MAKERERE UNIVERSITY

COLLEGE OF NATURAL SCIENCES, SCHOOL OF BIOLOGICAL SCIENCES,
DEPARTMENT OF ZOOLOGY, ENTOMOLOGY AND FISHERIES SCIENCES

DIVERSITY AND DISTRIBUTION OF BEES IN SELECTED DISTRICTS OF CENTRAL UGANDA

KABASOMI LYDIA
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SUPERVISORS:

ASSOCIATE PROF. ANNE M. AKOL
DR. MOSES CHEMUROT

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DECLARATION

I, Kabasomi Lydia, hereby declare that to the best of my knowledge, this dissertation is my work, submitted to the School of Biosciences, College of Natural Sciences, and that it has never been submitted to any institution or University for any award.

Signature..Date 26th /11/2025..........

KABASOMI LYDIA

APPROVAL

This dissertation has been submitted with our approval as supervisors.

Signature.......................................Date....5/11/2024..........

Assoc. Prof. Anne M. Akol

BSc, PGDE, MSc, PhD

Department of Zoology, Entomology and Fisheries Sciences

College of Natural Sciences,

Makerere University

Signature.......................................Date....6/11/2024..........

Dr. Moses Chemurot

BSc, MSc, PhD

National Livestock Resources Research Institute (NaLIRRI), National Agricultural Research Organisation (NARO).

DEDICATION

I dedicate this work to everyone who supported me (financially, academically, and spiritually) during my studies. May Almighty God bless you!

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ACRONYMS

NDP	National Development Plan
SDGs	Sustainable Development Goals
UBOS	Uganda Bureau of Statistics

ABSTRACT

Bees play a vital role in maintaining ecosystem functioning and agricultural productivity through pollination. However, their diversity and distribution are increasingly threatened by habitat degradation, land use changes, and unsustainable agricultural practices. This study investigated the diversity and distribution of bees in selected districts of Central Uganda, analysed the key environmental factors influencing their occurrence, and evaluated the effectiveness of different sampling methods for studying bee diversity. Data were collected from farmland, woodland, and grassland habitats using two sampling techniques, including pan traps and sweep nets, across both wet and dry seasons. Vegetation characteristics, including tree, shrub, herb, and grass cover, were also assessed to determine their influence on bee diversity and composition. Identification for some specimens was carried out to the genus and for others to species level. Diversity indices, ordination analyses, and complementarity assessments were applied to quantify community structure and sampling efficiency. A total of 112 species representing 47 genera and four bee families (Apidae, Colletidae, Halictidae, and Megachilidae) were recorded. Farmland supported the highest bee richness and abundance, likely due to habitat heterogeneity and floral diversity, while woodland and grassland harboured rare and habitat-specific species. Redundancy analysis revealed that herb and grass cover were more strongly associated with bee diversity than tree and shrub cover, suggesting dominance of generalist species that tolerate varying vegetation structures. Seasonal variation influenced genus composition. sweep nets captured a higher number of species and individuals than pan traps. Still, both methods exhibited partial overlap, indicating that combining them yields a more comprehensive assessment of bee communities. In conclusion, bee diversity in Central Uganda is shaped by habitat heterogeneity and vegetation cover, with herbaceous and grass cover providing essential foraging and nesting resources. The findings underscore the need to conserve a diversity of habitats, especially farmlands integrated with natural vegetation to support and sustain bee populations. It is recommended that future research adopt long-term, multi-seasonal monitoring using complementary sampling methods to improve species detection accuracy. Furthermore, local communities should be sensitised on sustainable land use practices that enhance floral diversity to promote bee conservation and pollination services.

CHAPTER ONE: INTRODUCTION

1.1 Background

Bees are insects in the order Hymenoptera and the superfamily Apoidea. They are recognised for their important ecological role as pollinators, supporting both natural ecosystems and agricultural productivity (Garibaldi et al., 2013; Potts et al., 2010). Globally, more than 20,000 bee species have been described, although estimates suggest the number may exceed 25,000 due to ongoing discoveries in under-sampled regions, especially in the tropics (Ascher, 2020; Michener, 2007). Bees are characterised by branched body hairs, specialised mouthparts for collecting nectar, and distinct morphological adaptations for carrying pollen, including pollen baskets (corbiculae) on the hind legs or dense scopae on the abdomen or hind legs (Michener, 2007). These structures enhance pollen collection efficiency and distinguish bees from other Hymenopteran insects such as wasps. They vary in nesting habits, diet preferences, social organisation, and sensitivity to environmental changes (Bryan, et al., 2019; Michener, 2007).

Despite their importance and diversity, bee populations are declining worldwide. Drivers of this decline include habitat loss, land use change, pesticide use, climate change, invasive species, and diseases (Brittain et al., 2010; Goulson et al., 2015; Potts et al., 2010; Zattara & Aizen, 2021). The problem is especially concerning in sub-Saharan Africa, where studies on bee diversity remain sparse and spatially uneven (Archer et al., 2014; Eardley et al., 2010). Although efforts have been made to document bees in Africa, Rodger et al. (2004) highlighted persistent gaps in pollination studies across the continent, particularly the lack of comprehensive surveys and ecological data on native bee communities. In Uganda, approximately 216 bee species have been reported (Ascher, 2020, 2024). However, this figure likely underrepresents the country's actual bee diversity due to limited sampling and research coverage. The existing work has expanded knowledge of both managed and wild bees, but remains fragmented. For example, Byarugaba (2004) documented stingless bees in Bwindi Impenetrable Forest and emphasised the value of indigenous knowledge in understanding bee ecology. More recently, bee health and population resilience have attracted attention. Chemurot et al. (2017) identified emerging pathogens such as *Nosema neumanni*, while Otim et al. (2020) reported viruses circulating in Ugandan honey bee colonies. These studies highlight the growing threats facing bee pollinators. Kasangaki et al.

(2017) further revealed low genetic diversity in Ugandan honey bee populations, raising conservation concerns about their vulnerability to environmental changes.

Despite these advances, the broader diversity and distribution of bees across Uganda remain poorly understood. Most available studies are spatially restricted, focusing on protected areas (Mutabazi, 2015), agroecosystems (Munyuli, 2012), or managed bee colonies (Kajobe et al., 2016). There is limited ecological information on how bee communities respond to land use change, vegetation cover, and seasonal variation across Uganda's landscapes. This gap reduces the ability to design effective strategies for bee conservation and sustainable use. This study aimed to fill critical gaps in knowledge on bee diversity and distribution in Uganda. It investigated how land use types, vegetation characteristics, and environmental factors affected bee communities in Central Uganda. It also evaluated the effectiveness of two sampling methods. pan traps and sweep nets, in capturing bee species across different habitats. These findings are essential for informing conservation strategies, guiding land use planning, and contributing to pollinator research in the region.

1.2 Statement of the Problem

Bees play a critical role in pollination, supporting both ecosystem stability and agricultural productivity. However, in Uganda, the diversity of wild species remains poorly documented: most research has focused on *Apis mellifera* or has been limited to single habitats, leaving unclear how bee communities vary across land use types such as farmland, grassland, and woodland, as well as over seasons. This gap is echoed across sub-Saharan Africa: for example, in Burkina Faso, human disturbance strongly influences bee community structure, with highly disturbed savanna sites hosting only subsets of species present in less disturbed areas (Stein et al., 2018). In East Africa, a survey in northern Tanzania documented 45 bee species across agricultural, grazing, and conserved savannah sites using both pan traps and netting, yet many taxa remain under-described (Lasway et al., 2023). Additionally, environmental gradients such as elevation and temperature significantly influence bee richness and diversity in East African forest reserves (Magina et al., 2025). Beyond taxonomic and ecological knowledge gaps, there is a methodological problem: commonly used sampling techniques, particularly pan traps and sweep nets, may sample different subsets of the bee community, but their complementarity has not been rigorously evaluated in Ugandan or comparable tropical African settings. Without this evaluation, survey data may under-represent certain species, undermining confidence in community assessments. These combined ecological and methodological uncertainties limit our capacity to understand bee community dynamics and hinder evidence-based planning for conservation and pollination management in rapidly changing landscapes.

1.3 Objectives

1.3.1 General Objective

To examine bee diversity and distribution across selected districts in Central Uganda to promote conservation and land management practices.

1.3.2 Specific Objectives

1. To determine bee diversity in selected habitats in the districts of Kayunga, Luwero, and Nakaseke.
2. To analyse the key environmental factors that influence bee diversity and distribution in selected districts of Kayunga, Luwero, and Nakaseke.
3. To evaluate the complementarity and effectiveness of pan traps and sweep nets as sampling methods for studying bee diversity.

1.4 Research Questions

1. How does bee diversity vary across selected habitats in the districts of Central Uganda?

2. What environmental factors influence bee diversity and distribution in Central Uganda?

3. How do pan traps and sweep nets differ in their effectiveness, and how do each complement the other for studying bee diversity?

1.5 Justification

This study was conducted to generate baseline data on the diversity and distribution of bees in Central Uganda, a region undergoing rapid land use change but poorly represented in existing research. Bees are essential pollinators that support both agricultural productivity and ecosystem stability, yet little was known about how their communities respond to different habitat types in this region. By examining farmland, woodland, and grassland habitats with contrasting vegetation structure and levels of human disturbance, the study provided insights into how habitat type influences bee diversity. Methodologically, the study addressed the need to evaluate the effectiveness of commonly used sampling techniques, pan traps, and sweep nets, in Ugandan ecosystems. Including both methods allowed for the assessment of their complementarity, thereby improving the reliability of biodiversity surveys and providing guidance for future monitoring programs. The findings also have practical and policy relevance. By generating habitat-specific data, the study supports national biodiversity management and conservation planning, contributing to the goals of Uganda's Vision 2040 and the National Development Plan. Moreover, it aligns with international commitments, including the Convention on Biological Diversity and the Sustainable Development Goals (SDG 2: Zero Hunger; SDG 15: Life on Land), by providing information necessary for maintaining pollinator populations and sustainable agricultural systems.

CHAPTER TWO: LITERATURE REVIEW

2.1 Bee Diversity

Bees belong to Class Insecta, Order Hymenoptera, and Superfamily Apoidea. Although the total number of bee species globally is uncertain, the number of described species has continued to rise. Earlier estimates by Ascher (2014) reported nearly 20,000 species, while more recent updates show approximately 20,555 described species (Ascher, 2024; Orr et al., 2021). In Uganda, about 216 species have been recorded (Ascher, 2020), though this number is likely an underestimate due to limited taxonomic and ecological studies. Bee species are categorised into seven main families: Stenotritidae, Colletidae, Andrenidae, Halictidae, Melittidae, Megachilidae, and Apidae (Michener, 2007). These families are further divided into 28 subfamilies and are broadly grouped into long-tongued and short-tongued bees based on labial palp morphology (Engel, 2001). Among these, six families have a global distribution, while Stenotritidae is restricted to Australia (Eardley et al., 2010).

Bees are one of the most diverse groups of insects, occurring in nearly all terrestrial ecosystems where flowering plants exist. Their diversity is expressed not only in the number of species but also in their ecological roles, nesting strategies, and foraging behaviors. Global estimates indicate that over 20,000 described bee species are distributed across a wide range of habitats and climates (Michener, 2007). This diversity enables bees to occupy different ecological niches, with some species being generalists that forage across many plant taxa, while others are specialists restricted to a few floral hosts. Such variation underlines the ecological flexibility of bees and their importance in maintaining plant–pollinator networks. In Africa, bees are well represented, yet their distribution remains patchily documented. Although surveys have recorded a high number of bee species in some parts of the continent, large areas remain unexplored, limiting a comprehensive understanding of species richness and endemism (Eardley et al., 2009). Regional assessments have shown that Africa hosts a rich assemblage of solitary bees, stingless bees, and honey bees, but information on population dynamics and ecological requirements is still scarce compared to Europe and North America (Orr et al., 2021), though some progress has been made to document species richness and distribution (Eardley et al., 2009). This lack of information hampers efforts to monitor trends and design conservation strategies that reflect

Africa’s unique ecological contexts. Uganda, in particular, has not been comprehensively surveyed for bee diversity. Existing research has mainly focused on managed honey bees (*Apis mellifera*) for honey and beeswax production, with little attention to the broader bee fauna. While studies such as Byarugaba (2004), Mutabazi (2015) have documented bees, they cover limited habitats and therefore provide only a partial picture of the country’s bee community. Consequently, the extent of bee diversity across Uganda’s varied landscapes remains largely unknown. The gap, therefore, lies in the lack of systematic, multi-habitat surveys that capture the true extent of bee diversity in Uganda. Without such information, it is difficult to assess how different land uses, ecological factors, and management practices shape bee communities. This study contributes to filling this gap by examining bee diversity across contrasting habitats in Central Uganda.

2.2 Importance of Bees in Ecosystems

Bees are key pollinators that play a central role in the maintenance of both natural ecosystems and human food systems. Their foraging activities ensure the reproduction of a vast number of flowering plants, thereby sustaining plant genetic diversity, ecosystem stability, and the provision of resources for other organisms (Klein et al., 2007). Through these interactions, bees contribute significantly to biodiversity conservation and ecosystem resilience. In agricultural landscapes, bees enhance crop yields and quality by improving fruit and seed set (Klein et al., 2007). Studies have shown that a substantial proportion of global food crops depend partly or entirely on animal pollination, with bees being the most efficient contributors (Gallai et al., 2009). This ecological service has been valued at billions of dollars annually (Gallai et al., 2009), underscoring its critical role in food security. Beyond cultivated systems, bees maintain the regeneration of wild plants, supporting habitats for numerous animal species and thereby sustaining ecosystem functions. Despite their ecological and economic importance, the value of bees in tropical ecosystems, including Uganda, has been less quantified compared to other regions. Much of the available data originates from temperate countries, leaving a knowledge gap regarding the specific contributions of bees in African ecosystems. Where research has been conducted in Uganda, such as in coffee agroecosystems (Munyuli, 2012, 2011), findings demonstrate that bees substantially improve fruit set, indicating that their ecological role extends beyond wild habitats to directly benefit smallholder farming systems. However, studies remain fragmented and habitat-specific, limiting the generalization of results to wider ecological contexts. The research gap, therefore, lies in the lack of comprehensive assessments of how bees contribute to both natural and human-modified ecosystems in Uganda. By exploring bee diversity and distribution across multiple land use systems, this study provides insights into the ecological significance of bees within a landscape undergoing rapid transformation.

2.3 Status of Bee Research in Africa and Uganda

Bee research in Africa has expanded in recent decades, yet it remains limited compared to other continents. Most available studies have concentrated on honey bees, particularly *Apis mellifera* and stingless bees, due to their role in honey production and trade (Chemurot et al., 2021; Kajobe, 2007b, 2007a). While these studies have advanced understanding of managed bee colonies, they have contributed little to the documentation of the wider bee community, particularly solitary bees that form the majority of bee diversity on the continent (Eardley et al., 2009). Consequently, the distribution, ecology, and conservation status of many African bee taxa remain poorly understood. In Uganda, research on bees has historically focused on beekeeping potential and the economic value of honey and beeswax production. Studies on wild bee communities are relatively few, and those available are geographically restricted. For instance, Byarugaba (2004)and Mutabazi (2015) surveyed bees in selected protected areas. These studies provided important insights but were limited in spatial and ecological scope. They failed to capture the diversity of bees across the variety of habitats that characterise the Ugandan landscape, such as grasslands, woodlands, and farmlands. Another limitation is that most available data are outdated or fragmented, making it difficult to conclude trends in bee diversity and distribution over time. For example, while earlier surveys documented species presence in certain locations, they did not systematically analyse how land use types, vegetation cover, or seasonal changes shape bee communities. As a result, the ecological drivers of bee diversity in Uganda remain poorly quantified. The gap, therefore, lies in the absence of comprehensive and systematic surveys of bee communities across Uganda's main habitat types. Addressing this gap is essential to provide baseline information for pollinator conservation and to understand how ecological and land use factors influence bee distribution in rapidly changing landscapes. This study responds to that need by documenting bee diversity and distribution in Central Uganda.

2.4 Threats to Bees and Their Habitats

Globally, bee populations face numerous threats that compromise their diversity, abundance, and ecological functions. Habitat loss and fragmentation caused by agricultural expansion, urbanisation, and deforestation are among the most critical drivers of bee decline (Potts et al., 2010). These changes reduce the availability of floral resources and nesting sites, leading to the isolation and local extinction of bee populations (Requier & Leonhardt, 2020). Pesticide use further compounds these threats, as exposure to agrochemicals negatively affects bee survival, navigation, and reproduction (Goulson et al., 2015). In addition, climate change alters flowering phenology and resource availability, disrupting the synchrony between plants and their pollinators (Goulson et al., 2015). Collectively, these pressures have raised global concern over pollinator declines and their implications for biodiversity and food security. In Africa, research on threats to bees is less extensive but indicates similar patterns (Potts et al., 2010). In Uganda, evidence on threats to bee communities remains fragmented. The extent and magnitude of these threats across different habitats have not been comprehensively assessed. Much of the available knowledge focuses on honey bees, leaving uncertainty about how diverse bee taxa are affected by habitat conversion, vegetation clearance, and the use of agrochemicals. Moreover, little attention has been given to how seasonal variations and ecological disturbances interact with land use change to shape bee communities. The gap, therefore, lies in the limited empirical evidence on the drivers of bee population change in Uganda, particularly for non-managed bees. This study addresses this gap by assessing how land use types and associated ecological factors influence bee diversity and distribution in Central Uganda.

2.5 Methods of Sampling Bees

Accurately assessing bee diversity requires the use of reliable and complementary sampling techniques. Different methods vary in their efficiency depending on habitat type, season, and the foraging behaviour of bees. Among the most widely used are pan traps and sweep nets, which each have unique advantages and limitations (Westphal et al., 2008). Pan traps, usually consisting of coloured bowls filled with soapy water, are effective for capturing a wide range of bee species with minimal observer bias (Campbell & Hanula, 2007; Droege, 2015). They allow for standardised sampling across sites and times, providing comparable data on species richness and abundance. However, pan traps may under-sample larger or more active bees, and their effectiveness can be influenced by environmental conditions such as temperature, vegetation cover, and colour preferences of bees (Prendergast et al., 2020). sweep netting, by contrast, involves actively capturing bees while they forage on flowers. This method is highly effective for recording flower visitation, plant–pollinator interactions, and larger-bodied species that are less likely to be captured by traps. The technique, however, is labour-intensive, dependent on observer skill, and may introduce sampling bias if effort is not standardized across sites (Grundel et al., 2011).

Globally, researchers have emphasized the importance of combining methods to achieve a more complete picture of bee communities (Grundel et al., 2011; Nielsen et al., 2011; Westphal et al., 2008). In Uganda, however, there has been little systematic evaluation of how different sampling methods perform in local ecological contexts. Existing studies, used either pan traps or sweep nets, but rarely assessed their relative efficiency or complementarity across habitats. This creates uncertainty about whether current biodiversity data adequately represent the true diversity of bees. The gap, therefore, lies in the lack of comparative assessments of bee sampling methods in Uganda. Addressing this is critical for developing standardized approaches that yield reliable data for ecological monitoring and conservation planning. This study responds to that gap by evaluating the complementarity and effectiveness of pan traps and sweep nets in capturing bee diversity across multiple land use types in Central Uganda.

CHAPTER THREE: MATERIALS AND METHODS

3.1 Description of the Study Area

The study was conducted in selected districts of Kayunga, Luwero, and Nakaseke in Central Uganda, an area characterized by a mosaic of land use types including farmland, grassland, and woodland. These habitats represent the dominant vegetation cover and land use practices typical of the region. For this study, farmland refers to land used primarily for crop cultivation; grassland denotes areas dominated by perennial grasses with scattered shrubs or trees; and woodland describes habitats where trees are the dominant vegetation type. According to the Uganda Bureau of Statistics (UBOS, 2024). Agriculture remains the main economic activity in Central Uganda, with a large proportion of households engaged in smallholder farming, while livestock keeping and mixed land use are also common. The region's landscape is undergoing rapid transformation due to population growth and expanding agricultural activity. Detailed site locations are presented in Figure 3.1.

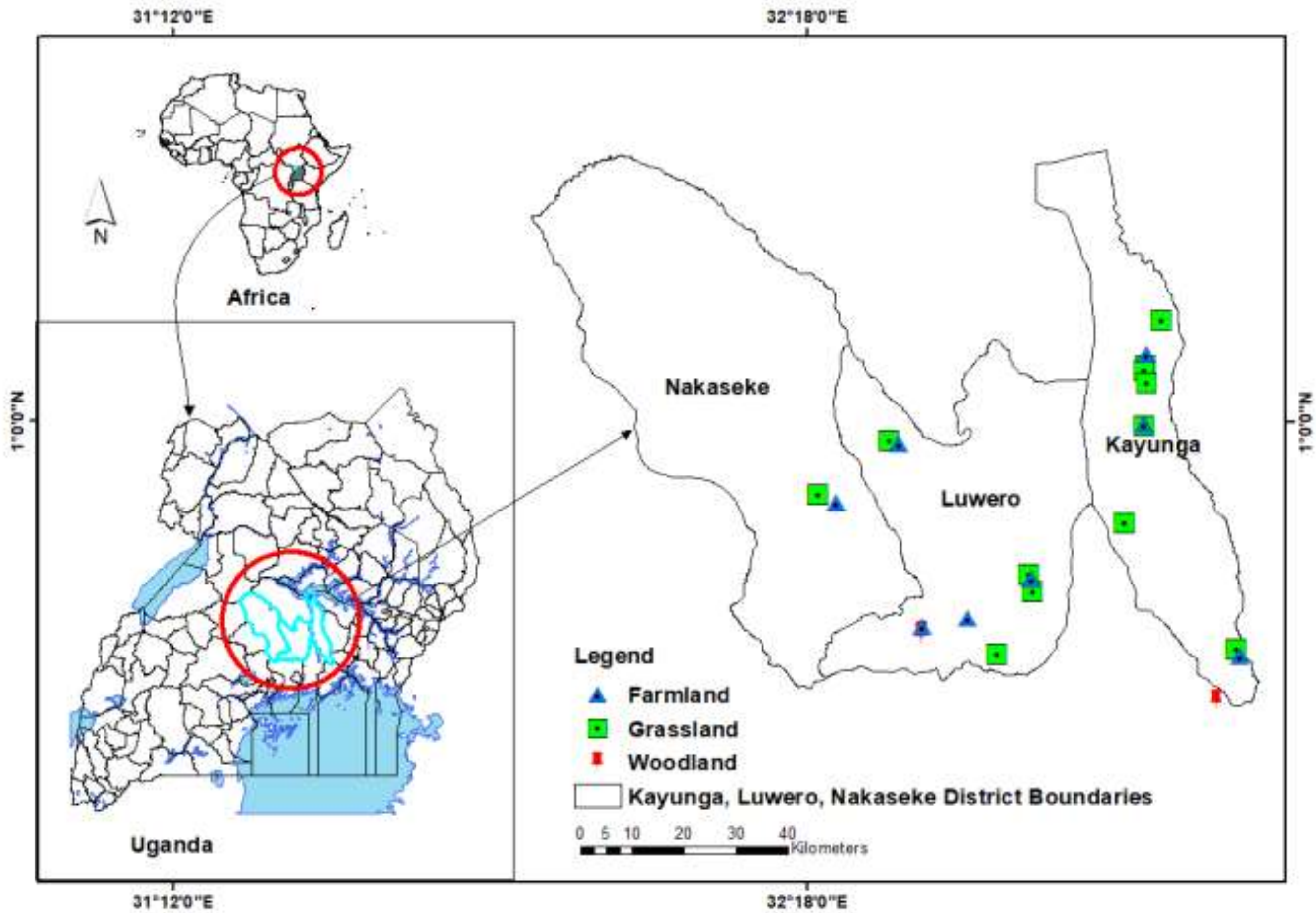

Figure 3. 1: Location of the study area, sampled districts and plots sampled

3.2 Study Design

A total of twenty-two (22) sampling plots, as depicted by Table 3.1were established to capture variation across the three land use types. Site selection was guided by ecological representativeness, accessibility, and security considerations. District political boundaries were not considered, as the objective was to represent key ecological gradients and major land use categories influencing bee diversity and distribution. Each site was separated by at least 1 km to reduce the likelihood of sampling the same bee populations, consistent with known foraging ranges (Gathmann & Tscharntke, 2002; Greenleaf et al., 2007; Walther-Hellwig & Frankl, 2000). Although the study districts are predominantly agricultural, continuous farmland plots of 100 m × 100 m were not always available. Many agricultural areas were small, fragmented, or intensively managed, limiting the ability to sample large homogeneous plots. Consequently, fewer farmland plots were included compared to grassland, while ensuring that selected plots remained ecologically representative and logistically feasible. This approach balanced accessibility, safety, and ecological coverage. Similarly, the limited number of woodland plots recorded may have been influenced by the size of the sampling plots relative to the distribution of woodland patches. Large plots could not be accommodated in the fragmented woodland areas, while smaller plots may not have captured the habitat adequately, resulting in under-representation. Eight bee surveys were conducted from August 2020 to September 2021, spaced 4 to 6 weeks apart to minimize repeated sampling effects on bee populations (Gezon et al., 2015). The overall research framework, including site selection, sampling methods, and data analysis, is summarized in Figure 3.2 to illustrate the sequence and integration of field activities.

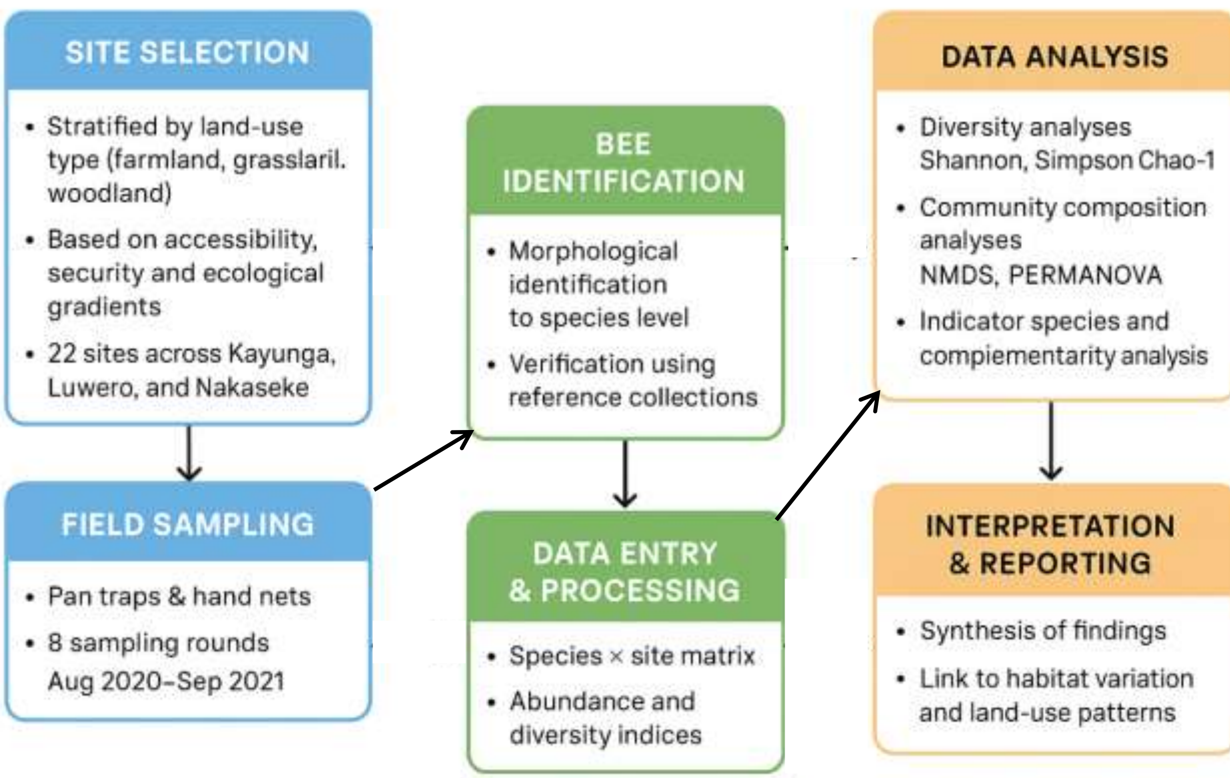

Figure 3. 2: Schematic representation of the study design

Table 3. 1: Study plots per district and land use

District	Number of sampled plots per land use type			
	Woodland	**Grassland**	**Farmland**	**Total**
Kayunga	1	7	3	11
Luwero	2	3	4	9
Nakaseke	0	1	1	2
Total	**3**	**11**	**8**	**22**

3.3 Bee Samples Collection

At each study site, a plot of 100 m x 100 m was established, and then divided into five sub-plots of 20 m x 20 m, with four sub-plots set at each corner and the fifth in the centre of the plot. During each survey, all plots were sampled once using two sampling techniques: pan-traps and sweep nets to maximise capture of available bees. Each sampling technique has its own bias, and certain bee taxa are well sampled using some techniques, but poorly sampled in others (Roulston, 2007; Westphal et al., 2008). In addition, different techniques are effective in different landscapes and habitat types. Therefore, a combination of techniques was used to minimise bias and sample the bee community as much as possible (Prendergast et al., 2020).

Pan traps of 17 cm diameter were used to sample bees in each subplot. Within each subplot, three pan traps of different colours, including blue, white, and yellow, were set; hence, a total of 15 pan traps per plot were deployed while alternating colours. To avoid interference between pan traps, a distance of 5 m was used to separate the pan traps in each sub-plot (Droege et al., 2010). Before deployment, each pan trap was sprayed with either white, yellow, or blue UV-reflecting paint and allowed to dry (Droege, 2015). Different colours were used because they attract different bee species and probably different sexes of the same species (Gollan et al., 2011). Pan traps were placed on stakes at a height of one metre above the ground (Figure 3.3) following a method outlined by Tuell & Isaacs (2009). About 200 ml of slightly soapy water was added to each to prevent the escape of any bees that were drawn to the pan trap. All pan traps were recovered 48 hours after deployment. Bee samples from pan traps of the same colour (in total, five traps of the same colour per plot) were pooled and individually transferred using a pair of flathead forceps to vials containing 70% ethanol. Data were recorded on the date and time of the pan trap set, the number of individual bees captured per pan trap colour, and the number and name of the bee species captured per pan trap colour.

Figure 3. 3: Established pan traps to collect bee samples

Additionally, a funnel-shaped sweep net was used to collect foraging bees encountered on flowers. At each plot, two diagonal transects of 140 m length and 2 m width were established; hence, a total of 44 transects were sampled per sampling event. At each transect, bees were sampled using a sweep net within a standardised 20-minute sampling time between 7:00 am to 6:00 pm during sunny, partially cloudy, bright, or overcast days. Sampled bees were immobilized using 70% ethanol and individually transferred to vials containing 70% ethanol. Bee samples from the two transects of each plot were pooled. To minimize bias, each transect was sampled at various times throughout the study. At each transect, data on date and time of sweep net, transect code, the number of individuals, and the name of the bee species recorded per transect.

3.4 Bee Sample Preservation, Storage, and Identification

In the laboratory, the collected bees were pinned on stainless steel insect pins (of variable sizes – #0, #1, #2, or #3 – depending on insect size) or glued to pinned card mounts if the bees were tiny

(≤ 3 mm) for easy identification (Droege, 2015). Bees were first sorted into morphospecies groups then identified to the genus level using published keys (Akol, et al., 2024; Eardley et al., 2010) (Eardley et al., 2010). Subsequently, species-level identifications were verified by three professional bee systematists, Skyler Burrows (Utah State University / USDA Bee Lab), Terry Griswold (USDA-ARS Bee Biology & Systematics Laboratory), and Alain Pauly (Royal Belgian Institute of Natural Sciences). All Voucher specimens were curated and assigned catalogue numbers before being added to the insect collection held at Makerere University Zoology Museum.

3.5 Plant Sampling

Three vegetation surveys were conducted in March, May, and September 2021. A nested quadrats plot design was used to conduct an inventory on the availability and diversity of floral resources in each plot (Bailey & Poulton, 1968; C. L. Elzinga et al., 1998). To cater for the different sizes of bee forages, at each plot, 50 m x 50 m plot was sampled for trees, four plots of 30 m x 30 m for shrubs, four plots of 5 m x 5 m for grasses, and four plots of 1 m x 1 m for herbaceous plants. At each plot, data on the percentage coverage of each plant habit (trees, grasses, shrubs, and herbs) was recorded. These were estimated using the Visual estimation of cover class following (Bailey & Poulton, 1968; C. Elzinga et al., 1998).

3.6 Variable Measurement and Quantification

Species abundance was recorded as the total number of individuals per species in each plot. Species richness (S) was defined as the number of distinct species recorded within a sampling plot or habitat. Bee diversity was quantified using the Shannon–Wiener index (H′), computed as $H' = -\Sigma pi\ ln(pi)$, where pi represents the proportion of individuals belonging to species i (Shannon, 1948). Evenness (J′) was calculated as $J' = H' / \ln(S)$, indicating the degree to which individuals were evenly distributed among species (Jost, 2010; Pielou, 1966). Dominance (D) was computed using the Simpson's dominance index, which estimates the probability that two individuals randomly selected from a sample belong to the same species (Simpson, 1949). The frequency of occurrence (FO) for each species was expressed as a percentage of the total plots in which a species was present, calculated as FO = (ni / N) × 100, where ni is the number of plots where species i occurred, and N is the total number of sampled plots. Following Palma (1975), species were classified based on their FO as primary (FO ≥ 50%), secondary (25% ≤ FO < 50%), or incidental (FO < 25%) species as cited by (Iantas et al., 2017). Environmental variables were also recorded for each sampling plot. Vegetation cover was quantified by visually estimating the percentage cover of trees, shrubs, herbs, and grasses within each plot. These cover estimates were later standardized (converted to proportions between 0 and 5) for use in multivariate analyses. Seasonal variation was incorporated into the study because bee activity and distribution in tropical regions vary strongly between dry and wet periods (Classen et al., 2015; Michener, 2007; Roulston & Goodell, 2011a). Each sampling round was classified as occurring in either the wet or dry season based on direct field observations, including rainfall patterns, soil moisture, flowering intensity, and vegetation condition recorded during each visit. In addition, information from local community members was used to confirm whether a given month was traditionally considered wet or dry in the area, as residents are familiar with local seasonal cycles. To further validate these assessments, rainfall and temperature data sheets were requested from the nearest meteorological stations for the corresponding sampling months. These combined sources allowed accurate categorization of sampling periods into wet and dry seasons for subsequent analyses All bee and environmental data were linked using a unique Plot Code identifier to facilitate dataset merging and analysis.

3.7 Data Analysis

All statistical analyses were conducted using R software (version 4.4; R Core Team, 2023) with the packages vegan (Oksanen, 2017), car (Fox J, 2019), and indicspecies (De Cáceres & Legendre, 2009). Abundance data were log-transformed to minimize the influence of dominant species and meet assumptions of normality (Welham et al., 2014). In this study, all environmental variables were count data and were standardized (z-scores) before analysis, and multicollinearity was assessed using Variance Inflation Factors (VIF), with variables exceeding a threshold of 10 removed (Fox J, 2019).

Objective 1: Determining Bee Diversity in Selected Districts

Bee diversity was quantified using Shannon–Wiener index (H′), Simpson’s dominance index (D), evenness (J′), and species richness (S), calculated using the diversity() and specnumber() functions in vegan. These indices capture different facets of diversity: H′ incorporates richness and evenness, D emphasizes dominance, and J′ quantifies evenness. Differences in diversity among habitats were tested using one-way ANOVA, with the Kruskal–Wallis test applied when assumptions of normality or homogeneity of variance were violated. Post-hoc pairwise comparisons were performed using Tukey's Honest Significant Difference (HSD) test (Tukey, 1949). To assess similarity in bee species composition among habitats, the Jaccard similarity index was calculated using presence or absence data. Pairwise comparisons between farmland, grassland, and woodland were conducted using the vegdist() function in the vegan package in R, and values were interpreted to quantify the proportion of shared species between habitats.

Objective 2: Analysing Key Environmental Factors Influencing Bee Diversity

To identify environmental drivers of bee community composition, Redundancy Analysis (RDA) was performed using the rda() function in vegan (Borcard et al., 2018; Rao, 1964). The significance of environmental predictors (trees, shrubs, herbs, grasses, land use, and season) was assessed using anova.cca(). To complement the multivariate approach, multiple linear regression was fitted with Shannon diversity as the dependent variable and vegetation cover, habitat type, and season as independent variables. This combination of RDA and regression provides both multivariate and univariate perspectives on environmental influences, minimising redundant analyses.

Objective 3: Evaluating the Complementarity and Effectiveness of Pan Traps ond Sweep nets

Differences in bee community composition between pan traps and sweep nets were assessed using Permutational Multivariate Analysis of Variance (PERMANOVA) based on Bray–Curtis dissimilarity (Anderson, 2017; Bray-Curtis, 1957). Community patterns were visualised using Principal Coordinates Analysis (PCoA), while species accumulation and rarefaction curves (specaccum() and rarecurve()) evaluated sampling completeness across methods (Gotelli, 2008). Indicator Species Analysis (multipatt() function) was conducted to identify species significantly associated with either method (De Cáceres & Legendre, 2009). Finally, a complementarity index quantified the proportion of unique species contributed by each sampling method (Colwell & Coddington, 1994). To explore the influence of habitat on method-specific captures, a multiple regression model was fitted with Shannon diversity as the response and habitat as the predictor. Habitat was treated as a categorical variable.

CHAPTER FOUR: RESULTS

4.1 Diversity of Bees in Selected Habitats in the Districts of Central Uganda

4.1.1 Sample Coverage and Completeness

Sample coverage was high across all three habitats: farmland, grassland, and woodland (Figure 4.1). Species accumulation curves did not reach an asymptote, indicating that additional bee species were likely present but remained undetected, particularly in grassland and woodland (Figure 4.2)

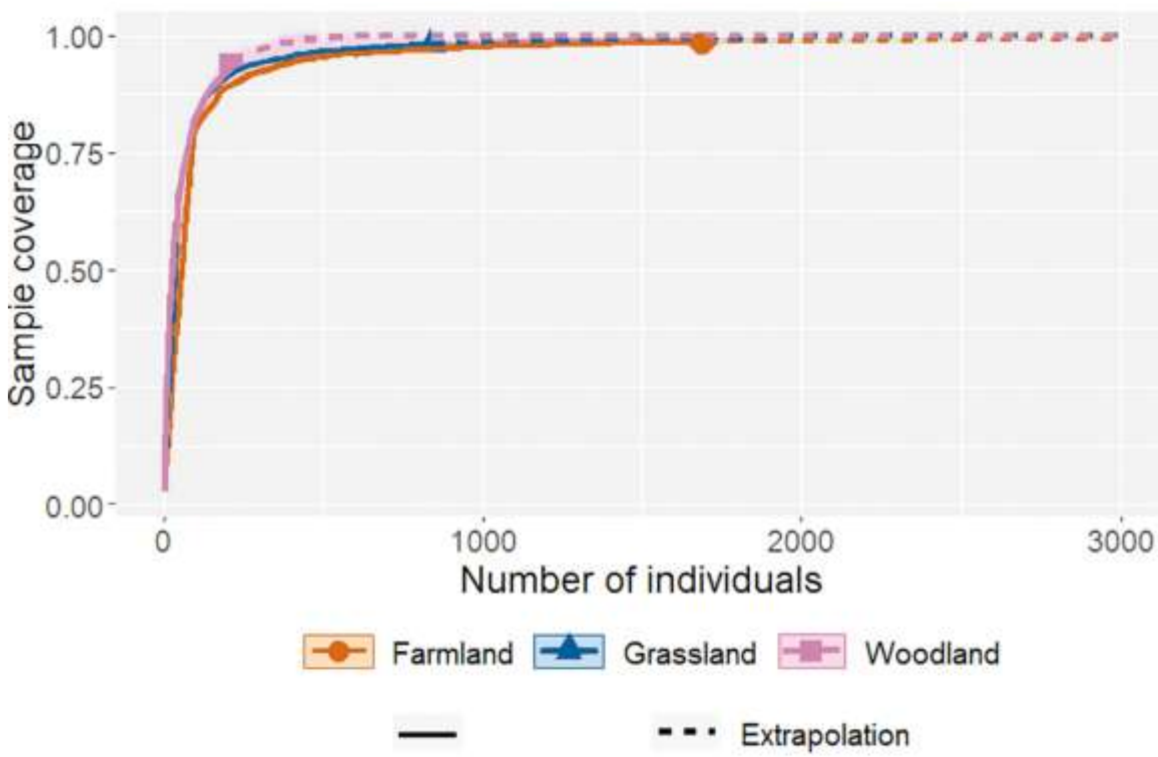

Figure 4. 1: Bee species sample coverage

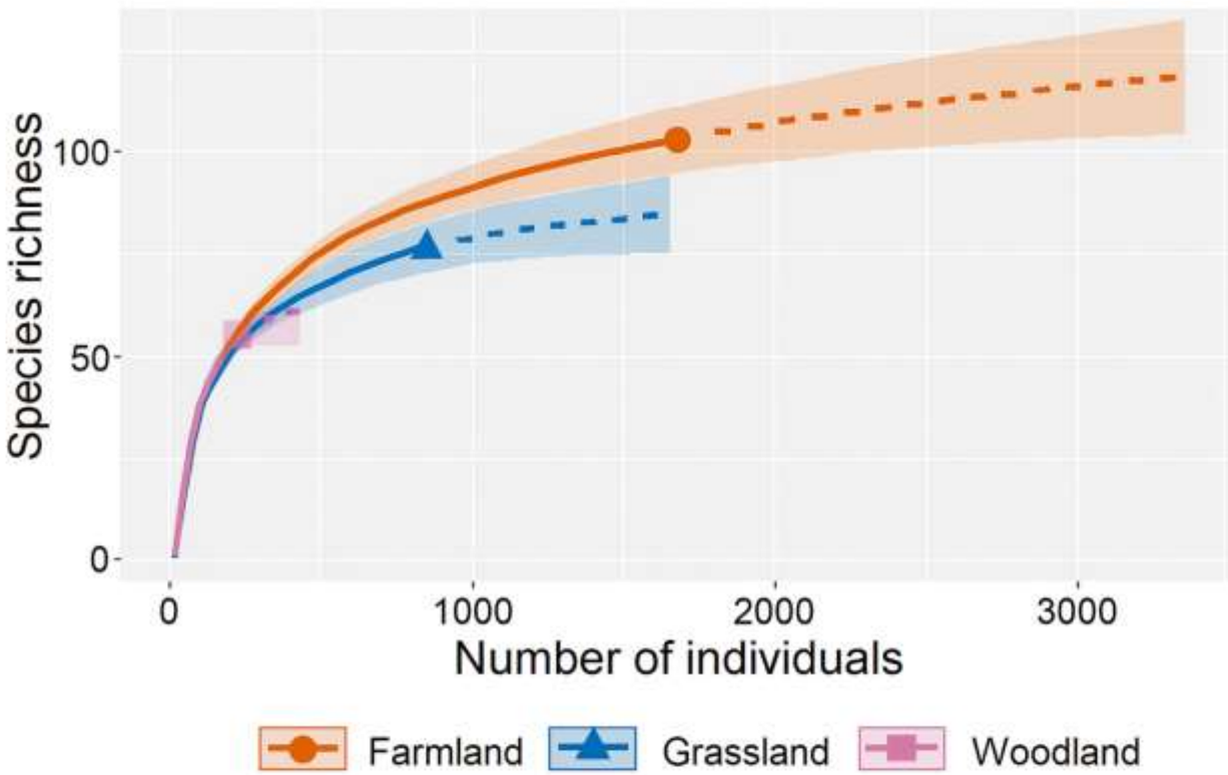

Figure 4. 2: Bee species accumulation curve

4.1.2 Overall bee community composition and habitat distribution

A total of 2,743 individuals were collected, comprising 4 families (Apidae, Colletidae, Halictidae, and Megachilidae), 47 genera, and 112 species across the three habitats over eight sampling events. Across habitats, as shown in Table 4.1, farmland supported the highest species richness (103 species), followed by grassland (76 species) and woodland (55 species), with corresponding differences in abundance (1,685 individuals in farmland, 841 in grassland, and 217 in woodland). At the district level, as shown in Table 4.1, Kayinga recorded the highest richness (80 species) and abundance (1896 individuals), followed by Luwero (65 species; 667 individuals) and Nakaseke (41 species; 180 individuals). Genus-level, as revealed by Table 4.1 richness varied across habitats and districts, with farmland recording the highest number of genera (40), followed by grassland (34) and woodland (29) Across districts, Kayunga had the greatest genus richness (38), compared to Nakaseke (24) and Luwero (34), as summarised in Table 4.1. Family Apidae had the highest percentage of individuals (50.5%), the greatest number of species (56) and genera (18), followed by Halictidae (28.6% of individuals, 33 species, 14 genera), Megachilidae (20.5% of individuals, 21 species, 13 genera), and Colletidae (0.1% of individuals, 2 species, 2 genera) (Figure 4.3). Apis mellifera was the most abundant species (n = 228, Appendix 1). A total of 20 singleton and 6 doubleton species were recorded (Appendix 1). Family Apidae was the most represented family across all habitats, indicating dominance in the sampled communities. Genera such as *Allodape*, *Amegilla*, and *Ceratina* had multiple species distributed across all habitats, while certain species were limited to specific habitats (Appendix 5). Family Colletidae occurred in fewer habitats, with *Colletes* sp. in grassland and woodland, and *Hylaeus* sp. restricted to farmland. Halictidae showed considerable diversity, with *Nomia* and *Thrinchostoma* species across all habitats, whereas *Nubenomia* and *Pachynomia* species were habitat-specific. Megachilidae showed broad presence, with genera *Megachile* and *Coelioxys* in all habitats, but *Afrostelis tegularis* was restricted to woodland (Appendix 5). Most abundant species per habitat included Apis mellifera (n = 228), *Plebeina armata* (n = 102), and *Lipotriches* sp. (n = 85) in farmland (Appendix 2); *Megachile rufipennis* (n = 45), *Nomia* sp. (n = 42), and *Xylocopa olivacea* (n = 40) in grassland (Appendix 3); and *Allodape collaris* (n = 38), *Xylocopa olivacea* (n = 35), and *Halictus* sp. (n = 33) in woodland (Appendix 4).

Table 4. 1: Distribution of bee taxa (family, genus, species) and individuals across habitat types and districts in the study area.

Taxon	**Habitat**			**District**			**Total**
	Farmland	**Grassland**	**Woodland**	**Luwero**	**Kayunga**	**Nakaseke**	
Family	4	4	4	4	4	3	4
Genus	40	34	29	34	38	24	47
Species	103	76	55	65	80	41	112
Individuals	1685	841	217	667	1896	180	2743

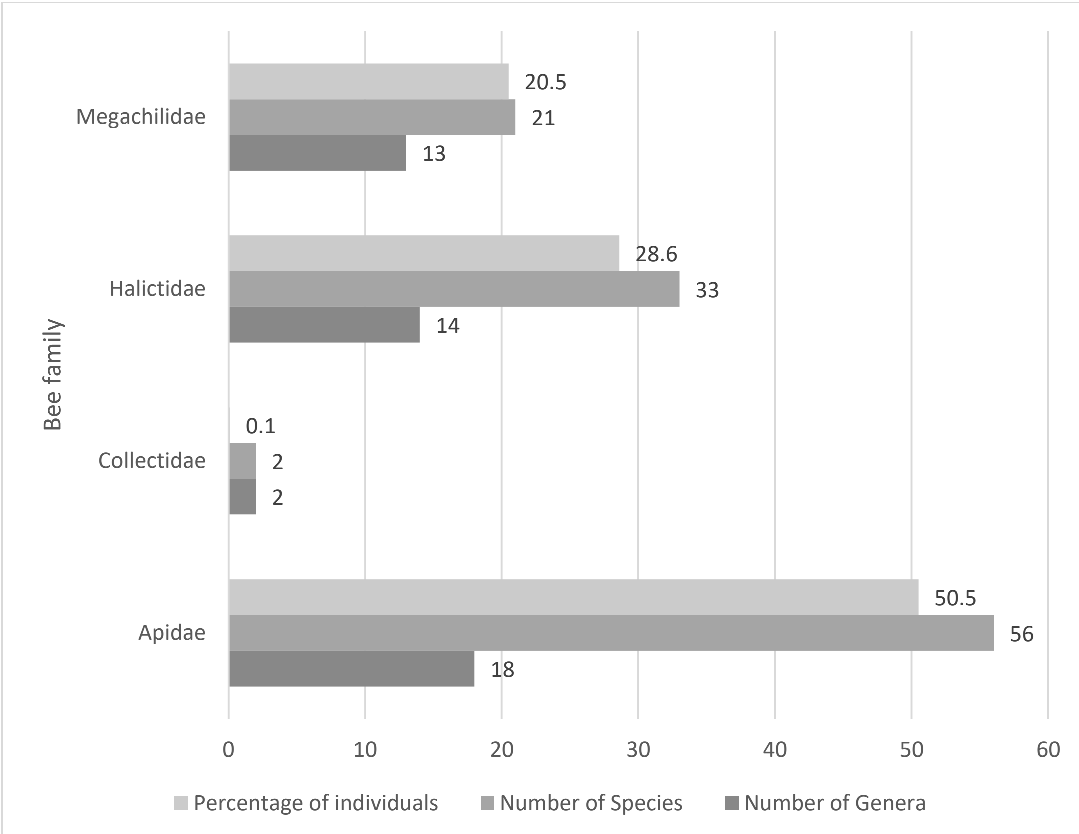

Figure 4. 3: **Bee occurrence by family**

4.1.3 Frequency of Occurrence and Dominance Patterns

Out of 112 species, 72 (64.29%) were incidental, 26 (23.21%) were primary, and 14 (12.50%) were secondary (Figure 4.4). In Apidae, 25 species (45%) were incidental, 19 species (34%) were primary, and 12 species (21%) were secondary. In Halictidae, 21 species (64%) were incidental, 6 species (18%) were primary, and 6 species (18%) were secondary (Table 4.2). Megachilidae showed a more balanced distribution, with 10 species (48%) incidental, 7 species (33%) primary, and 4 species (19%) secondary while all species in Colletidae were incidental (Table 4.2). Primary species such as *Apis mellifera* (FO: 100%), *Braunsapis facialis* (FO: 95.5%), and *Ceratina* sp. 1 (FO: 86.4%) were frequently encountered across habitats. Conversely, species like *Allodape collaris* (FO: 9.09%) and *Braunsapis lyrata* (FO: 9.09%) were rarely observed (Appendix 6). Dominance values were generally low, indicating most species were incidentally present; however, *Apis mellifera* (0.083), *Plebeina armata* (0.055), and *Megachile rufipennis* (0.059) had the highest dominance (Appendix 6).

Table 4. 2: Species frequency summary by family

Family	Frequency Category			Total Species
	Incidental	**Primary**	**Secondary**	
Apidae	25	19	12	56
Colletidae	2	0	0	2
Halictidae	21	6	6	33
Megachilidae	10	7	4	21

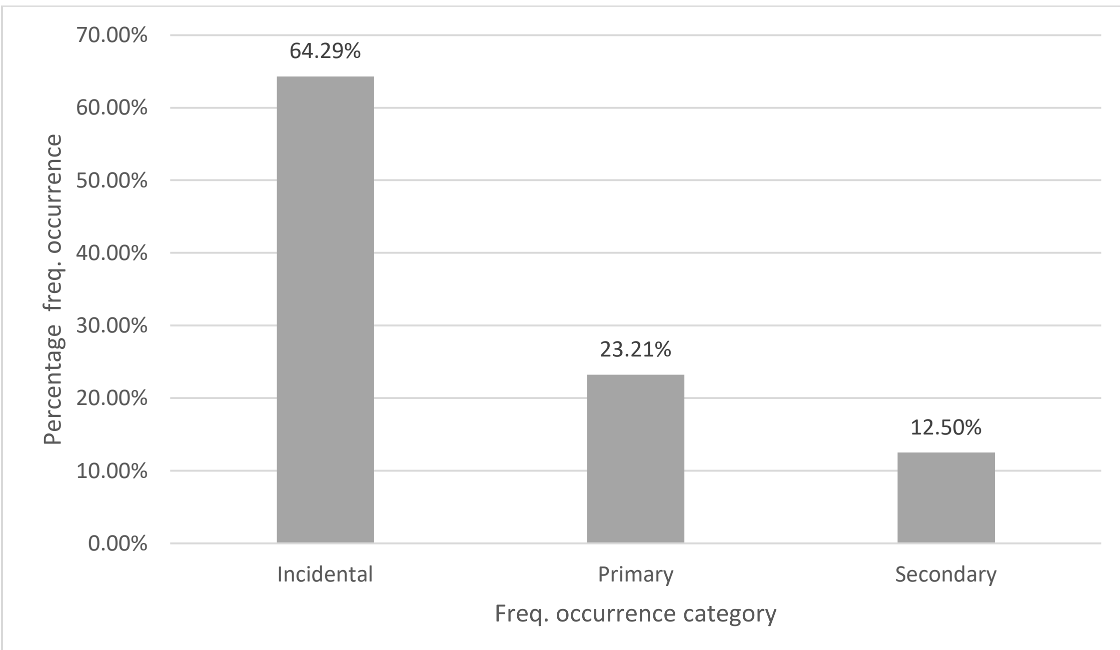

Figure 4. 4: Frequency of bee occurrence per category

4.4.4 Bee Diversity and Species Similarity Across Habitats

There were no significant differences in bee diversity (Shannon-Wiener (H') or Dominance indices) among habitats (ANOVA, H': F=1.02, p=0.368; Dominance: F=1.05, p=0.3679). However, farmland had the highest Shannon diversity (3.73), followed by grassland (3.69) and woodland (3.68). Dominance was lowest in woodland (0.074), resulting in more even distribution of species, with the highest Evenness index (0.919). Species richness was highest in farmland, followed by grassland and lowest in woodland (Table 4.3). Approximately 37.63% of species were shared between farmland, and grassland. Jaccard Index between farmland and woodland was 0.3874, and between grassland and woodland 0.3861, indicating moderate similarity across habitats (Table 4.4).

Table 4. 3: Bee diversity indices across different habitats

Habitat	**Species**	**Shannon**	**Dominance**	**J-evenness**
<chr>		*<dbl>*	*<dbl>*	
Total Species recorded	112			
Farmland	102	3.73	0.115	0.8053534
Grassland	77	3.69	0.125	0.8531916
Woodland	55	3.68	0.074	0.9189658

Table 4. 4: Similarity of bee species composition across habitats

Habitat	**Jacard index**
Farmland-Grassland	0.3763
Grassland-Woodland	0.3861
Woodland-Farmland	0.3874

4.2 Environmental Factors Influencing Bee Diversity and Distribution

The dendrogram (Figure 4.5) revealed that KP4Grass and KP5Wood plots formed separate branches, distinct from other plots, based on bee species composition. Grassland plots KP7Grass, KP10Grass, KP13Grass, and LP14Grass cluster together, while farmland plots LP10Farm, LP5Farm, and KP2Farm also form a cluster. KP6Farm and KP9Grass share a branch, indicating similar grouping across these plots. A Redundancy Analysis (RDA) model, which included vegetation cover and season as predictors, explained approximately 21.4% of the total variation in genus composition, and the overall test of significance was not statistically significant (p =

0.75) (Table 4.6). The first two RDA axes accounted for 12.8% and 8.6% of the constrained variation, respectively. Vectors representing herbs and grasses were longer than those of trees and shrubs, indicating stronger associations with changes in genus composition. Season appeared moderately aligned along the first axis, suggesting slight seasonal differences among sampling plots. The ordination displayed a scattered distribution of genera across gradients, indicating varying responses of bee genera to vegetation cover and seasonal variation. Variance Inflation Factors (VIFs) for environmental predictors were below 2.1 (Table 4.5), indicating no multicollinearity among the explanatory variables. Individual permutation tests for each environmental factor showed no significant effect ($p > 0.05$), though herbs and grasses explained a slightly higher portion of variation compared to trees and shrubs (Table 4.6). The multiple linear regression model examined the relationship between bee diversity and environmental variables, including vegetation cover (trees, shrubs, herbs, and grasses) and season. The model results (Table 4.7) showed that tree, shrub, herb, and grass cover had no statistically significant effect on bee diversity ($p > 0.05$). However, season had a significant positive effect ($p = 0.008$), indicating that bee diversity was higher during the wet season compared to the dry season. The regression coefficient for the wet season (0.763) suggests an increase of approximately 0.76 units in bee diversity relative to the dry season baseline. Genera *Lithugus, Lipotriches* and *Pseudapis* were more associated with herb cover, *Megachile* with grasses while *Plebeina* and *Ceratina* with wet season (Figure 4.7). Most of the genera clustered near the origin indicating their distribution is not associated with any environmental factor (Figure 4.6 and 4.7)

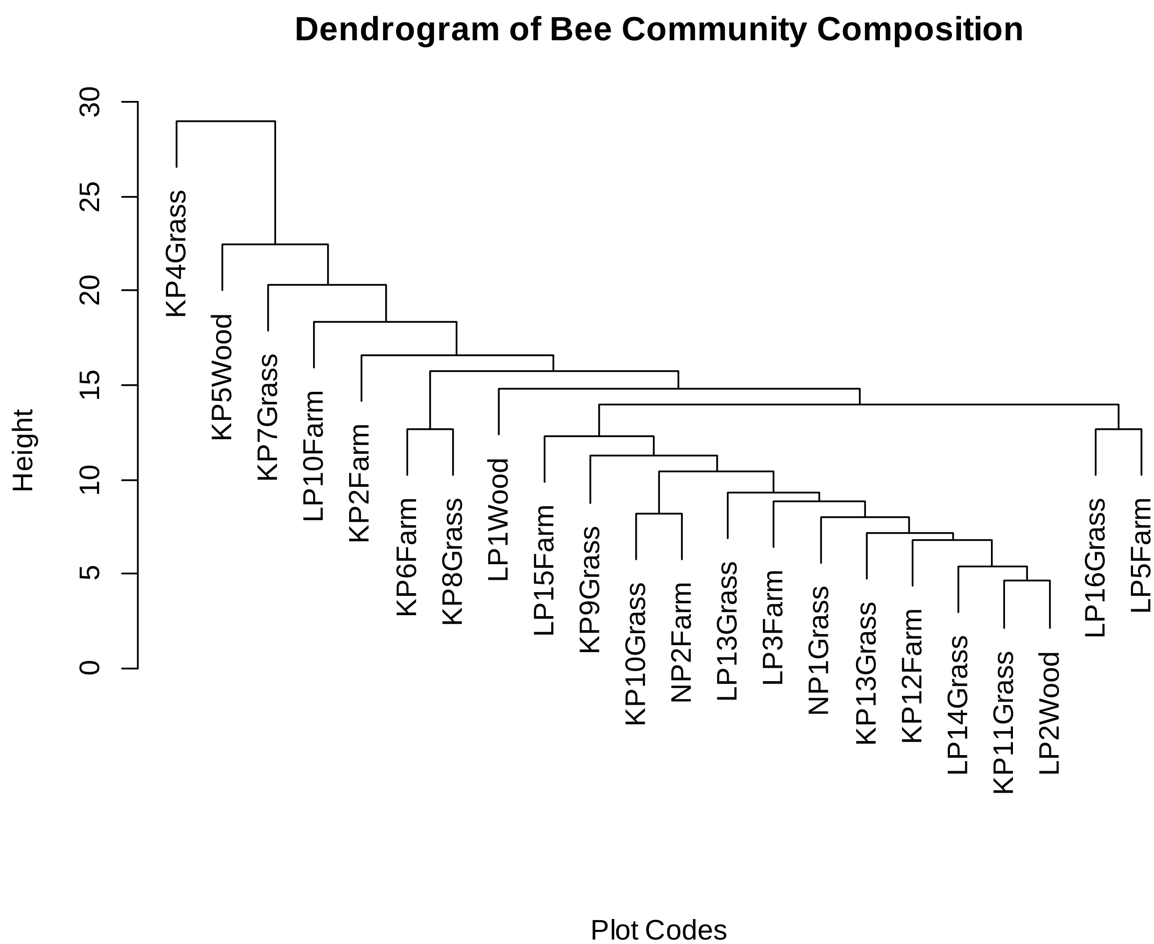

Figure 4. 5: Hierarchical clustering of bee community composition across different study plots

Table 4. 5: Variance Inflation Factors (VIFs) for environmental predictors.

Variable	Variance Inflation Factors
Trees	1.34
Shrubs	1.33
Herbs	2.01
Grasses	1.90
Season (Wet/Dry)	1.03

Table 4. 6: Summary of RDA model performance and permutation test.

Statistic	Value
Total variance explained (R^2)	0.214
Permutation test p-value	0.75
Number of plots	22

Table 4. 7: Relationship between bee diversity and environmental variables

	coef	**std err**	**t**	**P>|t|**	**[0.025**	**0.975]**
const	1.987	0.198	10.030	0.000	1.586	2.389
Trees	-0.062	0.158	-0.399	0.692	-0.383	0.257
Shrubs	0.076	0.158	0.485	0.631	-0.245	0.398
Herbs	-0.008	0.191	-0.045	0.965	-0.395	0.378
Grasses	-0.085	0.183	-0.470	0.641	-0.456	0.285
Season Wet	0.763	0.274	2.787	0.008	0.208	1.319

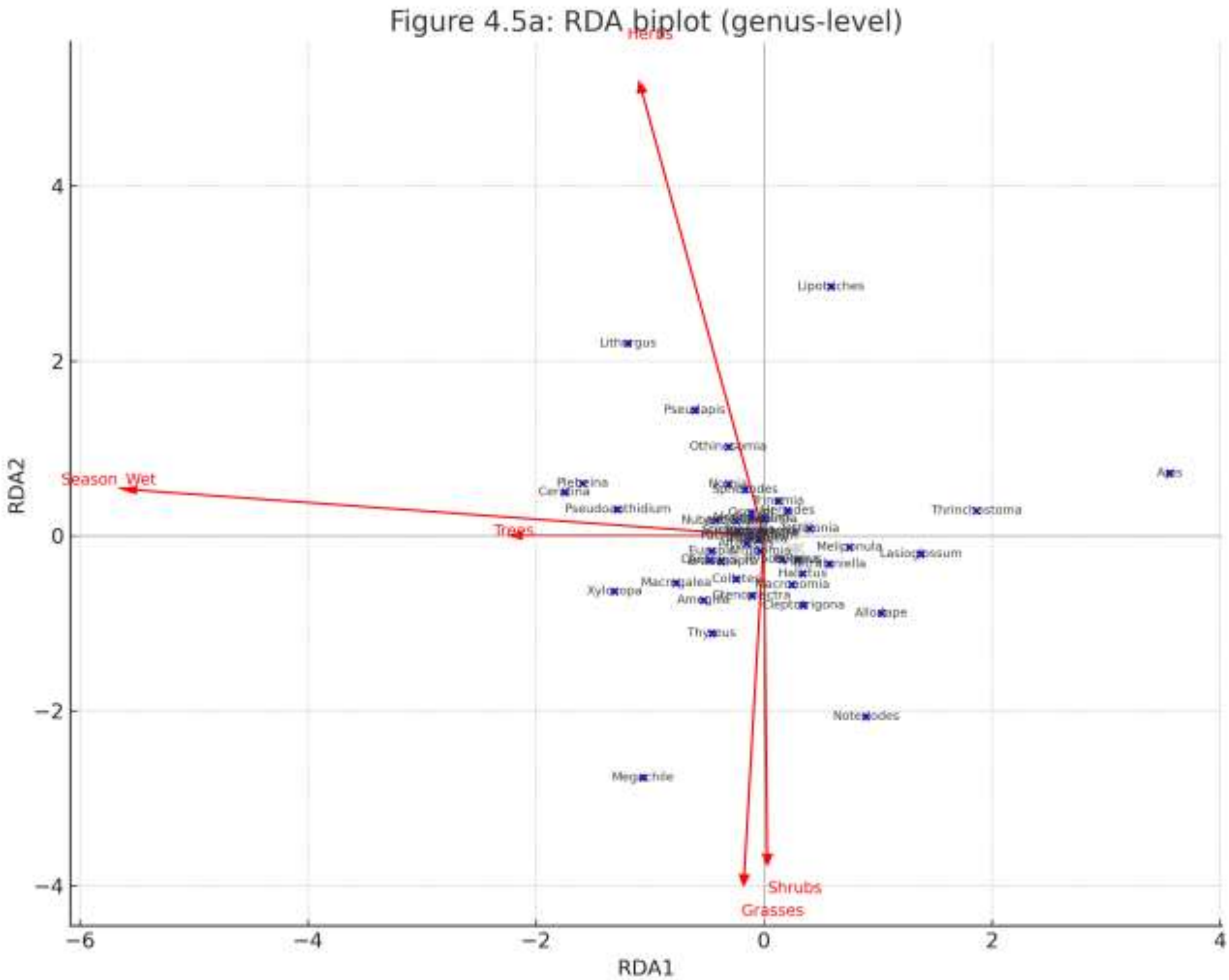

Figure 4. 6: RDA biplot of bee genera and environmental gradients (trees, shrubs, herbs, grasses, and season).

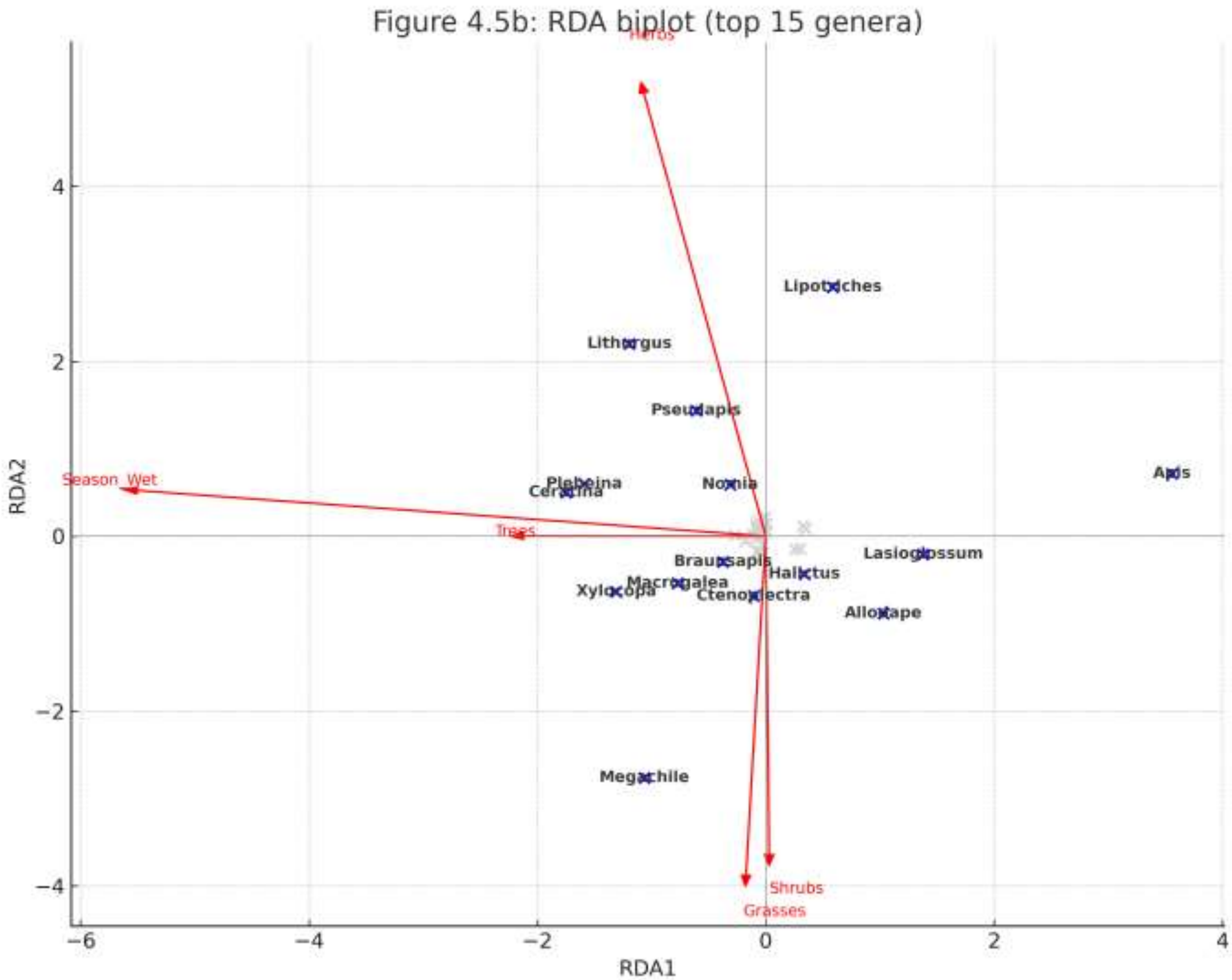

Figure 4. 7: RDA biplot of the top 15 most abundant genera in relation to key environmental variables.

4.3 Complementarity and Effectiveness of Pan Traps and Sweep nets as Sampling Methods for Studying Bee Diversity

4.3.1 Species Richness and Shannon Diversity in Sweep net and Pan Trap Sampling Methods

The sweep net method captured higher number of species (103) compared to 68 species in pan traps (Table 4.8). The Wilcoxon signed-rank test for species richness produced a p-value of 0.002959, indicating a statistically significant difference between the two methods. sweep nets had a value of 3.88 for the Shannon Diversity Index, compared to 3.19 for pan traps. However, the Wilcoxon signed-rank test yielded a p-value of 1, indicating no significant difference in bee diversity captured by the two methods. In terms of abundance, the sweep net method captured a higher number of individuals than the pan trap (1974 and 683 individuals respectively), and the difference in the number of individuals captured by the two methods was significant (p=0.0055). sweep nets captured a total of 44 species, which were not captured by pan traps. Pan traps captured 09 species that were not captured by sweep nets. There was an overlap of 59 species that were captured by both sweep nets and pan traps (Figure 4.8).

Table 4. 8: Species richness, Shannon diversity and Simpson diversity for Sweep net and pan trap sampling methods

Method	Species_Richness	Shannon_Diversity	Simpson_Diversity
<chr>	*<int>*	*<dbl>*	*<dbl>*
Sweep net	103	3.88	0.969
Pan trap	68	3.19	0.934

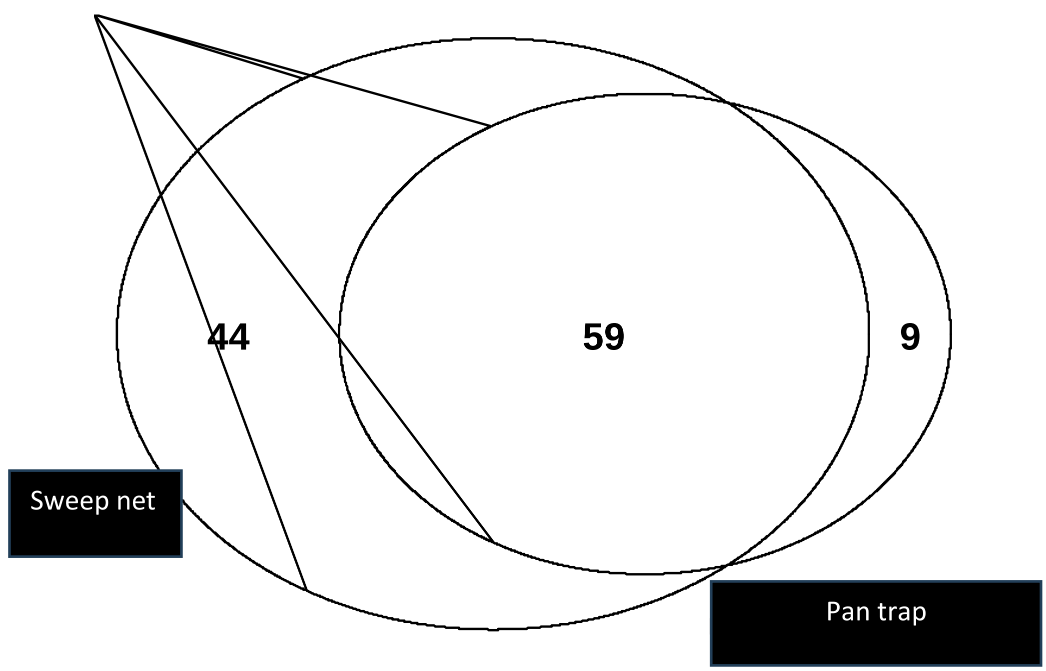

Figure 4. 8: Venn diagram illustrating the overlap and unique bee species captured by sweep nets and pan traps

4.3.2 Bee Community Composition Across Sampling Methods

Results indicated that each method sampled distinct subsets of the bee community, though there was an overlap as both methods captured similar species (Figure 4.9). Similarly, there were clear distinctions in bee species composition captured based on the sampling method and habitat. The analysis revealed a distinct clustering of bee species according to the sampling method used and the specific habitat type. Each sampling method captured unique subsets of the bee community, as evidenced by the clustering patterns (Figure 4.9). However, the PERMANOVA results indicated that the method of sampling did not have a statistically significant effect on the dissimilarity of bee communities ($F = 0.5909$, $p = 1$). The explained variance by the sampling method was very low ($R^2 = 0.00348$).

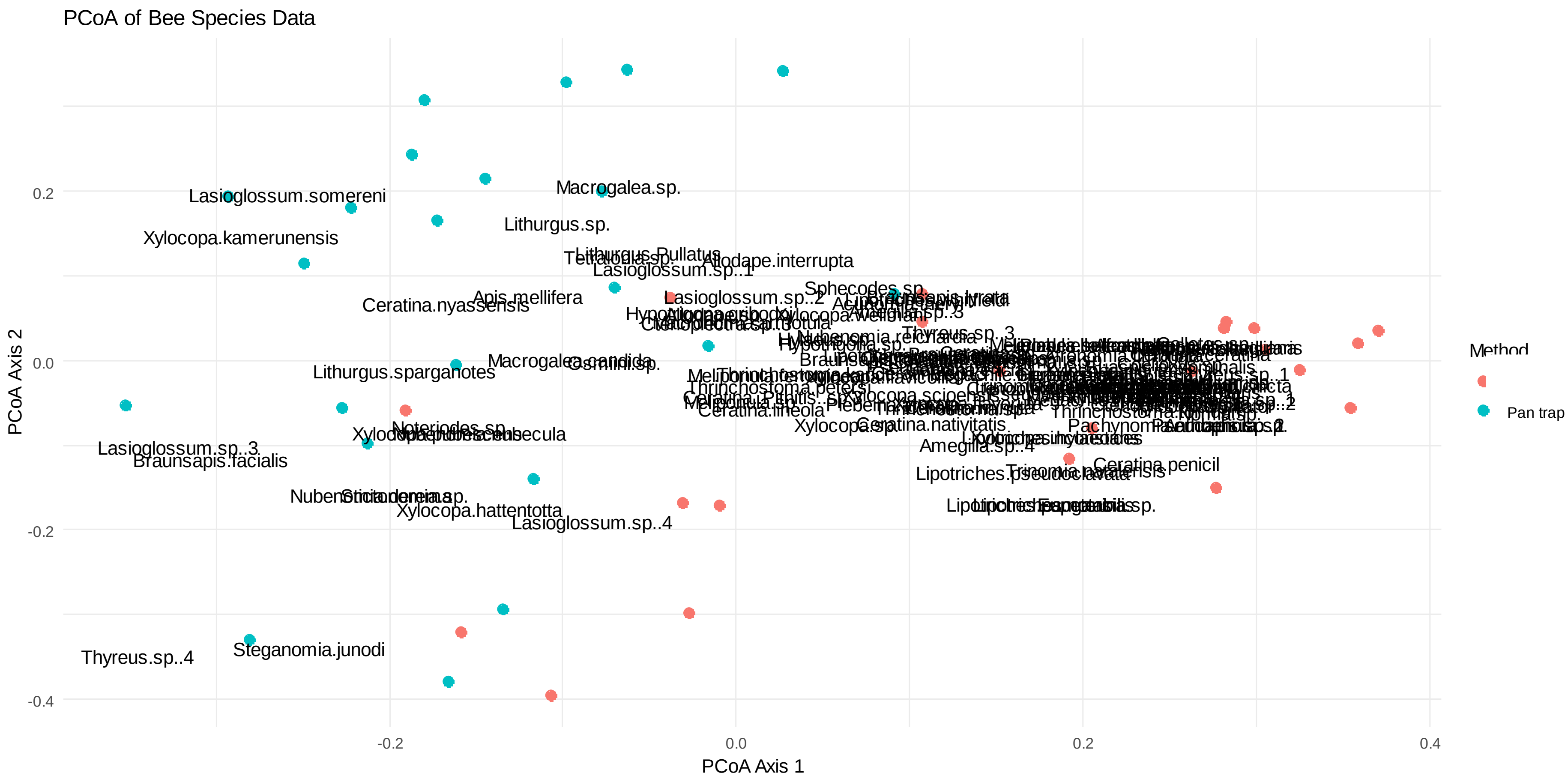

Figure 4. 9: Principal coordinates analysis plot of bee species composition captured by methods

4.3.3 Species Accumulation Analysis for Sampling Methods

Based on the species accumulation curves (Figure 4.10), sweep nets consistently captured more species across all sample sizes compared to pan traps. At the smallest sample size, the species richness detected by sweep nets were higher than that of pan traps, and this trend continued as more samples were collected. The curve for sweep nets show a steeper increase in species richness, indicating that this method is more efficient in capturing a diverse range of bee species. In contrast, the pan traps curve rose more slowly, indicating a lower rate of species detection. The difference between the two methods was evident, as shown by the clear gap between the two curves. The sweep nets reached a species richness of over 80 species by the sixth sample, while pan traps only captured around 60 species by the same point. Both curves appear to approach an asymptote, implying that additional sampling may result in diminishing species accumulation. Based on the rarefaction curves comparing the two sampling methods, sweep nets consistently recorded higher species richness for a given number of individuals compared to Pan Traps. Both methods demonstrated an increase in species richness as more individuals were sampled, with sweep nets reaching higher species richness values more rapidly (Figure 4.11).

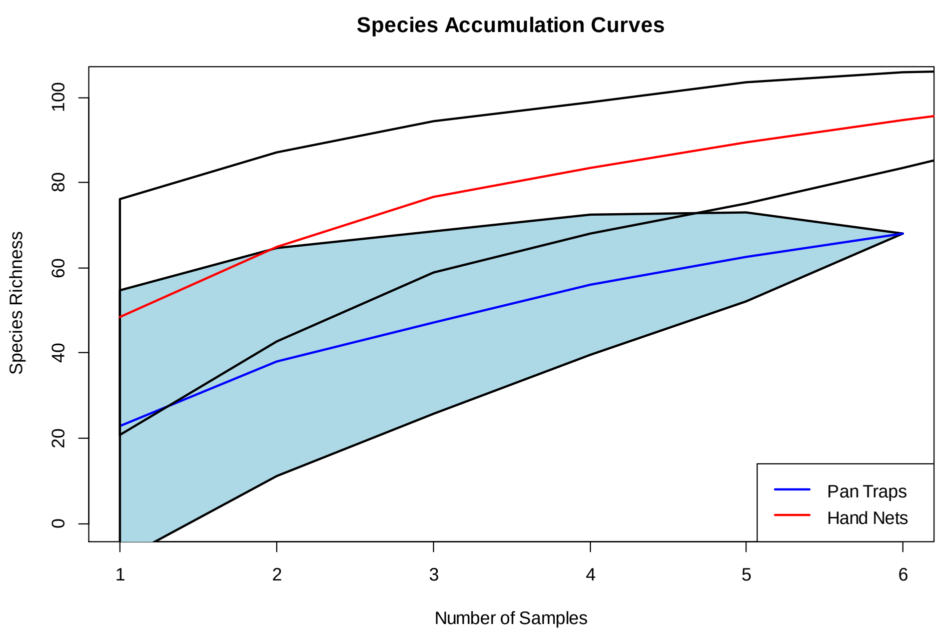

Figure 4. 10: Species accumulation by sampling methods

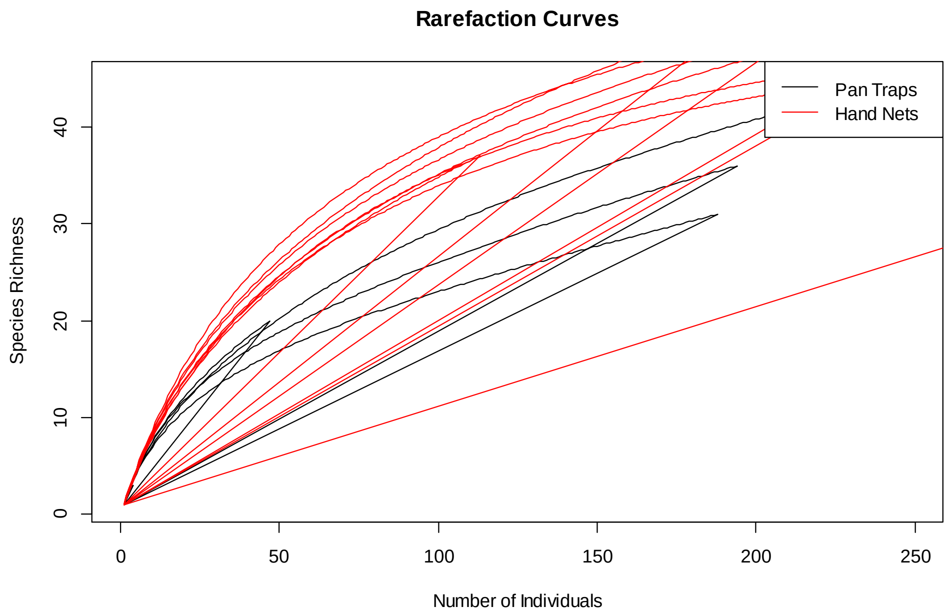

Figure 4. 11: Rarefaction curves showing species richness as a function of the number of individuals sampled using two methods: Pan traps (black) and Sweep nets (red).

4.3.4 Complementarity and Redundancy Analysis of Pan Traps and Sweep Nets in Sampling Bee Diversity

The complementarity index was found to be approximately 0.47. This indicates that 47% of the species observed were captured by either pan traps or sweep nets. The pan trap method recorded a set of species not captured by sweep nets, and vice versa while 53% of the species were common to both methods. When combined the data from both pan traps and sweep nets, the total species richness was higher (112 species) compared to 103 and 68 species for sweep net and pan trap respectively. Similarly, overall diversity index was hight (4.28) compared to the diversity capture by each individual method. There was a notable variation in species captured exclusively by either method or shared between them (Appendix 7). For instance, *Afronomia fimbriata*, *Afrostelis tegularis*, *Braunsapis lyrata*, *Ceratina ceratina*, *Ceratina penicil*, *Ceratina penicillata*, *Cleptotrigona cubiceps*, *Euaspis abdominalis* where only recorded by the sweep net method (Appendix 7). In contrast species such as *Braunsapis facialis*, *Ceratina nyassensis*, *Lasioglossum somereni*, *Lithurgus pullatus*, *Nubenomia derema*, *Nubenomia nubecula*, and *Xylocopa kamerunensis* were only recorded by Pan trap while *Acunomia theryi*, *Allodape* *collaris, Allodape interrupta, Apis mellifera* and *Braunsapis foveate were recorded by both methods* (Appendix 7).

4.3.4 Performance of Methods in Across Habitats

The results indicate that the sweep net method consistently captured a higher species richness across all habitats compared to the pan trap method (Figure 4.12). The grassland and woodland habitats, in particular, showed the greatest species richness when sampled using the sweep net, with a wider range of species captured. In contrast, pan traps performed poorly in all habitats, capturing far fewer species, especially in the woodland and grassland habitats (Figure 4.12). Although there were differences in the number of species captured by each method across habitats, these differences were not statistically significant (P>0.05).

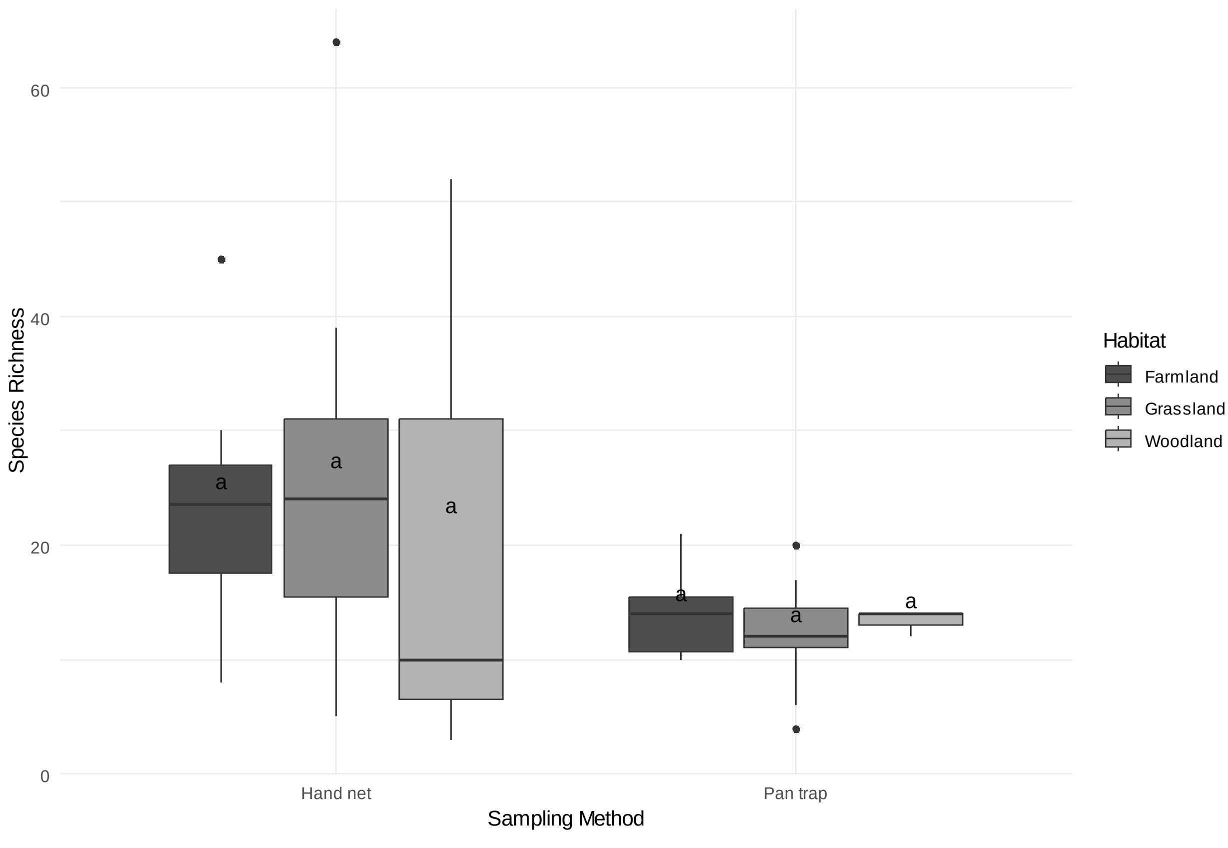

Figure 4. 12: Performance of Sweep net and Pan trap methods across habitats

CHAPTER FIVE: DISCUSSION, CONCLUSIONS, AND RECOMMENDATIONS

5.1 Discussion

Sample coverage was high across all three habitats farmland, grassland, and woodland indicating that the dominant bee species were effectively captured by the sampling methods used. However, species accumulation curves did not reach an asymptote, particularly in grassland and woodland, suggesting that additional bee species were likely present but remained undetected. This pattern is consistent with other studies in tropical and heterogeneous habitats, where incomplete species accumulation curves often reflect the presence of rare or cryptic species despite substantial sampling effort (Conrad et al., 2021; Maia et al., 2020). The under-detection of species may result from factors such as habitat heterogeneity, differences in species' foraging behaviour, or limited attraction to the sampling methods used. Studies have also shown that using multiple complementary sampling methods improves detection of species, particularly rare ones, highlighting the need for diverse sampling approaches in bee surveys (Klaus et al., 2024; Prendergast et al., 2020). Increasing sampling effort, covering multiple seasons, and employing complementary methods could therefore provide a more complete assessment of bee diversity across these habitats.

5.1.1 Bee Diversity Across Habitats

The study revealed that farmland habitats supported the highest bee species richness, followed by grassland and woodland, although differences in Shannon Wiener diversity were not statistically significant. This general pattern suggests that heterogeneous farmland landscapes provide a wider range of floral resources and nesting sites, supporting a greater number of bee species, including both generalists and specialists. Similar trends have been reported in other tropical and subtropical regions, where modified habitats with mixed vegetation cover support higher bee richness compared to relatively undisturbed woodlands or monoculture systems (Kasina et al., 2009; Stanley et al., 2009). A major observation in this study is the dominance of the Apidae family across all habitats, particularly *Apis mellifera*, which was the most abundant species. This could be due to the presence of apiary farms within the study area. Despite its dominance, *A. mellifera* coexisted with a range of other species, indicating a relatively balanced bee community ecosystem. This pattern is consistent with studies from other tropical regions where Apidae commonly dominates bee assemblages due to its ecological adaptability (Eardley et al., 2009). The Halictidae family also showed considerable diversity, reflecting its capacity to thrive in different habitat conditions. In contrast, the Colletidae family was less represented, which may reflect specific habitat preferences, consistent with other studies that have found Colletidae to be relatively uncommon in tropical ecosystems (Eardley et al., 2009). These findings highlight the need for conservation actions that take into account the ecological requirements of less common families, which may be more sensitive to environmental change.

Although the Shannon and Dominance indices did not differ significantly among habitats, the slightly higher diversity observed in farmland agrees with findings from other studies, which show that habitat heterogeneity particularly compositional and configurational heterogeneity within agricultural landscapes often promotes pollinator richness and stability compared with homogeneous land uses (Fahrig et al., 2011; Garibaldi, et al., 2014; Kennedy et al., 2013). The results also suggest that habitat modification does not always lead to a loss of bee diversity. Instead, the structure and arrangement of vegetation can help maintain diverse bee communities. For example, farmlands containing scattered trees, shrubs, and herbaceous plants may provide continuous floral resources throughout the season, while woodland habitats, though structurally complex, may have fewer flowering plants accessible to some bee species.

The higher species richness and abundance recorded in farmland compared to grassland and woodland suggest that heterogeneous agricultural environments provide a mosaic of floral resources and nesting substrates that support diverse bee communities. This pattern aligns with findings from tropical smallholder systems, where habitat heterogeneity has been shown to enhance wild bee richness and community structure (Basu et al., 2016). However, district-level differences indicate that broader landscape factors also strongly influence bee diversity. For example, Kayunga exhibited particularly high richness, which may reflect favorable land use intensity, diverse vegetation structure, and abundant resources, whereas the relatively lower richness observed in Luwero and Nakaseke could be linked to higher land use disturbance or reduced habitat diversity. Similar landscape-driven differences in bee communities have been reported in East African agro-ecological systems, where the availability of nesting sites and landscape connectivity strongly shape bee distribution (Guenat et al., 2018; Vogel et al., 2021). Overall, these results underscore that both local habitat conditions and broader landscape structure jointly determine the distribution and diversity of bee species across the study area.

The presence of rare and low-frequency species, including singletons and doubletons, demonstrates the high level of bee diversity in Central Uganda. Although these species are not dominant in abundance, they contribute to the overall biodiversity and may occupy unique ecological niches. Their occurrence indicates the need to conserve all species, including those that are less common, since rare species can contribute to ecosystem stability and resilience (Mouillot et al., 2013; Winfree et al., 2015). The occurrence of these rare species, especially in woodland and grassland habitats, shows that these areas, despite having fewer total species, contribute uniquely to the regional diversity by providing habitats for specialists.

Maintaining a variety of habitats within the landscape is therefore important for sustaining bee diversity and ecological resilience, as also reported in other tropical agroecosystems (Kasina et al., 2009). In conclusion, while the study found no statistically significant differences in diversity indices, the observed trends indicate that farmland heterogeneity supports greater bee richness, whereas woodland and grassland habitats contain more habitat-specific species. These findings have important implications for conservation planning and sustainable land use management in Central Uganda, emphasizing the importance of maintaining habitat diversity within agricultural landscapes to support a wide range of bee species.

5.1.2 Environmental Factors Influencing Bee Diversity and Distribution

The clustering patterns observed in the dendrogram (Figure 4.4) suggest that bee communities exhibit some degree of spatial structuring, with certain grassland and farmland plots forming distinct groups. Such clustering may reflect local variations in floral composition or microhabitat conditions, even if these differences are subtle. Similar spatial differentiation of bee assemblages across habitats has been reported in other tropical ecosystems, where heterogeneous landscape elements create microenvironments that influence community composition (Kremen et al., 2002; Winfree et al., 2011).The Redundancy Analysis indicated that vegetation cover and season together explained a modest proportion of the variation in genus composition, with herbs and grasses showing slightly stronger associations than trees and shrubs. This pattern aligns with previous studies showing that herbaceous flowering plants are often key drivers of bee community composition, as they provide more accessible nectar and pollen resources for a wide range of genera, particularly small and ground-nesting bees (Garibaldi et al., 2014; Potts et al., 2003). Trees and shrubs, while important for certain specialist species, may contribute less to overall genus turnover in these landscapes due to their more spatially patchy or seasonally restricted floral resources.

These findings were further supported by regression analysis (Table 4.5), which revealed that vegetation cover variables including trees, shrubs, herbs, and grasses had no significant effect on bee diversity. In contrast, season exerted a significant positive influence, with bee diversity markedly higher during the wet season. This pattern aligns with previous studies reporting increased bee activity and species richness during periods of greater floral abundance and favorable climatic conditions (Classen et al., 2017). The results therefore suggest that temporal variation in resource availability, driven by seasonal changes, plays a more decisive role in influencing bee diversity than vegetation structure alone. This highlights the importance of considering seasonal dynamics when assessing pollinator communities in agro-ecological landscapes of Central Uganda.

The low explanatory power of season and vegetation cover, along with the weak relationships between diversity and environmental predictors, suggests that bee diversity in these sites is relatively resilient to short-term seasonal changes and minor differences in habitat structure. Such stability has been observed in other tropical and subtropical regions, where generalist bee species dominate communities and buffer overall diversity against seasonal or habitat fluctuations (Roulston & Goodell, 2011; Winfree, et al., 2009). However, the presence of scattered genera responding differently along environmental gradients indicates that individual taxa may have specific habitat or floral preferences, even if these patterns do not strongly influence overall diversity metrics.

The findings support other suggestions that factors other than simple vegetation cover or seasonal variation such as floral abundance, nesting substrate availability, landscape connectivity, and microclimatic conditions may play a more important role in shaping bee diversity and distribution (Kennedy et al., 2013; Klein et al., 2007). The weak influence of measured predictors suggests that the studied landscapes maintain a relatively homogenized bee assemblage dominated by generalist species, with rare or specialized species responding to more fine-scale environmental cues not captured in this study. While herbs and grasses appear to have a slightly stronger association with bee genus composition, overall bee diversity was stable across habitats and seasons, reflecting the resilience of the community. These results highlight the need for multi-scale and multi-factor approaches in future studies to better understand the drivers of bee diversity, particularly the roles of habitat structure, floral resource dynamics, and landscape configuration.

5.1.3 Complementarity of Sampling Methods

The differences in species captured by pan traps and sweep nets (Table 4.8) in this study can be explained by bee foraging behavior and ecological traits. sweep nets were more effective at capturing actively foraging bees, which likely explains their higher species richness and abundance compared to pan traps. Pan traps, in contrast, tend to capture bees that are attracted to bright colors and may not be actively visiting flowers, accounting for the species' unique to this method (Lezzeri et al., 2024). The partial overlap in species between the two methods indicates that some generalist species are readily detectable by both methods. These species are likely abundant and exploit multiple floral resources, which makes them easier to sample regardless of method. This finding aligns with previous studies showing that generalist bees are often captured by multiple sampling methods (Grundel et al., 2011; Westphal et al., 2008). The two sampling methods formed distinct clustering patterns (Figure 4.7), indicating that each method captures unique subsets of the bee community. Similar patterns have been reported in other studies, where sweep nets and pan traps sample different bee groups due to their behavioural and ecological biases (Belavadi, 2020; Popic et al., 2013). Method-specific clustering also interacted with habitat type, showing that certain species were consistently associated with particular habitats when sampled by one method but not the other. This supports earlier findings that net sampling tends to capture larger and more active foragers, whereas pan traps are more effective for small-bodied, solitary, or inconspicuous bees (Eeraerts & Meeus, 2025; Westphal et al., 2008). The presence of method-specific species highlights that relying on a single method risks underestimating diversity, particularly of rarer or behaviorally specialized species. This pattern reinforces the ecological principle that species differ in detectability depending on their foraging behavior, activity periods, and habitat use (Wilson et al., 2016). By combining methods, the study was able to capture both common and rare species, providing a more complete picture of the bee community in Central Uganda. The complementarity observed between pan traps and sweep nets also explains the high total diversity recorded. Method-specific detections likely reflect differences in microhabitat use or floral preferences that would be missed if only one method were used. This pattern is consistent with studies in other tropical and temperate systems, which demonstrate that multi-method approaches provide a more accurate representation of pollinator communities (Grundel et al., 2011).

5.2 Conclusions

Farmland supports the highest bee richness and abundance, driven by its structural heterogeneity, varied vegetation, and ample nesting sites. This highlights the role of farmland as a key refuge for bees and informs the recommendation to maintain diverse cropping systems and semi-natural vegetation within farmlands.

Woodland and grassland support rare and habitat-specific species, showing that each habitat contributes uniquely to overall bee diversity. This finding supports the conservation recommendation to protect a mosaic of habitats rather than focusing on a single habitat type.

Bee diversity and genus composition showed only modest variation across habitats, but herb and shrub cover were still important predictors of how species were distributed. This indicates that while overall diversity patterns remain relatively stable, vegetation structure influences which species dominate in different habitats.

Season had a stronger and statistically significant effect on bee diversity than vegetation cover, with higher diversity occurring in the wet season. This highlights the importance of seasonal sampling and indicates that temporal factors, such as rainfall and flowering cycles, play a major role in shaping bee communities.

Sweep nets and pan traps sampled different subsets of the bee community, each capturing species that the other method missed. This supports the continued use of both methods in future monitoring programs to ensure more complete detection of rare, cryptic, and behaviourally diverse species.

5.3 Recommendations

Enhance habitat heterogeneity in farmlands by retaining flowering plants, grasses, shrubs, and herbs to support both generalist and specialist bee species.

Conserve woodland and grassland habitats that harbor rare and habitat-specific species, including less abundant families such as Colletidae, to maintain overall bee diversity and ecosystem resilience.

Conduct detailed studies on habitat preferences, floral host range, and resource requirements of different bee species, including rare and low-abundance taxa, across farmland, grassland, and woodland habitats.

Assess dispersal range, population connectivity, and movement intensity of bees to understand landscape-level influences on community composition and resilience.

Quantify plant-bee interactions and construct real pollination networks to determine the ecological roles of both generalist and specialist species.

Employ a combination of sampling methods, including sweep nets and pan traps, to capture a broader spectrum of species and detect rare or behaviorally specialised taxa.

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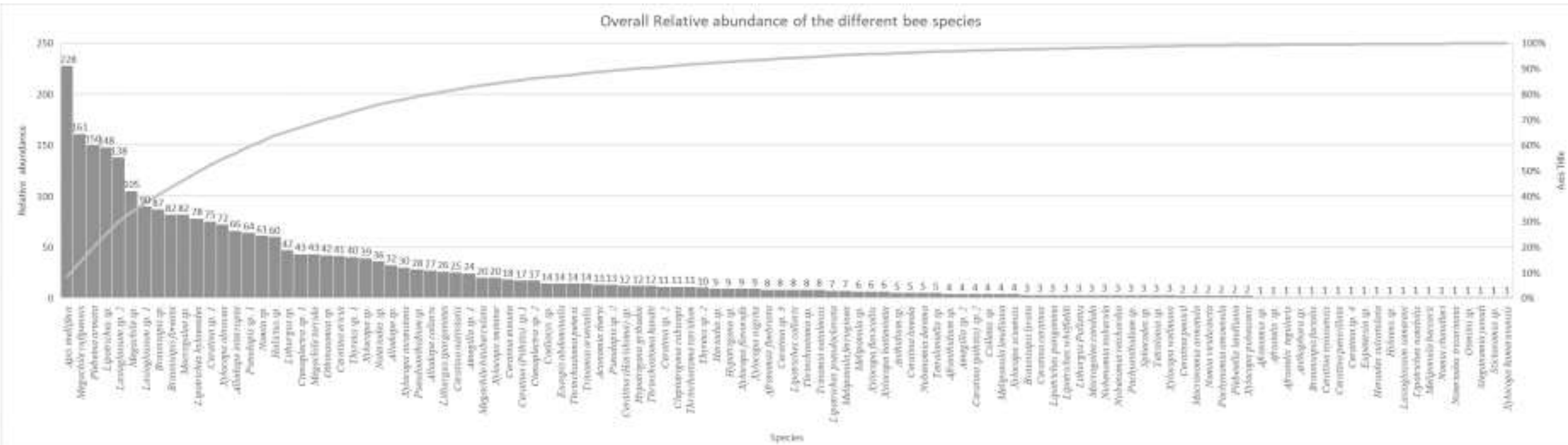
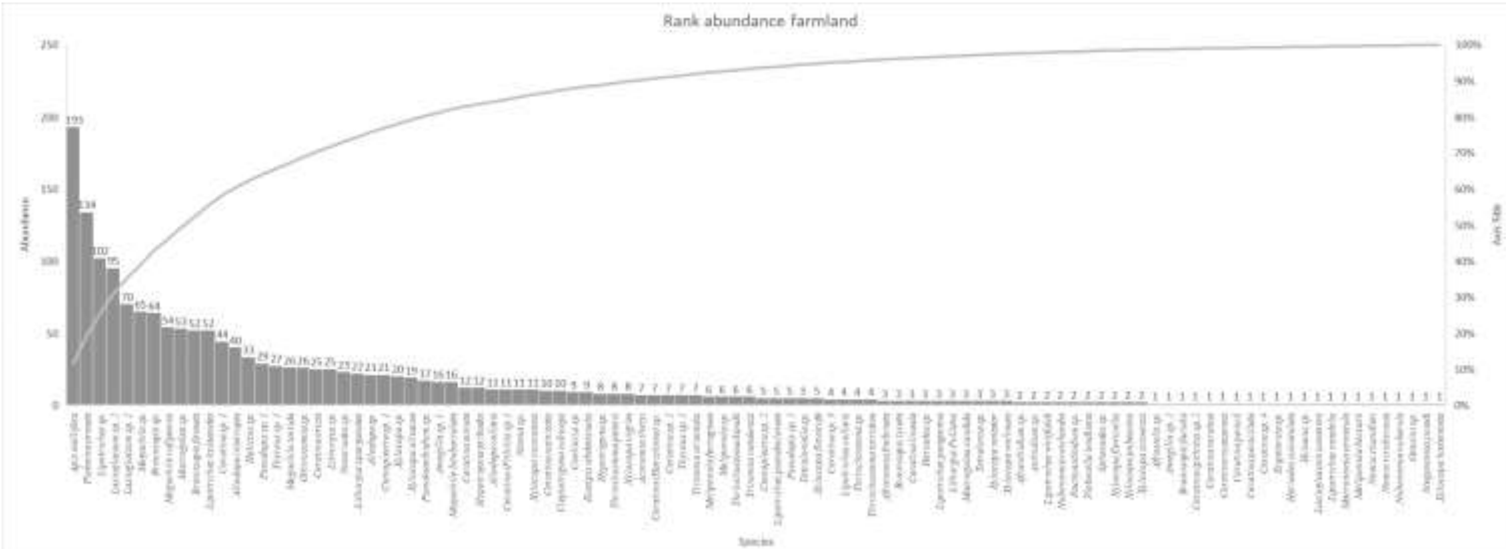
Appendices

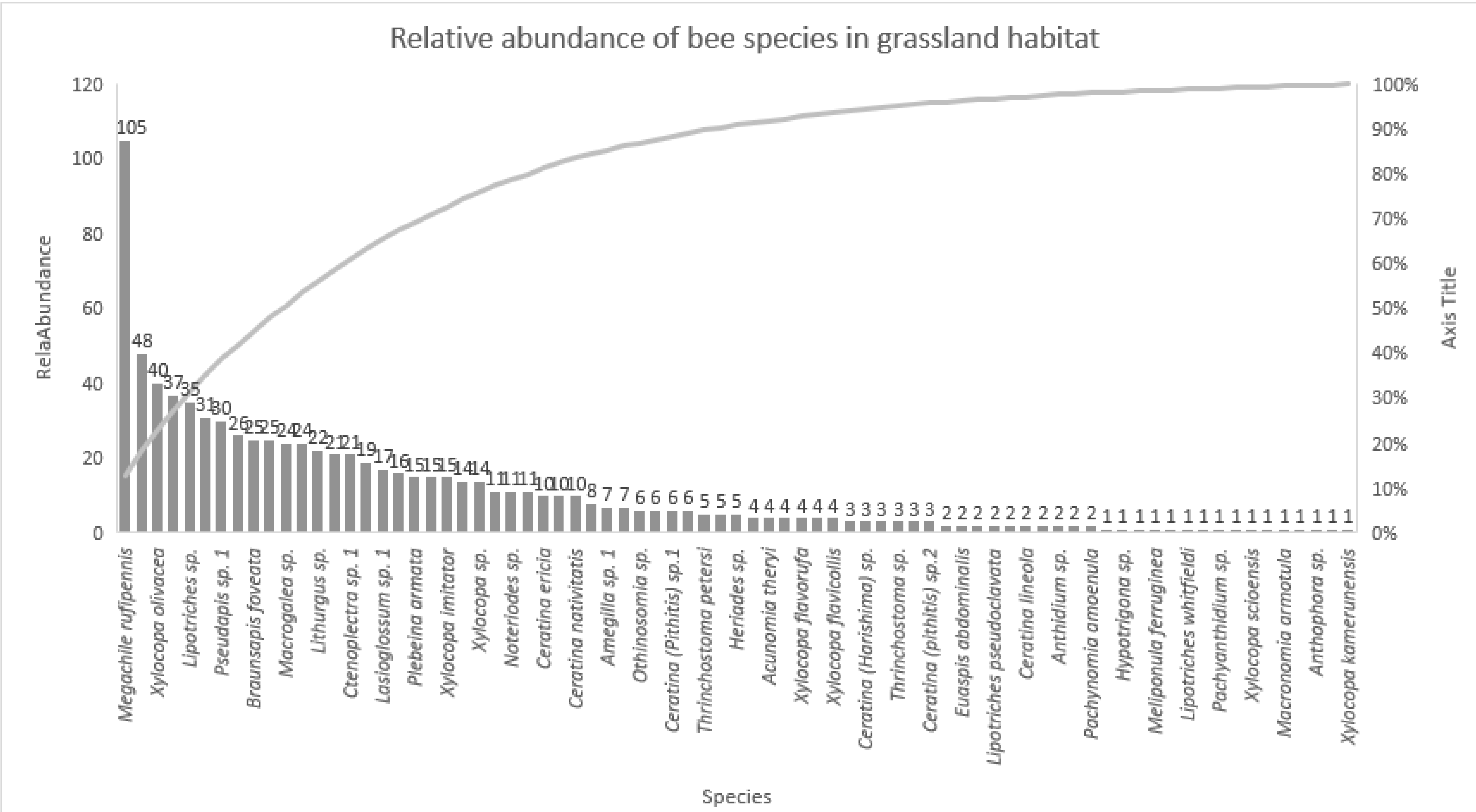
Appendix 1: Overall relative abundance of bee species in the area



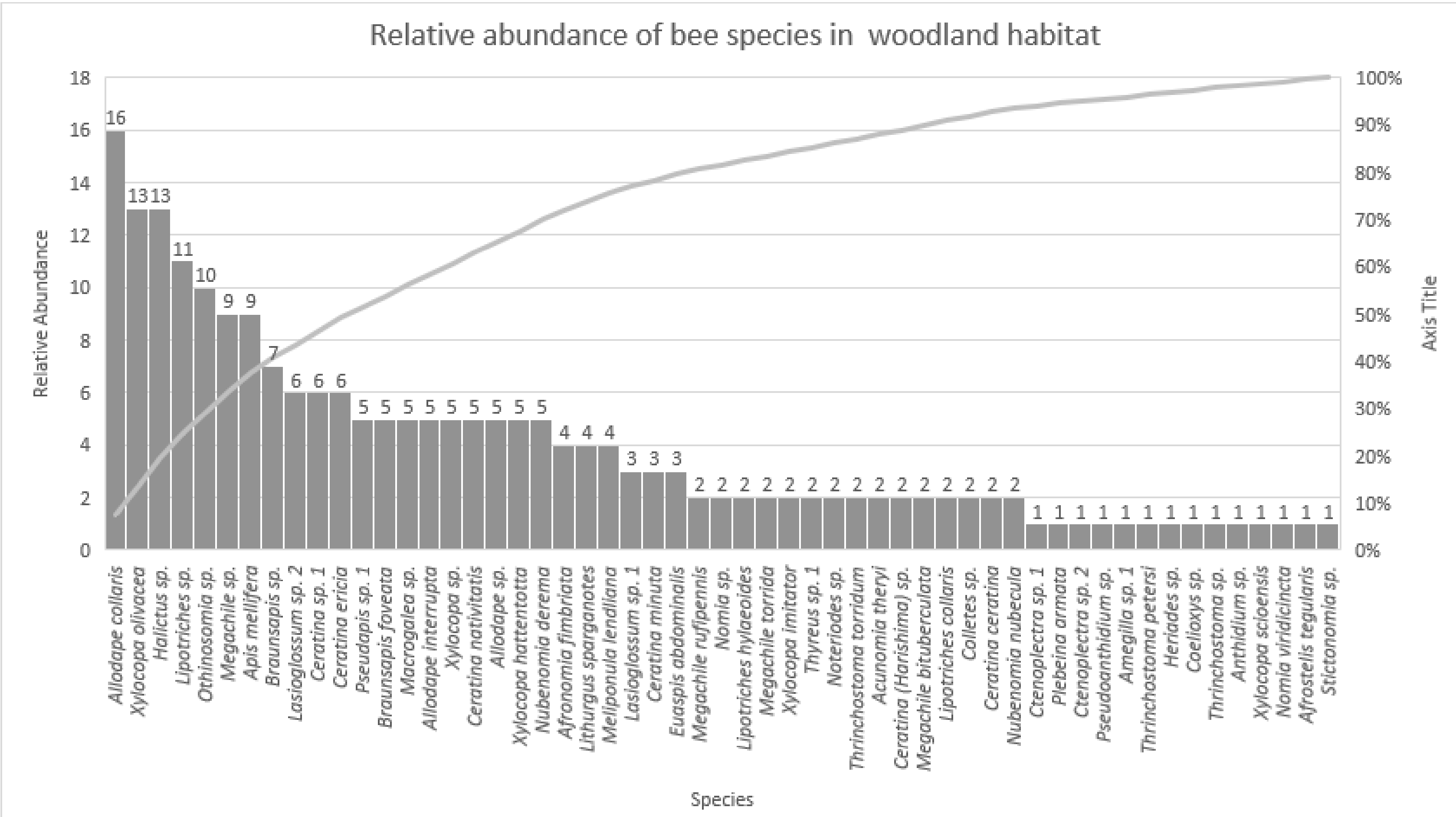
Appendix 2: Relative abundance of bee species in farmland habitat



Appendix 3: Relative abundance of bee species in grassland habitat



Appendix 4: Relative abundance of bee species in woodland habitat



Appendix 5: Presence/Absence record of wild bees across different habitats

Family	Species	Farmland	Grassland	Woodland
	Total species recorded per Habitat	**103**	**76**	**55**
Apidae	*Allodape collaris*	1	0	1
Apidae	*Allodape interrupta*	1	1	1
Apidae	*Allodape* sp.	1	1	1
Apidae	*Amegilla* sp. 1	1	1	1
Apidae	*Amegilla* sp. 2	1	1	0
Apidae	*Anthophora* sp.	0	1	0
Apidae	*Apis mellifera*	1	1	1
Apidae	*Braunsapis facialis*	1	0	0
Apidae	*Braunsapis foveata*	1	1	1
Apidae	*Braunsapis lyrata*	1	0	0
Apidae	*Braunsapis* sp.	1	1	1
Apidae	*Ceratina (Harishima)* sp.	1	1	1

Apidae	*Ceratina (Pithitis)* sp.1	1	1	0
Apidae	*Ceratina (pithitis)* sp.2	1	1	0
Apidae	*Ceratina ceratina*	1	0	1
Apidae	*Ceratina ericia*	1	1	1
Apidae	*Ceratina lineola*	1	1	0
Apidae	*Ceratina minuta*	1	1	1
Apidae	*Ceratina nativitatis*	1	1	1
Apidae	*Ceratina nyassensis*	1	0	0
Apidae	*Ceratina penicil*	1	1	0
Apidae	*Ceratina penicillata*	1	0	0
Apidae	*Ceratina* sp. 1	1	1	1
Apidae	*Ceratina* sp. 2	1	1	0
Apidae	*Ceratina* sp. 3	1	1	0
Apidae	*Ceratina* sp. 4	1	0	0
Apidae	*Cleptotrigona cubiceps*	1	1	0

Apidae	*Ctenoplectra* sp. 1	1	1	1
Apidae	*Ctenoplectra* sp. 2	1	1	1
Apidae	*Hypotrigona gribodoi*	1	0	0
Apidae	*Hypotrigona* sp.	1	1	0
Apidae	*Macrogalea candida*	1	0	0
Apidae	*Macrogalea* sp.	1	1	1
Apidae	*Macronomia armotula*	1	1	0
Apidae	*Meliponula beccarii*	1	0	0
Apidae	*Meliponula ferruginea*	1	1	0
Apidae	*Meliponula lendliana*	0	0	1
Apidae	*Meliponula* sp.	1	0	0
Apidae	*Plebeiella lendliana*	1	0	0
Apidae	*Plebeina armata*	1	1	1
Apidae	*Tetralonia* sp.	1	0	0
Apidae	*Tetraloniella* sp.	1	0	0

Apidae	*Thyreus* sp. 1	1	1	1
Apidae	*Thyreus* sp. 2	1	1	0
Apidae	*Xylocopa flavicollis*	1	1	0
Apidae	*Xylocopa flavorufa*	1	1	0
Apidae	*Xylocopa hattentotta*	1	0	1
Apidae	*Xylocopa imitator*	1	1	1
Apidae	*Xylocopa inconstans*	1	1	0
Apidae	*Xylocopa kamerunensis*	0	1	0
Apidae	*Xylocopa nigrita*	1	1	0
Apidae	*Xylocopa olivacea*	1	1	1
Apidae	*Xylocopa pubescens*	1	0	0
Apidae	*Xylocopa scioensis*	1	1	1
Apidae	*Xylocopa* sp.	1	1	1
Apidae	*Xylocopa wellmani*	1	0	0
Collectidae	*Colletes* sp.	0	1	1

Collectidae	*Hylaeus* sp.	1	0	0
Halictidae	*Acunomia theryi*	1	1	1
Halictidae	*Afronomia fimbriata*	1	1	1
Halictidae	*Afronomia* sp.	1	0	0
Halictidae	*Eupetersia* sp.	1	0	0
Halictidae	*Halictus* sp.	1	1	1
Halictidae	*Lasioglossum somereni*	1	0	0
Halictidae	*Lasioglossum* sp. 1	1	1	1
Halictidae	*Lasioglossum* sp. 2	1	1	1
Halictidae	*Lipotriches collaris*	1	1	1
Halictidae	*Lipotriches hylaeoides*	1	1	1
Halictidae	*Lipotriches notabilis*	1	0	0
Halictidae	*Lipotriches panganina*	1	0	0
Halictidae	*Lipotriches pseudoclavata*	1	1	0
Halictidae	*Lipotriches* sp.	1	1	1

Halictidae	*Lipotriches whitfieldi*	1	1	0
Halictidae	*Nomia chandleri*	1	0	0
Halictidae	*Nomia* sp.	1	1	1
Halictidae	*Nomia viridicincta*	1	0	1
Halictidae	*Nubenomia derema*	0	0	1
Halictidae	*Nubenomia nubecula*	1	0	1
Halictidae	*Nubenomia reichardia*	1	1	0
Halictidae	*Pachynomia amoenula*	0	1	0
Halictidae	*Pseudapis* sp. 1	1	1	1
Halictidae	*Pseudapis* sp. 2	1	1	0
Halictidae	*Sphecodes* sp.	1	1	0
Halictidae	*Steganomia junodi*	1	0	0
Halictidae	*Stictonomia* sp.	0	0	1
Halictidae	*Thrinchostoma kandti*	1	1	0
Halictidae	*Thrinchostoma petersi*	1	1	1

Halictidae	*Thrinchostoma* sp.	1	1	1
Halictidae	*Thrinchostoma torridum*	1	1	1
Halictidae	*Trinomia natalensis*	1	1	0
Halictidae	*Trinomia orientalis*	1	1	0
Megachilidae	*Afranthidium* sp.	1	1	0
Megachilidae	*Afrostelis* sp.	1	0	0
Megachilidae	*Afrostelis tegularis*	0	0	1
Megachilidae	*Anthidium* sp.	1	1	1
Megachilidae	*Coelioxys* sp.	1	1	1
Megachilidae	*Euaspis abdominalis*	1	1	1
Megachilidae	*Heriades* sp.	1	1	1
Megachilidae	*Heriades sulcatulata*	1	0	0
Megachilidae	*Lithurgus pullatus*	1	0	0
Megachilidae	*Lithurgus* sp.	1	1	0
Megachilidae	*Lithurgus sparganotes*	1	0	1

Megachilidae	*Megachile bituberculata*	1	1	1
Megachilidae	*Megachile rufipennis*	1	1	1
Megachilidae	*Megachile* sp.	1	1	1
Megachilidae	*Megachile torrida*	1	1	1
Megachilidae	*Noteriodes* sp.	1	1	1
Megachilidae	*Noteriodes tricarinata*	0	1	0
Megachilidae	*Osmiini* sp.	1	0	0
Megachilidae	*Othinosomia* sp.	1	1	1
Megachilidae	*Pachyanthidium* sp.	1	1	0
Megachilidae	*Pseudoanthidium* sp.	1	1	1

Notes: 0=Absent and 1=Present.

Appendix 6: Frequency of occurrence and dominance of recorded bees

Family	species	Freq.	Freq. Category	Dominance
	<chr>	*<dbl>*		
Apidae	*Allodape collaris*	9.1	Incidental	0.0098
Apidae	*Allodape interrupta*	63.6	Primary	0.0241
Apidae	*Allodape* sp.	54.5	Primary	0.0117
Apidae	*Amegilla* sp. 1	40.9	Secondary	0.0087
Apidae	*Amegilla* sp. 2	13.6	Incidental	0.0015
Apidae	*Anthophora* sp.	4.6	Incidental	0.0004
Apidae	*Apis mellifera*	100.0	Primary	0.0831
Apidae	*Braunsapis facialis*	4.6	Incidental	0.0004
Apidae	*Braunsapis foveata*	95.5	Primary	0.0299
Apidae	*Braunsapis lyrata*	9.1	Incidental	0.0011
Apidae	*Braunsapis* sp.	81.8	Primary	0.0317
Apidae	*Ceratina (Harishima)* sp.	31.8	Secondary	0.0044

Apidae	*Ceratina (Pithitis)* sp.1	50.0	Primary	0.0062
Apidae	*Ceratina (pithitis)* sp.2	18.2	Incidental	0.0015
Apidae	*Ceratina ceratina*	9.1	Incidental	0.0011
Apidae	*Ceratina ericia*	68.2	Primary	0.0149
Apidae	*Ceratina lineola*	22.7	Incidental	0.0018
Apidae	*Ceratina minuta*	50.0	Primary	0.0066
Apidae	*Ceratina nativitatis*	50.0	Primary	0.0091
Apidae	*Ceratina nyassensis*	4.6	Incidental	0.0004
Apidae	*Ceratina penicil*	9.1	Incidental	0.0007
Apidae	*Ceratina penicillata*	4.6	Incidental	0.0004
Apidae	*Ceratina* sp. 1	86.4	Primary	0.0273
Apidae	*Ceratina* sp. 2	22.7	Incidental	0.0040
Apidae	*Ceratina* sp. 3	22.7	Incidental	0.0029
Apidae	*Ceratina* sp. 4	4.6	Incidental	0.0004
Apidae	*Cleptotrigona cubiceps*	22.7	Incidental	0.0040

Apidae	*Ctenoplectra* sp. 1	36.4	Secondary	0.0157
Apidae	*Ctenoplectra* sp. 2	27.3	Secondary	0.0062
Apidae	*Hypotrigona gribodoi*	18.2	Incidental	0.0044
Apidae	*Hypotrigona* sp.	22.7	Incidental	0.0033
Apidae	*Macrogalea candida*	9.1	Incidental	0.0011
Apidae	*Macrogalea* sp.	59.1	Primary	0.0299
Apidae	*Macronomia armotula*	9.1	Incidental	0.0007
Apidae	*Meliponula beccarii*	4.6	Incidental	0.0004
Apidae	*Meliponula ferruginea*	27.3	Secondary	0.0026
Apidae	*Meliponula lendliana*	4.6	Incidental	0.0015
Apidae	*Meliponula* sp.	18.2	Incidental	0.0022
Apidae	*Plebeiella lendliana*	4.6	Incidental	0.0007
Apidae	*Plebeina armata*	63.6	Primary	0.0547
Apidae	*Tetralonia* sp.	13.6	Incidental	0.0011
Apidae	*Tetraloniella* sp.	9.1	Incidental	0.0018

Apidae	*Thyreus* sp. 1	50.0	Primary	0.0146
Apidae	*Thyreus* sp. 2	22.7	Incidental	0.0036
Apidae	*Xylocopa flavicollis*	18.2	Incidental	0.0022
Apidae	*Xylocopa flavorufa*	36.4	Secondary	0.0033
Apidae	*Xylocopa hattentotta*	13.6	Incidental	0.0022
Apidae	*Xylocopa imitator*	18.2	Incidental	0.0073
Apidae	*Xylocopa inconstans*	27.3	Secondary	0.0109
Apidae	*Xylocopa kamerunensis*	4.6	Incidental	0.0004
Apidae	*Xylocopa nigrita*	18.2	Incidental	0.0033
Apidae	*Xylocopa olivacea*	40.9	Secondary	0.0262
Apidae	*Xylocopa pubescens*	9.1	Incidental	0.0007
Apidae	*Xylocopa scioensis*	18.2	Incidental	0.0015
Apidae	*Xylocopa* sp.	72.7	Primary	0.0142
Apidae	*Xylocopa wellmani*	9.1	Incidental	0.0011
Collectidae	*Colletes* sp.	9.1	Incidental	0.0015

Collectidae	*Hylaeus* sp.	4.6	Incidental	0.0004
Halictidae	*Acunomia theryi*	36.4	Secondary	0.0047
Halictidae	*Afronomia fimbriata*	22.7	Incidental	0.0029
Halictidae	*Afronomia* sp.	4.6	Incidental	0.0004
Halictidae	*Eupetersia* sp.	4.6	Incidental	0.0004
Halictidae	*Halictus* sp.	77.3	Primary	0.0219
Halictidae	*Lasioglossum somereni*	4.6	Incidental	0.0004
Halictidae	*Lasioglossum* sp. 1	86.4	Primary	0.0328
Halictidae	*Lasioglossum* sp. 2	100.0	Primary	0.0503
Halictidae	*Lipotriches collaris*	13.6	Incidental	0.0029
Halictidae	*Lipotriches hylaeoides*	63.6	Primary	0.0284
Halictidae	*Lipotriches notabilis*	4.6	Incidental	0.0004
Halictidae	*Lipotriches panganina*	4.6	Incidental	0.0011
Halictidae	*Lipotriches pseudoclavata*	13.6	Incidental	0.0026
Halictidae	*Lipotriches* sp.	95.5	Primary	0.0540

Halictidae	*Lipotriches whitfieldi*	9.1	Incidental	0.0011
Halictidae	*Nomia chandleri*	4.6	Incidental	0.0004
Halictidae	*Nomia* sp.	22.7	Incidental	0.0222
Halictidae	*Nomia viridicincta*	9.1	Incidental	0.0007
Halictidae	*Nubenomia derema*	4.6	Incidental	0.0018
Halictidae	*Nubenomia nubecula*	9.1	Incidental	0.0011
Halictidae	*Nubenomia reichardia*	13.6	Incidental	0.0011
Halictidae	*Pachynomia amoenula*	4.6	Incidental	0.0007
Halictidae	*Pseudapis* sp. 1	68.2	Primary	0.0233
Halictidae	*Pseudapis* sp. 2	13.6	Incidental	0.0047
Halictidae	*Sphecodes* sp.	13.6	Incidental	0.0011
Halictidae	*Steganomia junodi*	4.6	Incidental	0.0004
Halictidae	*Stictonomia* sp.	4.6	Incidental	0.0004
Halictidae	*Thrinchostoma kandti*	22.7	Incidental	0.0044
Halictidae	*Thrinchostoma petersi*	31.8	Secondary	0.0051

Halictidae	*Thrinchostoma* sp.	27.3	Secondary	0.0029
Halictidae	*Thrinchostoma torridum*	13.6	Incidental	0.0040
Halictidae	*Trinomia natalensis*	13.6	Incidental	0.0029
Halictidae	*Trinomia orientalis*	22.7	Incidental	0.0051
Megachilidae	*Afranthidium* sp.	9.1	Incidental	0.0015
Megachilidae	*Afrostelis* sp.	4.6	Incidental	0.0004
Megachilidae	*Afrostelis tegularis*	4.6	Incidental	0.0004
Megachilidae	*Anthidium* sp.	18.2	Incidental	0.0018
Megachilidae	*Coelioxys* sp.	22.7	Incidental	0.0051
Megachilidae	*Euaspis abdominalis*	22.7	Incidental	0.0051
Megachilidae	*Heriades* sp.	31.8	Secondary	0.0033
Megachilidae	*Heriades sulcatulata*	4.6	Incidental	0.0004
Megachilidae	*Lithurgus pullatus*	13.6	Incidental	0.0011
Megachilidae	*Lithurgus* sp.	54.5	Primary	0.0171
Megachilidae	*Lithurgus sparganotes*	50.0	Primary	0.0095

Megachilidae	*Megachile bituberculata*	31.8	Secondary	0.0073
Megachilidae	*Megachile rufipennis*	59.1	Primary	0.0587
Megachilidae	*Megachile* sp.	81.8	Primary	0.0383
Megachilidae	*Megachile torrida*	22.7	Incidental	0.0157
Megachilidae	*Noteriodes* sp.	54.5	Primary	0.0131
Megachilidae	*Noteriodes tricarinata*	4.6	Incidental	0.0004
Megachilidae	*Osmiini* sp.	4.6	Incidental	0.0004
Megachilidae	*Othinosomia* sp.	59.1	Primary	0.0153
Megachilidae	*Pachyanthidium* sp.	9.1	Incidental	0.0011
Megachilidae	*Pseudoanthidium* sp.	40.9	Secondary	0.0102

Appendix 7: Summary of bee species collected by pan trap and Sweep net method

species	Sweep net	Pan trap	Both Method
Acunomia theryi	Yes	Yes	Yes
Afranthidium sp.	Yes	No	No
Afronomia fimbriata	Yes	No	No
Afronomia sp.	Yes	No	No
Afrostelis sp.	Yes	No	No
Afrostelis tegularis	Yes	No	No
Allodape collaris	Yes	Yes	Yes
Allodape interrupta	Yes	Yes	Yes
Allodape sp.	Yes	Yes	Yes
Amegilla sp. 1	Yes	Yes	Yes
Amegilla sp. 2	Yes	No	No
Anthidium sp.	Yes	No	No
Anthophora sp.	Yes	No	No
Apis mellifera	Yes	Yes	Yes
Braunsapis facialis	No	Yes	No
Braunsapis foveata	Yes	Yes	Yes
Braunsapis lyrata	Yes	Yes	Yes

Braunsapis sp.	Yes	Yes	Yes
Ceratina (Harishima) sp.	Yes	Yes	Yes
Ceratina (Pithitis) sp.1	Yes	Yes	Yes
Ceratina (pithitis) sp.2	Yes	No	No
Ceratina ceratina	Yes	No	No
Ceratina ericia	Yes	Yes	Yes
Ceratina lineola	Yes	Yes	Yes
Ceratina minuta	Yes	Yes	Yes
Ceratina nativitatis	Yes	Yes	Yes
Ceratina nyassensis	No	Yes	No
Ceratina penicil	Yes	No	No
Ceratina penicillata	Yes	No	No
Ceratina sp. 1	Yes	Yes	Yes
Ceratina sp. 2	Yes	Yes	Yes
Ceratina sp. 3	Yes	No	No
Ceratina sp. 4	Yes	No	No
Cleptotrigona cubiceps	Yes	No	No
Coelioxys sp.	Yes	No	No
Colletes sp.	Yes	No	No
Ctenoplectra sp. 1	Yes	Yes	Yes
Ctenoplectra sp. 2	Yes	No	No

Euaspis abdominalis	Yes	No	No
Eupetersia sp.	Yes	No	No
Halictus sp.	Yes	Yes	Yes
Heriades sp.	Yes	No	No
Heriades sulcatulata	Yes	No	No
Hylaeus sp.	Yes	No	No
Hypotrigona gribodoi	Yes	Yes	Yes
Hypotrigona sp.	Yes	Yes	Yes
Lasioglossum somereni	No	Yes	No
Lasioglossum sp. 1	Yes	Yes	Yes
Lasioglossum sp. 2	Yes	Yes	Yes
Lipotriches collaris	Yes	No	No
Lipotriches hylaeoides	Yes	Yes	Yes
Lipotriches notabilis	Yes	No	No
Lipotriches panganina	Yes	No	No
Lipotriches pseudoclavata	Yes	No	No
Lipotriches sp.	Yes	Yes	Yes
Lipotriches whitfieldi	Yes	Yes	Yes
Lithurgus Pullatus	No	Yes	No
Lithurgus sp.	Yes	Yes	Yes
Lithurgus sparganotes	Yes	Yes	Yes

Macrogalea candida	Yes	Yes	Yes
Macrogalea sp.	Yes	Yes	Yes
Macronomia armotula	Yes	Yes	Yes
Megachile bituberculata	Yes	Yes	Yes
Megachile rufipennis	Yes	Yes	Yes
Megachile sp.	Yes	Yes	Yes
Megachile torrida	Yes	No	No
Meliponula beccarii	Yes	No	No
Meliponula ferruginea	Yes	Yes	Yes
Meliponula lendliana	Yes	No	No
Meliponula sp.	Yes	Yes	Yes
Nomia chandleri	Yes	No	No
Nomia sp.	Yes	Yes	Yes
Nomia viridicincta	Yes	No	No
Noteriodes sp.	Yes	Yes	Yes
Noteriodes tricarinata	Yes	No	No
Nubenomia derema	No	Yes	No
Nubenomia nubecula	No	Yes	No
Nubenomia reichardia	Yes	No	No
Osmiini sp.	No	Yes	No
Othinosomia sp.	Yes	Yes	Yes

Pachyanthidium sp.	Yes	No	No
Pachynomia amoenula	Yes	No	No
Plebeiella lendliana	Yes	No	No
Plebeina armata	Yes	Yes	Yes
Pseudapis sp. *1*	Yes	Yes	Yes
Pseudapis sp. *2*	Yes	No	No
Pseudoanthidium sp.	Yes	Yes	Yes
Sphecodes sp.	Yes	Yes	Yes
Steganomia junodi	Yes	No	No
Stictonomia sp.	No	Yes	No
Tetralonia sp.	Yes	Yes	Yes
Tetraloniella sp.	Yes	No	No
Thrinchostoma kandti	Yes	Yes	Yes
Thrinchostoma petersi	Yes	Yes	Yes
Thrinchostoma sp.	Yes	Yes	Yes
Thrinchostoma torridum	Yes	No	No
Thyreus sp. 1	Yes	Yes	Yes
Thyreus sp. 2	Yes	Yes	Yes
Trinomia natalensis	Yes	No	No
Trinomia orientalis	Yes	Yes	Yes
Xylocopa flavicollis	Yes	Yes	Yes

Xylocopa flavorufa	Yes	Yes	Yes
Xylocopa hattentotta	Yes	Yes	Yes
Xylocopa imitator	Yes	No	No
Xylocopa inconstans	Yes	No	No
Xylocopa kamerunensis	No	Yes	No
Xylocopa nigrita	Yes	Yes	Yes
Xylocopa olivacea	Yes	Yes	Yes
Xylocopa pubescens	Yes	Yes	Yes
Xylocopa scioensis	Yes	Yes	Yes
Xylocopa sp.	Yes	Yes	Yes
Xylocopa wellmani	Yes	Yes	Yes