robusta coffee. These findings support previous research, which demonstrated that shade-grown coffee agroforestry systems enhance pollinator diversity (Perfecto et al., 2007; Ricketts et al., 2004). Shade in Robusta coffee provided favourable conditions foe bees likely due to the availability of diverse floral resources, cooler temperatures and more stable microclimate (Classen et al., 2014; Jha and Dick, 2010).

4.3.2 Diversity of bees in pumpkin plots

This study reveals that pumpkin plots ≤ 3 km from potential natural or semi-natural bee habitats host a more diverse and abundant bee community than those located >3 km. Proximity to potential natural or semi natural bee habitats increases access to essential resources such as diverse floral species and nesting sites, which promote pollinator activity (Garibaldi et al., 2011; Kennedy et al., 2013). *Apis mellifera* was the most abundant species in both distances, highlighting its dominance as a key pollinator in agricultural landscapes (Gikungu et al., 2006; Ricketts et al., 2008). Other species, like *Hypotrigona* sp. and *Ctenoplectra* sp., were common at both distances, indicating their adaptability to varying distances. However, higher abundances of these species were recorded in plots ≤ 3 km from natural habitats, reflecting the role of these habitats as critical refugia for pollinators**.**

Bee species richness was slightly higher in pumpkin plots ≤ 3 km than in those > 3 km. The presence of unique species in plots ≤ 3 km may be due to the availability of more diverse floral and nesting resources. Conversely, species unique to plots > 3 km may have evolved to tolerate the less favorable conditions further from natural habitats. However, the number of shared species between the two distance categories indicates the adaptability of many species to different environmental conditions. These findings show the importance of natural or semi-natural habitats in maintaining bee diversity in agricultural landscapes. The presence of unique species in pumpkin plots closer to natural habitats highlights the role of these areas as reservoirs of pollinator diversity, providing essential resources such as nesting sites and diverse floral resources (Ricketts et al., 2008; Garibaldi et al., 2011). This is consistent with previous studies that have shown that proximity to natural habitats can significantly enhance pollinator diversity and abundance in adjacent agricultural fields (Kremen et al., 2007).

Similarly, the presence of unique species in pumpkin plots located >3 km from potential natural or semi natural bee habitats suggests that some bee species may be more resilient to habitat fragmentation and can thrive in more modified environments. However, the overall lower diversity in these plots compared to those closer to natural habitats indicates that distance from these habitats can negatively impact bee diversity, likely due to reduced availability of essential resources (Winfree et al., 2009). Pumpkin plots ≤ 3 km from potential natural or semi natural bee habitats exhibited a higher Shannon diversity index compared to plots >3 km, suggesting that the nearer to potential natural or semi natural bee habitats not only increases the number of individual bees but also enhances species diversity and evenness. This finding is consistent with previous research that shows that landscapes with greater connectivity to natural habitats tend to support more diverse and stable pollinator communities (Garibaldi et al., 2011; Winfree et al., 2011). The Simpson diversity index (1-D) was slightly higher in plots ≤ 3 km (0.74) compared to plots > 3 km, further highlighting the role of these habitats in maintaining a balanced bee community structure, where no single species overwhelmingly dominates.

Additionally, the dominance index (D) was lower in plots ≤ 3 km compared to plots > 3 km, indicating that bee species in ≤ 3 km were more evenly distributed, with no single species dominating. This supports the hypothesis that natural habitats contribute to reducing the dominance of any one species, promoting a more diverse and resilient pollinator community (Kennedy et al., 2013). These results also reflect the potential impact of habitat fragmentation, since plots >3 km from potential natural or semi natural bee habitats exhibit lower diversity and abundance. These could probably due to reduced resource availability and increased isolation from source populations (Steffan-Dewenter and Tscharntke, 1999).

Pumpkin plots ≤ 3 km from potential natural or semi natural bee habitats recorded a significantly higher bee abundance than those > 3 km. This higher abundance may be attributed to the proximity of foraging and nesting resources in natural habitatswhich are essential for supporting diverse bee communities (Klein et al., 2003a). The presence of unique bee species in plots ≤ 3 km further emphasizes the role of nearby natural habitats in supporting diverse pollinator communities. Natural or semi-natural habitats play a critical role in supporting pollinator communities. The higher diversity, abundance, and evenness of bees in plots closer to natural habitats highlight the importance of landscape connectivity in agricultural systems (Garibaldi et al., 2011; Kennedy et al., 2013). Pollinators like *Braunsapis lyrata* were less abundant in plots > 3 km, indicating that some species may be more sensitive to habitat fragmentation (Winfree et al., 2009).

4.4 Conclusions

Overall, this study shows that shaded Robusta coffee agroforestry systems provide suitable conditions for diverse bee communities. The greater diversity and abundance of bees in shaded plots underscore the role of shade as a crucial component in sustainable coffee production. While some species are adaptable to both shaded and open sun environments (e.g., *Hypotrigona* sp.), others exhibit habitat-specific preferences, with more species favoring shaded plots. This highlights the importance of maintaining shade trees in coffee plantations as part of sustainable agricultural practices that support biodiversity conservation and improve pollination services and hence improved crop yield.

The study also highlights the importance of natural habitats in supporting bee diversity and abundance in pumpkin farms. Proximity to natural habitats significantly enhances species richness, abundance, and community evenness. The greater number of unique species and higher diversity indices in plots $\leq$ 3 km from natural habitats underscore the role of these areas as pollinator refuges. These findings have important implications for landscape management, emphasizing the need to conserve natural habitats near farmlands to promote pollinator biodiversity and improve crop yields.

4.5 Recommendations

1. Robusta coffee farmers should consider increasing shade in their plantations to foster greater bee diversity and abundance since shaded environments offer diverse resources and microclimatic benefits that support a richer bee community.
2. Conservation practices that may include preserving natural vegetation and ensuring a variety of floral resources should be promoted so as to protect and enhance habitat quality in shaded coffee systems.
3. To optimize pollinator diversity and crop yields, farmers should manage agricultural landscapes by preserving or restoring natural habitats close to crop fields, such as creating buffer zones or corridors.
4. More research should focus on the long-term effects of different shading practices on bee populations and coffee production, as well as identifying specific tree species that best support both Robusta coffee growth and pollinator diversity. This will help develop more resilient and sustainable coffee agroforestry systems in Uganda and other coffee-producing regions.
5. Encouraging farmers to adopt sustainable practices, such as organic farming and reduced pesticide use, can help create a more conducive environment for pollinators..

CHAPTER FIVE: CONTRIBUTION OF BEES TO THE YIELD OF ROBUSTA COFFEE AND PUMPKINS UNDER DIFFERENT CULTIVATION PRACTICES IN SELECTED DISTRICTS OF CENTRAL UGANDA

Abstract

This study aimed to investigate how different cultivation practices affected bee diversity, abundance, and their contribution to the yield of Robusta coffee and pumpkins in the central Ugandan districts of Nakaseke, Luwero, and Kayunga districts. Pollination exclusion field experiments were conducted from July 2020 to April 2022 on shaded and open sun Robusta coffee plots and in pumpkin plots ≤ 3 km or > 3 km from potential natural or semi-natural pollinator habitats. ANOVA was used to assess the role of bees in the yield of the two crops. Bee-mediated pollination in shaded Robusta coffee plots significantly enhanced fruit set and reduced the proportion of pea berries. For pumpkins, Plots located ≤ 3 km from potential natural or semi-natural bee habitats recorded higher pollination success, larger fruit mass, and more seeds compared to those located >3 km. The findings emphasize the importance of agroforestry systems and the proximity of crops to pollinator habitats as essential factors in sustaining bee populations and maximizing crop production for economically valuable crops like Robusta coffee and pumpkins in Uganda.

5.0 Introduction

More than 9 billion kilograms of coffee is consumed annually worldwide (International Coffee Organization 2016), suggesting that coffee is one of the most widely consumed beverages in the world. The coffee industry directly involves 25 million farmers globally and indirectly employs 125 million people with a global coffee market valued at USD 384.85 billion in 2021 and projected to reach USD 497.89 billion by 2028 (Donald, 2004**).** It is the world's second most important legally traded commodity after oil (Daviron and Ponte, 2005). In Uganda, it is a key export commodity for example, coffee exports for the 12 months (September 2020 - August 2021) amounted to 6,414,696 60-kilo bags worth US$ 607.81 million (UCDA, 2021). The Ugandan government has a target of producing 20 million 60-kilo bags of coffee beans per year by 2030 (TRIDGE, 2020). Proper agronomic practices that preserve biodiversity will have to be prioritized in order to achieve these targets since insect pollinators including bees increase the yield of Robusta coffee.

In Uganda, Robusta coffee is grown mainly in central Uganda and some parts of western Uganda and these accounts for 7% of global Robusta coffee exports, providing a livelihood to about 8 million people in Uganda (UCDA, 2017). Planting coffee under shade trees is a common practice in Uganda. The shade canopy usually consists of native tree species which play a role in reducing light intensity within the coffee, they also protect against temperature variability, erosion, and, excessive radiation (Piato et al., 2020). Shade trees in coffee farming is very important because they provide a means of mitigating against excessive temperatures and heat stress that are responsible for flower and fruit abortion due to climate change (Gosden., 2024). Shade in coffee alters ecological and microclimatic factors in a favourable way by decreasing extreme temperatures and reducing hydric stress by increasing relative humidity thereby improving on biodiversity (Partelli et al., 2014).

Coffee bean yield increases with higher diversity and abundance of insect pollinators including bees that visit during the blooming flower season (Klein et al., 2003a). An increase by more than 50% is observed compared to if only pollinated by the wind (Krishnan et al., 2012). Biodiversity of pollinators improve yields by 30% (Hipólito et al., 2012). Therefore, coffee management strategies to conserve pollination services on a farm is needed and agroforestry to provide the coffee with shade is one of them. Shade in coffee play an essential role in the life quality of insect pollinators including bees (Smith and Johnson, 2022). The total nitrogen content in coffee flower pollens protected by the shade is higher than that in coffee pollens that are exposed to light intensities (Prado et al., 2012). The Nitrogen content in pollen may increase the life quality of insect pollinators for the sufficiency of their feed nutrition. Coffee shade trees influence the climate factors, i.e., temperature, humidity, and light intensity around coffee (Mariño et al., 2016). These may also influence the behavior and population of insect pollinator including bees and hence improved coffee yield. Despite these benefits, there is still a limited understanding of the contribution of shade to bee pollinators behavior and hence Robusta coffee yield. This study seeks to get information on the interaction of shade on Robusta coffee, bee pollinators and hence to coffee. The information on the relationship between shade on coffee and insect pollinators is vital to manage shade trees in coffee plantations, which will provide benefits, both for the growth of coffee and insect pollinators to increase coffee bean yield.

However, the effects of shade on coffee bean size can be explained by the fewer branches produced under shade, with smaller number of nodes per branch, and fewer numbers of flowers per node (López-Bravo et al., 2019). These shade impacts contribute to a reduced fruit load under shade (Vaast et al., 2006). Moreover, shade also lowers the tree stress and hence favors slow fruit ripening, better filling of beans which increases bean size, and ultimately cup quality (Vaast et al., 2006). Vaast and Raghuramulu (2012) showed that the effects of shade on Robusta coffee bean size were largely dependent on the shade trees selected and rainfall conditions. Under low rainfall conditions, Robusta intercropped with *Artocarpus heterophyllus, Dalbergia latifolia*, and *Lagerstroemia microcarpa* had a higher percentage of larger than normal coffee bean size compared to those intercropped with *Grevillea Robusta*. However, Robusta coffee intercropped with *A. heterophyllus* or *G. Robusta* provided lower coffee bean percentage under high rainfall. Another study also reported that the bean percentage was strongly and positively influenced by the density of non-*Grevillea* shade trees but not by that of *G. Robusta* (Boreux et al., 2016). Recent studies from Cambodia showed that coffee bean size, as well as fruit ripening and yield, were not affected by shade trees (Ehrenbergerová et al., 2021).

The effect of shade on coffee depends on the tree species used and the physical features of the site (Avelino et al., 2020; Sarmiento-Soler et al., 2020). Shade tree type impacts significantly to the infestation of black coffee twig borer *Xylosandrus compactus* (Eichhoff), a pest which severely affects Robusta coffee plantations, including in Uganda (Bukomeko et al., 2018). However, Bukomeko et al. (2018) showed that mature shade trees and sap-exuding herbaceous plants such as *Carica papaya* significantly reduce black coffee twig borer on Robusta coffee plants. Besides tree type, the effects of shade on coffee can be site-specific thus depending on the clone selected and the site conditions (Montagnon et al., 2000). Generally, shade impacts positively both on growth and productivity of Robusta coffee (Piato et al., 2020). Nevertheless, shade on coffee plantations have been reported to have negative effects on growth and yield, exacerbating pest and disease problems (Avelino et al., 2020; Durand-Bessart et al., 2020). Venancio et al. (2019) found that shade reduced the average number of fruits per inflorescence, suggesting that vegetative growth may compete with fruit production. Furthermore, Venancio et al. 2019) showed that medium shade levels (i.e., 30–50%) may increase the proportion of cherries that are marketable.

Pumpkins are a source of income to small scale farmers in Uganda. They also provide a healthy diet due to the presence of carotenoids that have major roles in nutrition since they are a rich source of vitamin A (See et al., 2007). They are also rich in macro- and micro nutrients and antioxidants that promote the human body immunity against cancer and other diseases (Kiharason et al., 2017). The *C. pepo* species are usually recognized as the true pumpkin. The plants are typically monoecious and have imperfect flowers with separate individual male and female flowers on the same plant. Female flowers develop pumpkins after successful pollination and fertilization and can be identified by the stigma in the center of the flower and by a wider flower stem that resembles a small, immature fruit. Male flowers produce pollen to fertilize female stigmas and can be identified by the anther in the center of the flower and by a narrower flower stem. When open and receptive, female stigmas have a multifaceted shape with multiple sticky, shiny "knobs" while male anthers are simpler in shape with a single projection and appear dusty when releasing pollen (Robinson and Decker-Walters, 1997).

Pollination services to cucurbit crops by wild bees have been shown to relate to the amount of natural habitat surrounding a site. Pumpkin yield is strongly associated with the proportion of semi natural or natural habitat within a 1 to 2.5 km radius of farm site (Kremen et al., 2004). Kremen et al. (2002) showed that wild bee populations vary with cultivation practices and the distance from farms to natural pollinator habitats; farms that were near natural pollinator habitats hosted many wild bees to provide full pollination services for watermelon. Takashi and Kazuo. (2013) showed that the closer the proximity of a natural pollinator source and pumpkin field becomes, the higher the visitation rate by honey bees per pumpkin flower in the field. The higher the number of visits of honey bees the greater the fruit set, fruit size, and fruit weight of pumpkins (Nicodemus, 2009). Hence, cultivation practices like proximity to a natural pollinator source encourages wild pollinator populations and hence provide insurance against pollination losses. Improving the quantity and quality of pollen and nectar resources available for pollinators like bees, allowing areas to remain undisturbed for them to nest, mate, and hibernate benefits pollinator populations and therefore reduce pollination deficits (Bommarco et al., 2013). Wild flowers such as agricultural weeds and hedgerow flowers are important floral resources for pollinators, bees inclusive. Wild flowers co-flowering with crops increases bee abundance in *Cucurbita pepo* (Knapp et al., 2018; Bretagnolle and Gaba, 2015). Generally, pollination studies in pumpkins reveal that presence of wild habitats enhances pollinator activity in the surrounding agricultural fields. Most pollinators and especially bees need natural plant remnant habitats for foraging purposes, nesting or oviposition, source of water, mating and roosting caves (Roubik, 1995; Ricketts, 2004). Loss of natural habitats constrains the foraging ranges of bees (Kearns, 2001; Kremen et al., 2002). Therefore, most pollinator species that remain in the natural habitats interact with agricultural ecosystems. However, the contribution of management type to these species' survival is often ignored, as is the potential value of agroecosystems for conservation (Klein et al., 2002). Thus, this objective assesses the contribution of bees to the yield of Robusta coffee and pumpkins and assesses the influence of shade and distance from potential natural or semi natural pollinator habitats on yield of Robusta coffee and pumpkins respectively.

5.1 Materials and Methods

5.1.1 Study area

The detailed description of the study area is provided in Chapter Three, Section 3.1.

5.1.2 Site selection

The detailed description of the site selection is provided in Chapter Three, Section 3.2.

5.1.3 Pollination exclusion experiments on Robusta coffee and pumpkins

A total of six pollination exclusion experiments was conducted twice on the same plots when substantial flush of Robusta coffee flowers occurred. A total of 24 study sites were sampled during the first substantial flowering period and 23 sites during the second. For the first season, shaded coffee plots and open sun coffee plots were 12 each (24 in total), and a total of 23 sites for the second trial (11 shaded plots and 12 open sun plots). In each study site, a plot of 100 m^2 was demarcated. Ten healthy Robusta coffee plants were randomly selected per plot (10 plants/plot). From each of these plants, six branches well matched in length, shade, vertical position, and with whorls or clusters of floral buds were randomly selected (60 branches/plot). Each branch was tagged and labeled for visibility during monitoring using brightly coloured ribbons. From each branch, one cluster with 10 floral buds was selected (600 floral buds /plot).

The six pollination treatments per coffee plant was as follows: (1) Spontaneous self-pollination (SS); 10 floral buds in a branch were bagged with pollinator exclusion bags of very fine nylon mesh gauze (10 µm). (2) Open pollination (OP):10 floral buds in a branch were marked but left unbagged. (3) Wind pollination (WP): 10 floral buds in a branch were bagged with pollinator exclusion bags with 0.8 - 1 mm openings. It excluded insect visitors but theoretically permitted airflow with pollen grains (Robusta coffee pollen grains size is approximately 0.03mm). (4) Manual cross-pollination (CP): A cluster with 10 floral buds was bagged with very fine nylon mesh gauze (10µm). One day to anthesis, each floral sprout was hand emasculated by carefully removing the petals of each floral sprout. To manual-pollinate, dehiscing anthers were clipped off from three flowers from neighboring Robusta coffee plants using forceps. The clipped anthers were placed into a 1.5 ml Eppendorf tube and mixed together. A small hair paint brush was used to transfer the pollen from the tube to the stigmas of the emasculated flowers then re-bagged immediately. (5) Manual self-pollination (SP): A cluster with 10 floral buds was bagged with very fine nylon mesh gauze (10µm). One day to anthesis, each floral bud was hand emasculated by carefully removing the petals of each floral bud. To manual-pollinate, dehiscing anthers were clipped off from three flowers from the same plants using forceps. The clipped anthers were placed into a 1.5 ml Eppendorf tube and mixed together. A small hair paintbrush was used to transfer the pollen from the tube to the stigmas of the emasculated flowers then re-bagged immediately. (6) Single Bee Visit (SBV); The flowers were bagged with very fine nylon mesh gauze of 10µm before anthesis. One day to anthesis, each floral bud was hand emasculated by carefully removing the petals of each floral bud. At anthesis, the cluster was unbagged so that bees could visit the still virginal flower. After a single bee visited one or several single flowers, the cluster was securely re-bagged immediately after the visiting bee exited the cluster to avoid further visits of pollinators. A bee visit was defined as occurring when a bee touched the stigmas of the flower.

Five weeks after the end of the major flowering period (after the substantial flush of flowering), unbagging was done. The total number of green swollen ovules per cluster in a branch was counted for each treatment to measure the percentage fruit set (Klein et al., 2003a). Mature coffee berries were harvested after 10 - 11 months. Only undamaged, non-predated, fully ripe coffee berries, as determined by the bright red color of their skin, were harvested. The fresh weight of the berries for each cluster for each pollination treatment was measured using an electronic weighing scale sensitive to 0.01g. Fruits predated upon by the coffee berry borer beetle (with visible entry holes) were not considered.

Data was recorded per treatment on: Number of fruits set per cluster after five weeks. At harvest; fresh weight of the coffee berries in grams per cluster, Number of coffee berries per cluster, and quality of coffee berries. Quality coffee berries here are the normally developed coffee berries with two ovules and not the misshapen or deformed pea berries where only one ovule matures and one is aborted (Klein et al., 2003c; Free, 1993).

For pumpkins, the experiments were conducted for two growing seasons (August – December 2020 and April – August 2021) on 16 study sites. In each study site, five pollination treatments were set up. For each treatment, eight virgin pistillate pumpkin flowers in the bud stage were randomly selected per study site (40 pistillate flowers/study site). Hand-pollination was conducted between 07.00 and 11.00 to ensure pollen viability and stigma receptivity (Pfister et al., 2017). Stigmas are normally receptive until 13.30 (Nicodemo et al. 2007) and although pollen viability decreases during anthesis, it is predicted to be 75% at 13.00 (Nepi and Pacini, 1993). Effort was taken to pollinate the first female flower of a plant to avoid enhanced abortion rates through first-fruit dominance, thereby maximizing the chance of measuring seed set (Pfister et al., 2017).

The experiments were conducted during sunny or cool weather and not during rainy weather. The five treatments included: (1) Spontaneous self-pollination (SS): 8 pistillate flowers in the bud stage were bagged with pollinator exclusion bags of fine nylon mesh gauze (10 µm) to exclude insect and wind pollination thereby testing for possible parthenocarpy. (2) Open pollination (OP): 8 pistillate flowers in the bud stage were marked but left unbagged. (3) Manual self-pollination (SP), within the plant by hand:8 pistillate flowers in the bud stage were bagged with very fine nylon mesh gauze (10µm). To manually pollinate at anthesis, anthers rich in pollen grains from three decapitated staminate flowers from the same plant were transferred by hand and gently rubbed onto the stigma of one pistillate flower then re-bagged immediately and the process was repeated for each of the remaining 7 flowers. (4) Manual cross-pollination (CP), between plants by hand; 8 pistillate flowers in the bud stage were bagged with very fine nylon mesh gauze (10µm).

To manually pollinate at anthesis, anthers rich in pollen grains from three decapitated staminate flowers from different plants in the same plot were transferred by hand and gently rubbed onto the stigma of one pistillate flower then re-bagged immediately and the process repeated for each of the remaining 7 flowers. (5) Single Bee Visit (SBV): 8 pistillate flowers in the bud stage were bagged with very fine nylon mesh gauze of 10µm before anthesis. At anthesis each of the pistillate flowers was unbagged and one at a time a single bee visit on the still virginal pistillate flowers was observed and securely re-bagged immediately after the visiting bee exited the flower. After 7 days, all the unbagging was done and fruit set for each treatment was recorded. The mature pumpkins were harvested after 3 – 4 months and fruit weight of each pumpkin for each treatment was determined using an electronic balance weighing scale sensitive to 0.0 g.

Data was recorded per treatment on: Fruit set after 7 days, fruit weight at harvest in kg, and number of seeds per fruit at harvest.

5.1.4 Data analysis

Data management and storage was done using Microsoft Excel 2016, while data analysis was conducted with various tools, including R Software (Version 4.3.1, R Development Core Team 2017), PAST Software (Version 4.03), and IBM SPSS Statistics 25. A one-way analysis of variance (ANOVA) was conducted in R to evaluate significant differences in the mean mass of harvested Robusta coffee and pumpkin fruits, and the mean percentage mass of coffee berries and pumpkin fruits. Where significant variations were detected, a post hoc Tukey test was used to identify the sources of these differences.

5.2 Results

5.2.1 Contribution of bees to fruit set and yield of Robusta coffee

Overall, coffee plants grown in shaded areas had higher percentages of fruit set after five weeks compared to those grown in open environments, except for those exposed to Spontaneous Self-pollination, Wind pollination, and Manual self-pollination (Figure 5.1). Among the different pollination treatments, open pollination resulted in the highest percentage of coffee fruit set after five weeks, while spontaneous self-pollination resulted in the lowest values.

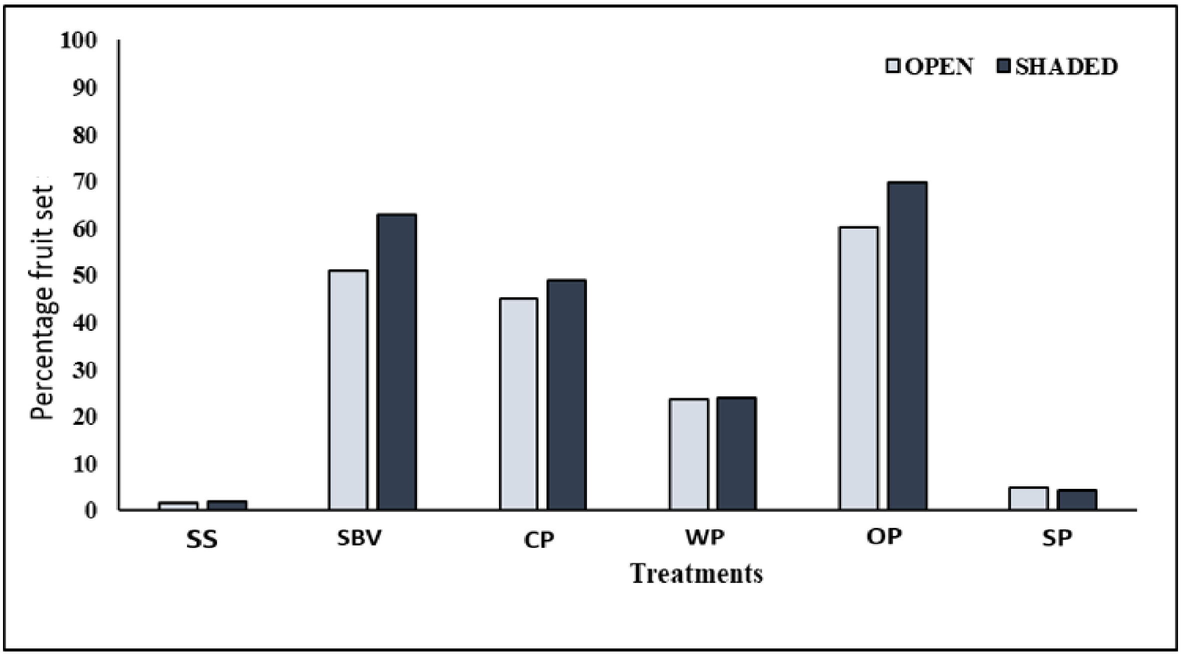

Figure 5.1: Percentage fruit set in Robusta coffee after five weeks under different pollination treatments exposed to varying levels of sunlight. Key: **SS** – Spontaneous Self-pollination, **SBV** – Single Bee Visit, **CP** – Manual Cross-pollination, **WP** – Wind pollination, **OP** - Open pollination, **SP** – Manual Self-pollination.

The mean mass of coffee fruit harvested across the different pollination treatments ranged from 0.2 ± 1.1 g to 3.8 ± 2.5 g for Open-sun coffee plants and 0.1 ± 0.9 g to 6.6 ± 3.3 g for shaded coffee plants. There was no significant variation in the mass of coffee berries among the different pollination treatments under open sun plots ($F_{(5, 388)} = 2.42$, $p = 0.09$). However, there was a significant difference in the mass of coffee berries harvested among the six pollination treatments under shaded plots ($F_{(5, 334)} = 128.42$, $p < 0.001$) (Figure 5.2). Post hoc Tukey test revealed that spontaneous self-pollination and manual self-pollinated coffee did not exhibit significant variation from each other. Similarly, single bee visit, manual cross-pollination, open pollination, and wind pollination did not show significant difference from each other. However, the mass of coffee berries produced by the single bee-visited coffee flowers varied significantly from those of manual self-pollination treatments.

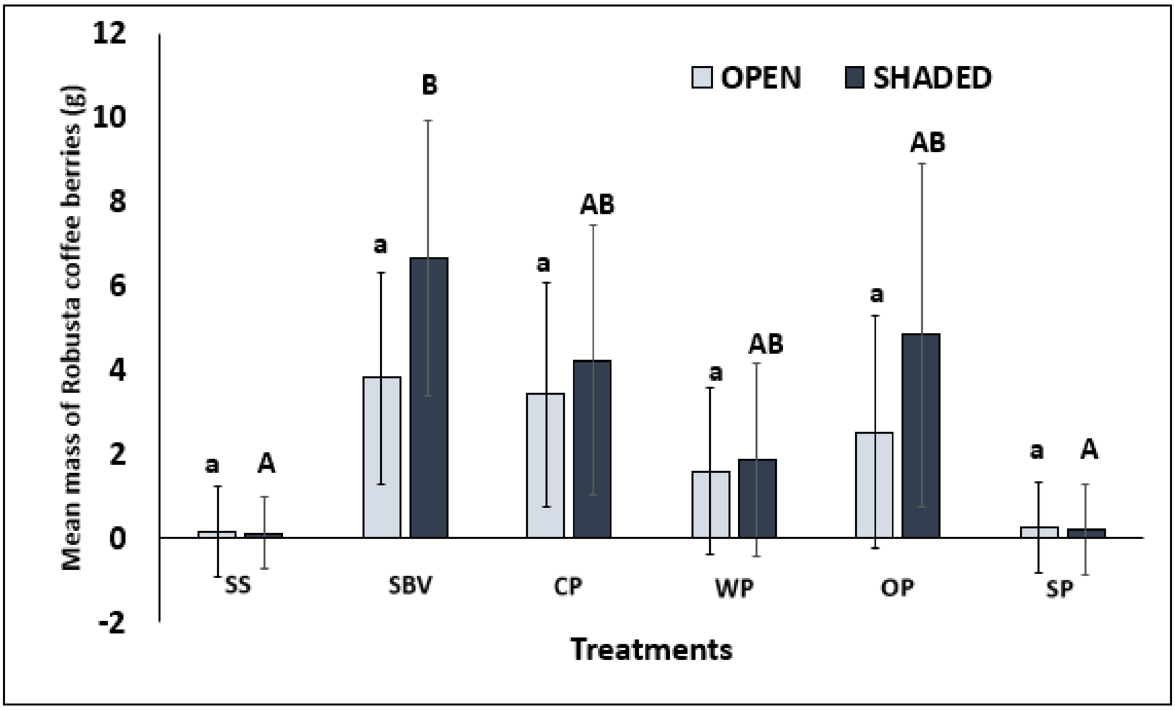

Figure 5.2: Mean mass of Robusta coffee berries at harvest under different pollination treatments exposed to varying levels of sunlight. **Key: SS** – Spontaneous Self-pollination, **SBV** – Single Bee Visit, **CP** – Manual Cross-pollination, **WP** – Wind pollination, **OP** - Open pollination, **SP** – Manual Self-pollination. ANOVA: ($F_{(5, 334)}$ =128.42, $p< 0.001$) for **Shaded plots** and ($F_{(5, 388)}$ =2.32 p =0.09) for **open sun plots**. Different small letters mean significant differences in treatments under open sun at p-value < 0.05. Different capital letters mean significant difference under shade at p-value < 0.05. Overlapping error bars within and between clusters indicate no significant difference in treatment.

Generally, the average yield of pea berries in open sun Robusta coffee plots was higher than shaded plots (Figure 5.3).

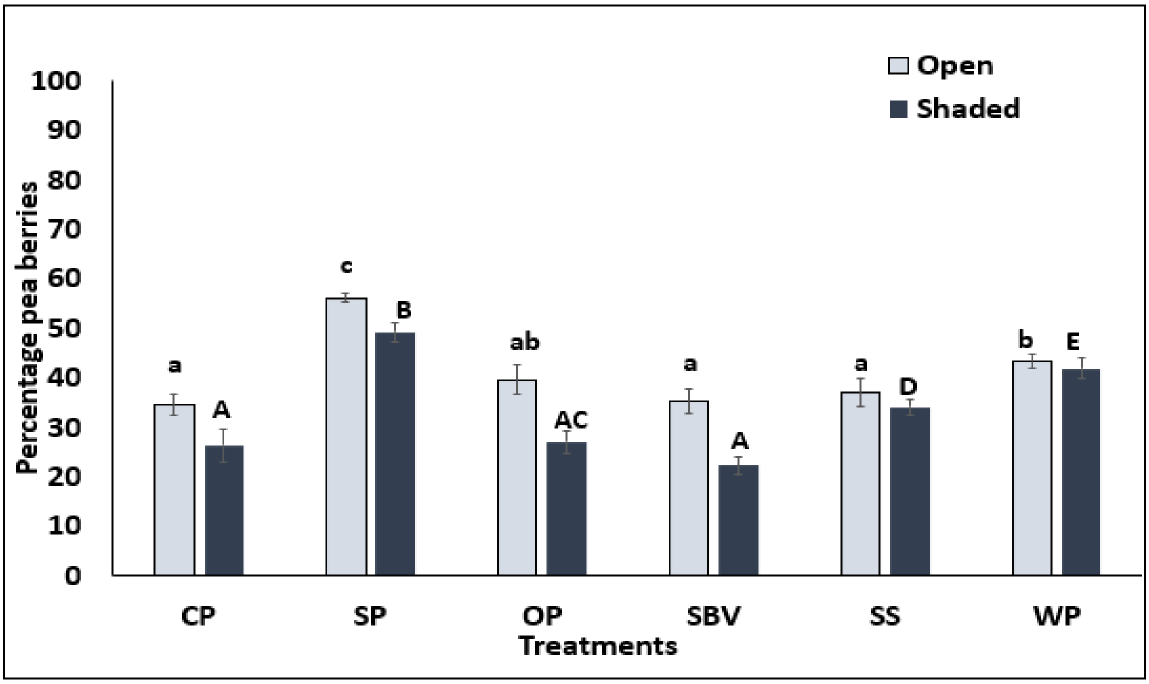

Figure 5.3: Mean percentage of coffee pea berries at harvest under different pollination treatments exposed to varying levels of sunlight. **Key: SS** – Spontaneous Self-pollination, **SBV** – Single Bee Visit, **CP** – Manual Cross-pollination, **WP** – Wind pollination, **OP** - Open pollination, **SP** – Manual Self-pollination.

There were significant differences in pea berry formation among the different pollination treatments, regardless of whether they were conducted in open sun or shaded Robusta coffee gardens. The average yield of pea berries in open sun plots varied significantly between the six treatments, with mean values ranging from 34.5 ± 2.1 to 56.36 ± 1.5 ($F_{(5, 410)} = 18.81$, $p < 0.01$). A post hoc test revealed that Single bee visited flower, cross-pollination, Spontaneous Self-pollination, and open pollination did not differ significantly in pea berry coffee. However, these four treatments differed significantly from Manual self-pollination clusters and wind pollination. Similarly, in the shaded environment, there was a significant variation in pea berry production among the treatments, with mean values ranging from 22.3 ± 1.8 to 49.3 ± 1.9 ($F_{(5, 388)} = 12.12$, $p < 0.01$). However, post hoc analysis found no significant variation between Single Bee Visit, Manual Cross-pollination, and Open pollination treatments. Meanwhile, these three treatments differed significantly from Manual Self-pollination and wind pollination.

5.2.2 Contribution of bees to the yield of pumpkins

Generally, pumpkins planted ≤ 3 km had better pollination success than those > 3 Km (Figure 5.4).

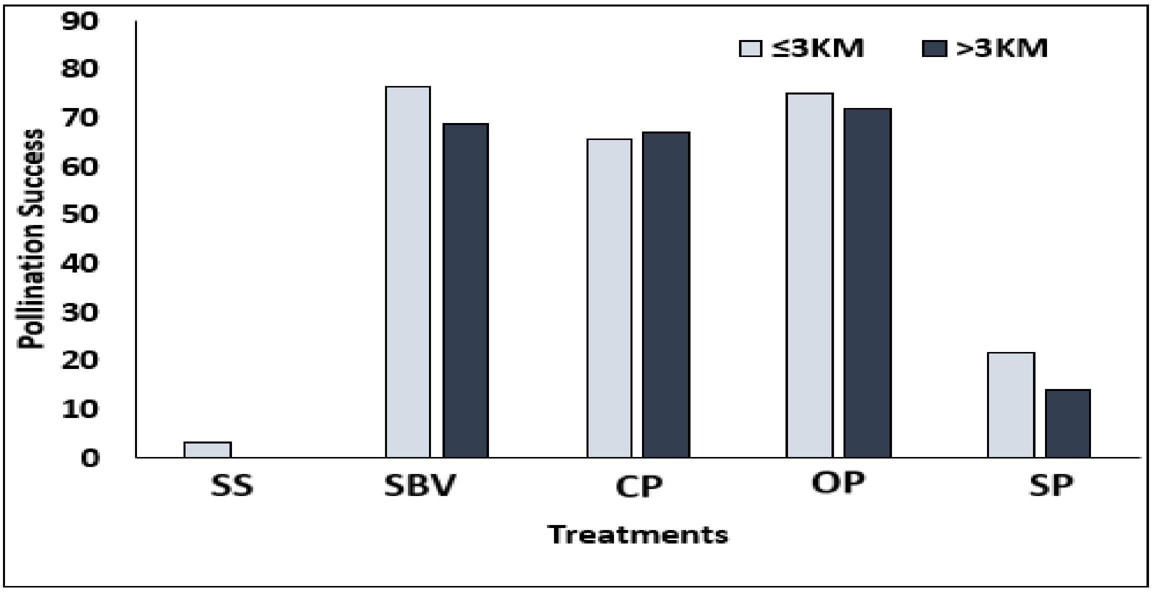

Figure 5.4: Percentage pollination success of pumpkins under different pollination treatments located at varying distances from potential natural or semi-natural bee habitats. **Key: SS** – Spontaneous Self-pollination, **SBV** – Single Bee Visit, **CP** – Manual Cross-pollination, **OP** - Open pollination, **SP** – Manual Self-pollination

Among the five different pollination treatments carried out, the single bee visit treatment had the highest success rate, with 76.6% of flowers being successfully pollinated. Open pollination also performed well, with a success rate of 75%, manual cross-pollination was the third best, while manual self-pollination treatments was the second last in pumpkin pollination success rates. On the other hand, spontaneous self-pollinated pumpkin flowers showed poor performance, with a fruit success of less than 5%.

At a distance of ≤ 3 Km away from potential natural or semi-natural bee habitats**,** mean mass of pumpkin fruits for the five pollination treatments ranged from 0 to 3 kg ± 1.8 while at a distance of > 3 Km, the mean pumpkin fruit mass for the five pollination treatments ranged from 0 to 3 kg ± 1.2 (Figure 5.5). There were significant variations in pumpkin fruit mass among the five treatments at both distances, with a *p*-value less than 0.05. The Turkey post hoc test identified that at distances of ≤ 3 Km, single bee visit, open pollination, and cross-pollination had similar fruit mass, which was significantly different from self-pollinated pumpkin. Meanwhile, at distances > 3 Km, single bee visit, open pollination, and cross-pollination had similar fruit mass, but only cross-pollination differed significantly from self-pollinated pumpkin. Bagged flower of pumpkin did not produce any fruit.

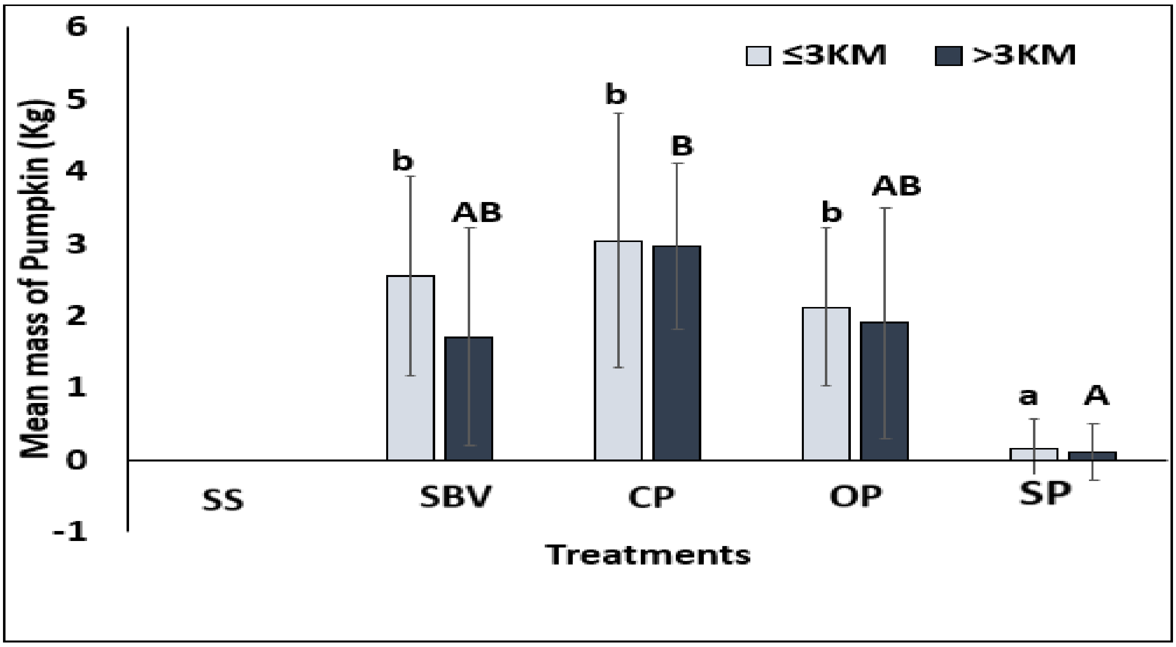

Figure 5.5: Mean mass of pumpkin fruits harvested under different pollination treatments located at varying distances of the plots from potential natural or semi-natural bee habitats. **Key: SS** – Spontaneous Self-pollination, **SBV** – Single Bee Visit, **CP** – Manual Cross-pollination, **OP** – Open pollination, **SP** – Manual Self-pollination. ANOVA test: ($F_{(4, 315)}$ =34.78, p< 0.001) **for > 3KM** and ($F_{(4, 255)}$ = 22.09, p > 0.05) **for ≤ 3KM**. Different small letters mean significant differences in treatments under **≤ 3KM** at p-value < 0.05. Different capital letters mean a significant difference in treatments under **> 3KM distance** at a p-value < 0.05. Overlapping error bar within and between clusters indicate no significant difference between treatments

Completely bagged pumpkin flowers did not produce any seed both at distances > 3 Km and even ≤ 3 Km from the potential natural or semi-natural bee habitat (Figure 5.6). At ≤ 3Km, there was significant variation in the numbers of pumpkins seeds produced among the four treatments ($F_{255,\ 4}$ = 22.09, p < 0.05), but at distances > 3 Km, there was no significant variation ($F_{(4, 315)}$ = 23.02, p > 0.05). The Turkey post hoc test showed significant variations between pairs of treatments at distances ≤ 3 km from the potential natural or semi-natural bee habitat. Specifically, open pollination differed significantly from self-pollinated pumpkin, while bee visited, open pollination, and cross pollination flower pumpkin did not exhibit any significant variation in the number of seeds in pumpkin fruits (p > 0.05).

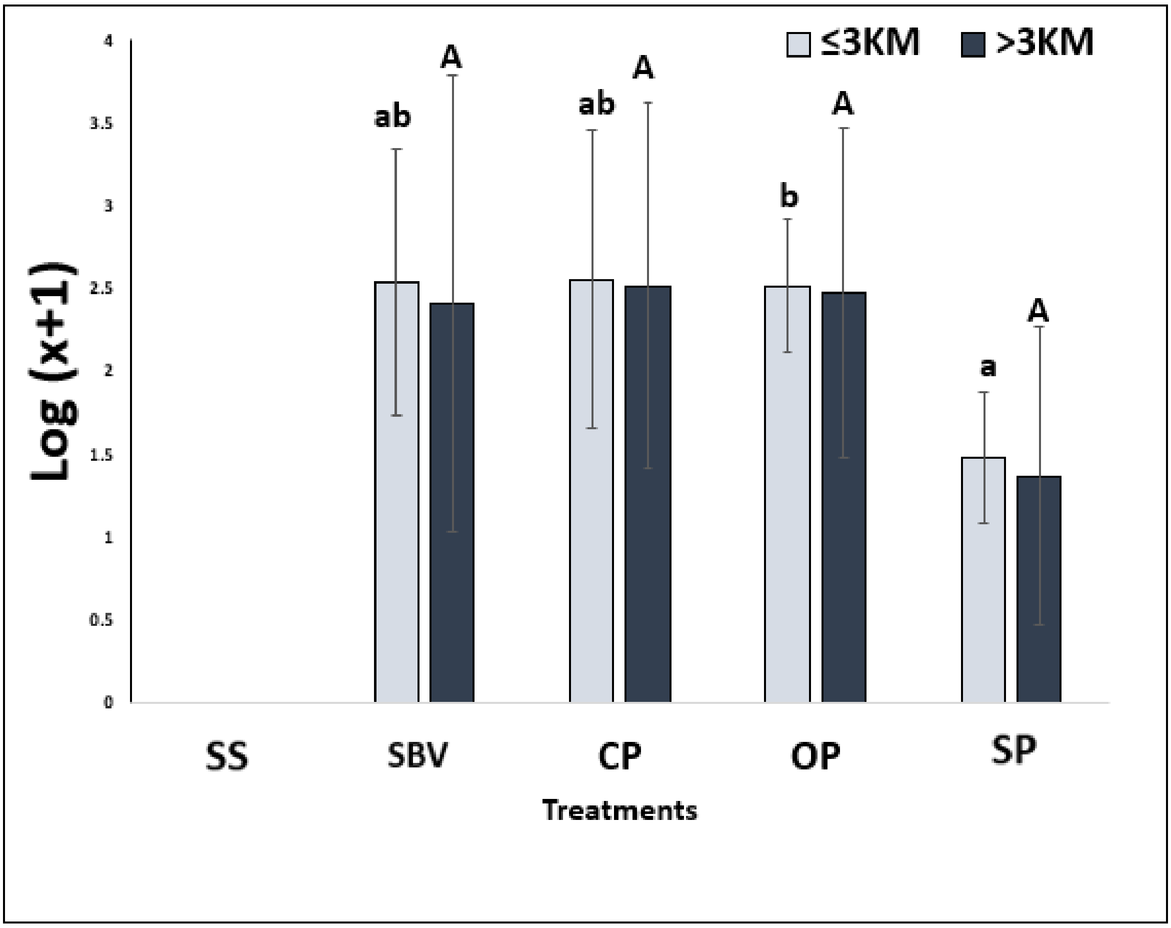

Figure 5:6: Number of seeds (x) per pumpkin fruits harvested under different pollination treatments located at varying distances from potential natural or semi-natural bee habitats. Key: **x**-Number of seeds, **SS** – Spontaneous Self-pollination, **SBV** – Single Bee Visit, **CP** – Manual Cross-pollination, **OP** - Open pollination, **SP** – Manual Self-pollination ANOVA test: ($F_{(4, 315)}$ =33.48, $p< 0.001$) for **> 3KM** and ($F_{(4, 255)}$ =23.02, $p > 0.05$) for **≤ 3KM**. Different small letters mean significant difference in treatments under **≤ 3KM** at p-value < 0.05. Different capital letters mean significant difference in treatments under **> 3KM distance** at p-value < 0.05. Overlapping error bars within and between clusters indicate no significant difference between treatments.

5.3 Discussion

5.3.1 Contribution of bees to the yield of Robusta coffee

Robusta coffee grown in shaded environments exhibited higher fruit set percentages compared to those grown in open-sun conditions, except for spontaneous self-pollination, wind pollination, and manual self-pollination treatments. Previous studies by Roubik (2002a) and Kasina et al. (2019) support this observation, highlighting that shaded environments enhance pollinator activity, particularly for social bees such as *Apis mellifera*. The cooler temperatures and stable humidity in shaded conditions improve the foraging efficiency of bees. Similar results have been documented in Costa Rica and Colombia (Vergara and Badano, 2009; Jha and Vandermeer, 2010). Open pollination produced the highest fruit set further emphasizing the essential role of bees and other pollinators in Robusta coffee pollination. In contrast, spontaneous self-pollination recorded the least fruit set indicating that coffee plants rely heavily on biotic pollinators for optimal yields. This finding aligns with research by Gemmill-Herren et al. (2007), who showed that open pollination could increase coffee yields by up to 50%.

The low fruit set observed in wind pollination and manual self-pollination treatments further demonstrates the limited efficiency of non-biotic factors in pollinating coffee. The relatively higher fruit set recorded in shaded coffee plots compared to open-sun plots under open pollination indicates that sunlight exposure may influence bee activity and the reproductive success of coffee plants. This is consistent with Klein et al. (2003a), who found that excessive sunlight could cause heat stress in both coffee plants and pollinators, thereby reducing foraging activity and pollination efficiency. These findings underscore the value of agroforestry systems, which create favorable conditions for both pollinator activity and coffee production.

The mean mass of coffee berries varied significantly across pollination treatments in shaded plots but not in open-sun plots. In shaded plots, berries from single bee pollination and cross-pollination treatments were significantly larger than those from self-pollination treatments, highlighting the importance of bees in improving berry size and quality. Gemmill-Herren et al. (2007) similarly reported that bees enhance fruit size and quality through efficient pollen transfer. However, in open-sun plots, there were no significant differences in berry mass across pollination treatments, suggesting that stressors such as direct sunlight and high temperatures may limit the benefits of bee pollination. Similar findings observed lower productivity and fruit quality in coffee plants exposed to open-sun conditions (Jha and Vandermeer., 2010),

The post hoc Tukey test revealed that coffee berries from single bee visits, manual cross-pollination, open pollination, and wind pollination were not significantly different in mass, suggesting that these treatments offer similar benefits under shaded conditions. However, berries from spontaneous and manual self-pollination treatments were significantly smaller than those from the other treatments. This aligns with findings by Roubik (2002a), who reported that self-pollinated coffee flowers produce smaller berries due to incomplete fertilization and reduced genetic diversity. The significant differences in berry mass between shaded and open-sun plots highlight the importance of environmental conditions for coffee production. Shaded plots provide a stable microclimate that supports better pollinator activity and enhances coffee development. This finding is consistent with studies by, who reported that shade trees promote pollinator diversity and improve coffee yield and quality (Klein et al., 2003a and Vergara and Badano. 2009)

Overall, the higher fruit set and berry mass observed in shaded plots compared to open-sun plots demonstrate the importance of shaded systems in promoting bee pollination and improving coffee yield and quality by providing a favourable micro climate for coffee development. These findings align with earlier studies that demonstrate the importance of shaded coffee systems in supporting higher bee diversity and pollination efficiency (Ricketts et al., 2004; Karanja et al., 2017). Single bee visits, cross-pollination, and open pollination consistently produced fewer pea berries compared to manual self-pollination and wind pollination treatments. This highlights the critical role of bee-mediated pollination in minimizing the occurrence of pea berries, which may be attributed to the more effective pollen transfer and greater genetic diversity facilitated by bees. These findings align with previous studies on pollinator-dependent crops, where natural pollination has been shown to improve yield quality. Kasina et al. (2009) reported that bee pollination in Robusta coffee significantly enhances both yield and quality, notably by reducing the prevalence of defects such as pea berries.

Significant differences in pea berry formation were observed among the various pollination treatments in both shaded and open-sun environments, highlighting the critical role of pollination in coffee fruit development. The lower percentages of malformed coffee berries across most pollination treatments in shaded coffee plots suggests that shading creates a microclimate that enhances bee activity and pollen transfer accuracy, a trend also noted by Roubik (2002a) in tropical coffee agroecosystems

The ANOVA results for shaded plots reveal that certain pollination treatments significantly reduce pea berry formation in Robusta coffee, with bee-mediated pollination being particularly effective. This finding aligns with research from Uganda by Gemmill-Herren et al. (2007), who reported that bee pollination in coffee plantations not only increased fruit set but also improved fruit quality by reducing the proportion of pea berries. Enhanced pollen transfer facilitated by bees promotes better fertilization, thereby reducing the likelihood of pea berry formation. Similar trends were documented in studies by Vergara and Badano (2009), where cross-pollinated and bee-pollinated coffee plants produced fewer pea berries compared to self-pollinated plants. This highlights the importance of pollinator diversity for improving coffee quality.

In open-sun plots, pea berry formation also varied significantly across treatments but the differences between treatments were less pronounced compared to shaded plots. This may be attributed to the harsher environmental conditions in open-sun plots, which could limit the beneficial effects of pollination on coffee fruit quality. However, as observed in shaded plots, completely bagged and self-pollination treatments produced significantly more pea berries compared to bee-visited and cross-pollinated treatments. This reinforces the importance of pollination in enhancing quality of Robusta coffee, as well as the negative impact of environmental stressors on fruit development. These findings are consistent with observations by Klein et al. (2003b), who reported that in full-sun coffee plots, higher temperatures and the absence of shade negatively affected fruit quality, increasing the frequency of defective berries regardless of pollination treatment.

Post hoc analysis revealed no significant difference between bagged clusters and self-pollination treatments in both environments. This suggests that, in the absence of external pollen sources, self-pollinated flowers are more likely to produce pea berries due to incomplete fertilization. Research has shown that self-pollination tends to result in lower-quality fruits, since it lacks the genetic diversity introduced through cross-pollination. As a result, higher defect rates, including the formation of pea berries, are observed (Roubik, 2002b).

These findings are consistent with previous studies conducted in Uganda, where areas with higher bee activity experienced better coffee quality and fruit formation (Mwangi et al., 2020). The presence of bees and other pollinators ensures effective pollen transfer, leading to more uniform berry development and a lower incidence of pea berries (Kasina et al., 2019). Pollination by wild insects, particularly bees, enhances coffee yield and quality, as pollinators facilitate cross-pollination, which is essential for Robusta coffee (Roubik, 2018). These findings align with the current study, as coffee plants in both shaded and open environments with access to pollinators produced fewer pea berries compared to those restricted to self-pollination.

The lack of significant differences between completely bagged and self-pollination treatments in both shaded and open-sun environments indicates that, in the absence of biotic pollination, coffee plants rely on autogamy (self-pollination), which is less effective at achieving full fruit set and quality. This trend is consistent with findings from other studies, where self-pollination in coffee resulted in high pea berry rates and smaller berry sizes due to limited pollen transfer and reduced genetic diversity (Klein et al., 2003b).

In summary, these results emphasize that pollination by bees and other agents significantly reduces the occurrence of defective coffee berries (pea berries), especially in shaded environments where conditions are more conducive for successful pollination. The consistent differences between bagged, self-pollination, and other pollination methods highlight the inadequacy of self-pollination in producing well-formed berries. This is likely due to insufficient pollen transfer and the genetic limitations associated with self-pollination. These findings reinforce the importance of maintaining pollinator populations and agroforestry systems to ensure high-quality coffee production.

5.3.2 Contribution of bees to the yield of pumpkins

The very high pollination success rate in single bee visit aligns with previous studies indicating the importance of bee visits for efficient pollination in crops like pumpkins. According to Gemmill-Herren et al. (2014), bee-mediated pollination in pumpkin is highly effective due to the bees' ability to transfer large quantities of pollen, ensuring higher fruit set rates. The high success rate in the single bee visit treatment underscores the importance of even a single visit by a pollinator to ensure effective pollination. This is consistent with the work by Kasina et al. (2009), who found that single visits by bees to pumpkin flowers significantly increased the fruit set in smallholder farms in Kenya.

The pollination success in open pollination also highlights the importance of natural pollinators in ensuring productive pumpkin farming since open pollination allows for the interaction of multiple pollinators, which ensures consistent pollen transfer across flowers. This is supported by Garibaldi et al. (2013), who showed that open pollination in various crops leads to higher yields, particularly when multiple pollinators are involved. Manual cross-pollination ranked third in pollination success, which demonstrates the effectiveness of hand pollination in ensuring fertilization when natural pollinators are scarce or absent. However, this method is labor-intensive and may not be practical for large-scale farming. These results align with studies like Klein et al. (2007), where manual cross-pollination showed promise in settings with pollinator deficits, but was less efficient than biotic pollination under natural conditions.

However, manual self-pollination and spontaneous self-pollination treatments showed poor results, with the latter performing particularly poorly. The low success rate in self-pollination can be attributed to the reliance on limited genetic diversity, which often leads to low-quality fruit or none at all. Similar findings were reported by Free (1993), who noted that pumpkins are primarily dependent on cross-pollination, and self-pollination tends to result in poor fruit set due to the lower viability of self-pollinated seeds. The results from the bagged flowers in the spontaneous self-pollination treatment, which served as a control, confirm the essential role that pollinators play in achieving successful fruit set. These findings emphasize the results of other studies in the region, including Achieng et al. (2014), which underscored the key role of biotic pollination in pumpkin fruit development, particularly in regions with high pollinator activity.

Overall, the stark difference in success rates between biotic pollination treatments and self-pollination treatments (both manual and spontaneous) underscores the critical role of pollinators in pumpkin cultivation. This suggests that reliance on spontaneous self-pollination in the absence of pollinators could lead to significantly reduced yields, affecting the economic viability of pumpkin farming. Fruit mass at both ≤ 3 km and > 3 km distances from potential natural or semi-natural bee habitat of single bee visits, open pollination, and cross-pollination led to significantly higher pumpkin fruit mass compared to self-pollination and bagged flowers. This indicates that biotic pollination, particularly by bees, is crucial for enhancing pumpkin yield suggesting that the presence of pollinators, especially at closer proximities, plays a significant role in boosting fruit mass.

The lack of fruit formation in bagged flowers, which prevented any form of pollination, further confirms the essential role of pollinators, as bagged flowers were isolated from both biotic and abiotic pollination agents. This aligns with previous studies by Kasina et al. (2009) in East Africa who found that bee pollination contributed significantly to pumpkin yields, particularly when farms were located near natural habitats that hosted pollinator populations. Similarly, Gemmill-Herren et al. (2014) emphasized the crucial role that pollinators, especially bees, play in boosting fruit mass and seed quality in crops like pumpkins and cucumbers in the region.

At distances ≤ 3 km from natural habitats, single bee visits, open pollination, and cross-pollination resulted in higher and statistically similar fruit masses. This suggests that closer proximity to pollinator habitats leads to a more consistent and effective pollination service. However, even at distances > 3 km, cross-pollination remained effective, suggesting that while the efficiency of pollination services decreases with distance, cross-pollination can still be effective. This echoes with findings by Garibaldi et al. (2011) that crop yield responses to pollinator presence tend to decline with distance from natural habitats, although cross-pollination often remains effective over larger distances.

However, the significant differences between self-pollination and other treatments, particularly cross-pollination, highlight the importance of genetic diversity in enhancing fruit size. Self-pollination is often less efficient and results in smaller fruits due to limited genetic exchange, which affects the development of the fruit. These findings are consistent with studies by Klein et al. (2007), who noted that self-pollination in crops like pumpkins generally results in lower-quality fruits compared to cross-pollination or bee visits, which introduce genetic diversity and improve fruit mass.

Pollinators play a critical role in number of seeds in pumpkins, particularly in relation to proximity to natural or semi-natural habitats that support pollinator populations including bees. Completely bagged pumpkin flowers, which were isolated from all pollination agents, did not produce any seeds at both distances (≤ 3 km and > 3 km), underscoring the necessity of biotic pollination. This aligns with the findings of Kasina et al. (2009), who showed that crops like pumpkins rely heavily on pollinators for successful seed set, with bagged or isolated flowers often resulting in no seed production.

Significant variations were observed among pollination treatments in pumpkin plots ≤ 3 km from potential natural or semi-natural pollinator habitats, with number of seeds in open pollination being significantly high compared to self-pollination. This supports the idea that proximity to natural habitats enhances pollination services due to the higher availability of pollinators including bees. Similar findings were reported by Gemmill-Herren et al. (2014) in their study on pumpkin pollination in East Africa, where they found that farms closer to pollinator habitats experienced higher seed yields compared to those farther away.

However, there was no significant variation in number of seeds across the different pollination treatments for pumpkin plots > 3 km. This suggests that the effectiveness of pollinators diminishes as the distance from natural habitats increases, a finding consistent with Garibaldi et al. (2011), who demonstrated that pollinator service declines as the distance from natural or semi-natural habitats increases. The lack of significant variation between single bee visits, open pollination, and cross-pollination at both distances indicates that these treatments all provide effective pollination services, with biotic pollination playing a critical role in ensuring higher seed production and hence higher number of seeds. The results demonstrate that self-pollination is less effective, particularly in terms of seed number, when compared to other pollination treatments. This is consistent with studies such as those by Klein et al. (2007), who found that cross-pollination and insect-mediated pollination enhance seed set in crops by facilitating genetic exchange, while self-pollination often leads to lower seed numbers and poorer fruit quality.

Overall, these findings highlight the importance of maintaining natural pollinator habitats near agricultural fields to support pollinator populations and ensure higher crop yields. The significant variation in number of seeds at distances ≤ 3 km suggests that proximity to potential natural or semi-natural pollinator habitats enhances pollination services, leading to better seed set and hence high seed number.

5.4 Conclusions

This study underscores the vital role of bees in maximizing fruit set in Robusta coffee plantations, with enhanced performance in shaded Robusta coffee plots. The study suggests that shade not only improves pollinator activity but also enhances the overall pollination efficiency, leading to better Robusta coffee yields. While coffee plants may utilize wind pollination to a limited extent, cross-pollination through bees significantly improves yield, especially under shaded conditions that encourage more consistent bee foraging. It highlights the importance of pollinators in reducing the percentage of pea coffee berries and emphasizes the importance of bee-mediated pollination in reducing pea coffee berries Robusta coffee. It highlights the limitations of wind and self-pollination methods, which are less effective in ensuring proper fruit development.

As for pumpkins, the results of this study underscore the critical role of bee-mediated pollination in enhancing pumpkin yields, particularly for plants located close to natural or semi-natural habitats. The results emphasize the importance of pollinator habitats in sustaining pumpkin yields. The study underscores the vital role of insect pollinators, particularly bees, in pumpkin seed production, they suggest that maintaining pumpkin fields within close proximity to natural bee habitats is essential for maximizing seed production.

5.5 Recommendations

1. Efforts should be made to conserve and restore natural habitats within agricultural landscapes to enhance pollinator populations. This includes creating buffer zones and planting native flowering plants that can support bees.
2. Shading improves coffee fruit set by creating favorable microclimates for bee activity. Therefore, incorporating a balanced number of shade trees in Robusta coffee gardens is recommended to enhance pollinator visits since shade enhances the microclimate for pollinators and reduce pea berry malformation.

3. Integrated pest and pollinator management strategies should be adopted in pumpkin production systems to optimize both pest control and pollination services, enhancing overall crop productivity.
4. Awareness campaigns should educate farmers on the benefits of natural pollinators and encourage them to support pollinator habitats.
5. Additional studies are needed to explore the microclimatic effects of shaded and open coffee systems on bee foraging behavior and the resulting pollination success.

CHAPTER SIX: GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

6.1 General discussion

This study emphasizes the critical role of habitat conditions, particularly shading, in supporting diverse and abundant bee populations in Robusta coffee plantations. Shaded plots consistently demonstrated higher bee diversity and abundance compared to open sun plots (section 4.2.1). This difference can be attributed to the more favorable microclimatic conditions provided by shaded environments, such as lower temperatures, stable humidity, and greater floral diversity. These conditions are essential for both bee foraging and the availability of nesting sites, which are necessary for sustaining diverse pollinator communities (Jha and Dick, 2010; Classen et al., 2014). Similar findings from tropical agroforestry studies suggest that shaded coffee systems significantly contribute to biodiversity conservation (Ricketts et al., 2004; Kremen et al., 2007).

Bee species like *Hypotrigona sp.* demonstrated flexibility in adapting to both shaded and open environments, though a clear preference for shaded plots was observed (section 4.2.2). This suggests that while certain bee species can thrive in diverse conditions, shaded environments offer more stable and resource-rich habitats, which are crucial for pollinator survival. The presence of specialized species such as *Megachile rufipennis* in shaded plots further highlights the importance of shaded environments for supporting specialized pollinators. Conversely, open sun environments may favor species that are adapted to harsher conditions, including higher temperatures and more direct exposure to sunlight (Kasina et al., 2009; Otieno et al., 2011). The diversity of bee species across both shaded and open environments highlights the importance of maintaining varied habitats within coffee agroecosystems to support a broad spectrum of pollinators.

The observed Shannon diversity and low dominance indices in shaded plots suggest a well-balanced bee community with minimal dominance by any single species, pointing to the potential of shaded coffee plots to maintain diverse pollinator communities (Jha and Dick, 2010; Klein et al., 2008). Despite the higher species richness and abundance in shaded environments, the even distribution of bee species across both plot types demonstrates the resilience of coffee agroecosystems in supporting stable and diverse pollinator communities.

The study also demonstrates the importance of habitat proximity in pumpkin plots, with higher bee abundance and diversity observed in plots situated within 3 km of natural or semi-natural habitats (section 4.3.2). These findings align with previous research showing that proximity to natural habitats provides critical resources like nesting sites and floral diversity, which sustain pollinator populations (Garibaldi et al., 2011; Kennedy et al., 2013). The prevalence of *Apis mellifera* as the most abundant bee species further emphasizes its role as a key pollinator in agricultural landscapes (Gikungu et al., 2006; Ricketts et al., 2008).

Notably, certain bee species, such as *Hypotrigona sp.* and *Ctenoplectra sp.,* were found across all distance categories, but their abundance was higher in plots closer to natural habitats. This suggests that although some species can adapt to various environmental conditions, their populations are more abundant in areas with better access to resources. The reduction in bee diversity in plots > 3 km highlights the negative effects of habitat fragmentation, supporting previous studies on the challenges posed by landscape fragmentation to pollinator communities (Winfree et al., 2009; Senapathi et al., 2017).

The species that were unique to plots ≤ 3 km and those > 3 km, suggests that habitat proximity plays a significant role in attracting specific pollinator species. This aligns with the theory that natural habitats act as refuges for pollinator diversity by offering essential resources like nesting sites and floral diversity (Ricketts et al., 2008; Garibaldi et al., 2011). However, the reduced diversity and higher dominance indices in plots > 3 km indicate that greater distances from natural habitats limit pollinator diversity and abundance, highlighting the importance of landscape connectivity for maintaining healthy pollinator communities (Winfree et al., 2011; Steffan-Dewenter and Tscharntke, 1999).

Regarding pollination efficiency and crop yield, shaded Robusta coffee plots supported higher bee abundance and a more diverse bee community, which directly contributed to better coffee yields (section 5.3.1). These findings highlight the significant role of shaded systems in enhancing pollination services. The greater diversity of bee species in shaded plots likely leads to more efficient pollination, which in turn boosts fruit set and berry mass (Mutembei et al., 2021; Karanja et al., 2017). In contrast, open-sun plots, with lower bee diversity, resulted in less efficient pollination and lower coffee yields, emphasizing the negative impact of environmental stressors such as high temperatures and direct sunlight on pollination success.

Interestingly, while wind pollination was found to supplement bee-mediated pollination in shaded environments, it was not as effective as bee pollination, especially for coffee. Coffee plants, which have large, sticky pollen, benefit most from bee visits for efficient pollination (Ndungu et al., 2016). These results suggest that shaded coffee systems, by supporting both biotic and abiotic pollination mechanisms, enhance pollination outcomes, which can directly impact the quality and yield of coffee. Thus, shaded environments are not only more favorable for pollinators but also contribute to better agricultural productivity.

6.2 General conclusions

Shaded coffee environments not only support more diverse pollinator communities but also contribute to broader biodiversity conservation, which can help ensure the long-term sustainability of coffee production. Heterogeneous landscapes within agricultural systems maintain adaptable and habitat-specific bee species underscores the importance of maintaining. Bees provide essential pollination services, and their presence in shaded environments leads to better fruit set and berry mass. By promoting pollinator-friendly environments, such as shaded coffee systems, farmers can enhance productivity while contributing to the conservation of pollinators and biodiversity.

6.3 General Recommendations

1. Farmers should maintain shaded coffee systems to support a favorable microclimate for pollinators leading to better yields since shaded coffee systems enhance pollinator diversity and improve pollination efficiency.
2. Creating corridors or buffer zones of natural vegetation around agricultural fields can improve habitat connectivity, supporting pollinator movement and mitigating the negative effects of habitat fragmentation.
3. For sustainable pumpkin production, farmers should adopt practices that promote pollinator diversity, such as planting wildflowers and reducing pesticide use.
4. Future research should focus on identifying landscape features that facilitate pollinator movement between habitats and agricultural fields so as to help improve connectivity and support pollinator populations, which are crucial for crop productivity.
5. Training on pollinator-friendly farming techniques and the benefits of maintaining shaded environments in coffee systems can encourage practices that support bee conservation and agricultural productivity.
6. Long-term studies are needed to assess how cumulative pollinator activity impacts coffee yields under various environmental conditions, especially in regions with different levels of shade.

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APPENDICES

Appendix 1: Summary of bee species composition and abundance in Robusta coffee under different levels of exposure of the coffee plots to sunlight

Family	Species	Open Sun plots	Shaded plots	Total
Apidae	*Allodape interrupta*	9	10	19
	Allodape sp.	3	1	4
	Amegilla sp.	5	13	18
	Apis mellifera	27	26	53
	Braunsapis foveate	5	13	18
	Braunsapis langenburgensis	1	1	2
	Braunsapis lyrate	1	0	1
	Braunsapis mixta	0	1	1
	Braunsapis sp.	25	31	56
	Braunsapis trochanterata	0	1	1
	Ceratina sp.	17	21	38
	Cleptotrigona cubiceps	10	26	36
	Ctenoplectra sp.	2	1	3
	Hypotrigona sp.	52	45	97
	Macrogalea candida	2	2	4
	Macrogalea sp.	5	6	11
	Meliponula ferruginea	1	3	4
	Pasites sp.	0	1	1
	Plebeina armata	18	7	25
	Tetralonia sp.	1	2	3
	Thyreus sp.	0	4	4
	Thyreus sp.1	1	2	3
	Thyreus sp.2	1	0	1
	Thyreus sp.3	0	1	1
	Thyreus sp.6	0	2	2
	Xylocopa caffra	14	8	22

	Xylocopa flavorufa	1	0	1
	Xylocopa imitator	2	4	6
	Xylocopa inconstans	1	0	1
	Xylocopa olivacea	13	4	17
	Xylocopa scioensis	1	0	1
Halictidae	*Halictus* sp.	16	7	23
	Heriades sp.	2	3	5
	Lasioglossum atricrum	28	30	58
	Lasioglossum scobe	2	3	5
	Lasioglossum sp.	30	36	66
	Lasioglossum sp. D	4	2	6
	Leuconomia atripes	1	1	2
	Leuconomia sp.	0	2	2
	Lipotriches collaris	1	0	1
	Lipotriches hylaeoides	1	1	2
	Lipotriches pseudoclavata	1	1	2
	Lipotriches sp.	19	13	32
	Nubenomia nubecula	7	8	15
	Patellapis sp.	11	22	33
	Pseudapis amoenula	1	3	4
	Pseudapis sp.	2	2	4
	Spatunomia filifera	1	0	1
	Thrinchostoma kandti	1	4	5
	Thrinchostoma petersi	18	22	40
	Thrinchostoma sp.	0	1	1
	Thrinchostoma torridum	1	9	10
	Trinomia orientalis	7	1	8
Megachilidae	*Afranthidium* sp.	1	0	1
	Afrostelis sp.	0	2	2
	Coelioxys sp.	1	1	2
	Coelioxys sp.3	0	1	1
	Euaspis abdominalis	1	1	2
	Heriades sp.4	0	2	2
	Heriades sulcatulata	0	2	2
	Lithurgus pillatus	1	0	1

Lithurgus sparganotes	7	8	15
Megachile bituberculata	1	5	6
Megachile maxillosa	0	1	1
Megachile rufipennis	10	16	26
Megachile sp.	3	3	6
Megachile sp.12	0	1	1
Megachile torrida	2	0	2
Othinosmia sp.	1	3	4
	400	453	853

Appendix 2: Summary of bee species captured in pumpkin plots under different distances of the plots from the potential natural or semi-natural bee habitats.

Family	Species	> 3 km	≤ 3 km	Total
Apidae	*Allodape interrupta*	1	3	4
	Allodape sp.	1	0	1
	Amegilla sp.	2	2	4
	Apis mellifera	27	17	44
	Braunsapis foveata	4	5	9
	Braunsapis lyrate	4	0	4
	Braunsapis sp.	10	8	18
	Ceratina sp.	12	1	13
	Cleptotrigona cubiceps	4	2	6
	Ctenoplectra sp.	5	14	19
	Hypotrigona gribodoi	2	0	2
	Hypotrigona sp.	17	15	32
	Macrogalea sp.	2	1	3
	Plebeina armata	3	3	6
	Tetralonia sp.	2	0	2
	Thyreus sp.7	0	1	1
	Xylocopa caffra	1	3	4
	Xylocopa flavorufa	0	1	1
	Xylocopa imitator	1	0	1
	Xylocopa inconstans	0	1	1
	Xylocopa olivacea	1	0	1
Colletidae	*Hylaeus* sp.1	1	0	1
Halictidae	*Acunomia epileuca*	0	1	1
	Acunomia somalica	0	1	1
	Crocosaspidia nigripes	0	1	1
	Eupetersia sp.	0	1	1
	Halictus sp.	2	5	7
	Lasioglossum atricrum	1	2	3
	Lasioglossum scobe	1	1	2
	Lasioglossum sp.	7	6	13
	Lasioglossum vagans	0	1	1

	Lipotriches collaris	2	0	2
	Lipotriches hylaeoides	1	0	1
	Lipotriches pseudoclavata	0	1	1
	Lipotriches sp.	2	5	7
	Nomia sp.	1	0	1
	Nomia viridicincta	0	1	1
	Patellapis sp.	5	10	15
	Pseudapis amoenula	4	3	7
	Thrinchostoma kandti	0	4	4
	Thrinchostoma petersi	1	2	3
	Trinomia cirrita	4	1	5
	Trinomia natalensis	1	0	1
Megachilidae	*Coelioxys* sp.	0	1	1
	Coelioxys sp.2	0	1	1
	Heriades bouyssoui	1	0	1
	Heriades canaliculata	0	1	1
	Heriades sp.3	0	2	2
	Heriades sulcatulata	2	0	2
	Lithurgus sparganotes	2	1	3
	Megachile bituberculata	0	3	3
	Megachile rufipennis	2	7	9
	Megachile sp.	3	10	13
	Megachile sp.13	0	1	1
	Megachile sp.9	1	0	1
	Megachile torrida	1	3	4
	Othinosmia sp.	1	0	1
	Pseudoanthidium truncatum	1	0	1
		146	153	299

Appendix 3: Field activity photos

Plate 1: Coffee floral sprouts that were tagged and left unbagged to allow for wind and insect pollination

Plate 2: Coffee floral sprouts that have been hand-emasculated ready for self, bee or cross-pollination

Plate 3: Pollinator exclusion bag of fine nylon mesh gauze (10µm) that excluded both insect and wind pollination

Plate 4: Pollinator exclusion bag with 1 mm opening to allow wind but prevent pollination by insects

Plate 5: Green swollen fruits set after five weeks

Plate 6: Mature coffee beans at harvest

Plate 7: White, blue, and yellow pan traps placed on wooden stakes approximately 50 cm above the ground

Plate 8: Captured bee specimens pinned at Makerere University laboratory awaiting identification