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CONTROL OF TERMITES AND LAND USE EFFECTS ON THEIR DIVERSITY IN MACHAKOS AND EMBU COUNTIES, KENYA

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other University.

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DEDICATION

To my wife, Elizabeth, children; Pauline, Brian and Edwin, my mum Pauline and my brothers and sisters and my close friends Stanley Ngei and Stephen Mbunzi.

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GENERAL ABSTRACT

Termites cause damage to agricultural crops, forests and natural vegetation, in several parts of Africa. In Eastern Kenya, termites have been reported to cause between 50 to 100% yield losses in maize agro-ecosystems. General soil microfauna diversity analyses have been done in Eastern region of Kenya but there is little information documented on diversity and distribution of termites. Understanding the diversity of termites allows implementation of appropriate management strategies and application of species-specific control methods. Bio-control agents and cultural methods such as intercrops have been reported to control termites, but there are no studies that document the comparative efficacy of these control methods in maize agro-ecosystems in Eastern Kenya. This study therefore aimed at determining the termite species diversity in Machakos and Embu sub-counties. The effects of soil properties on diversity of functional groups of termites, efficacy of various biological control agents of termites and effect of intercropping maize with legumes and sorghum on infestation levels of termites and damage of maize in Eastern region of Kenya were also evaluated. Three different habitats comprising of maize crop farms, maize intercropped with beans and natural vegetation were purposively sampled in Machakos and Embu counties. From these habitats, termites were sampled for diversity analyses. Soil samples were also taken from these sections and their physico-chemical properties analyzed to determine their effects on functional diversity of termites. To determine the effect of maize intercrops on infestation levels of termites, maize was intercropped with soybeans, field beans and sorghum in different plots measuring 10m x 10m with maize mono crop as a control. The experiment was carried out in Yatta sub-county in Machakos county and it was laid out in a completely randomized block design with each treatment replicated four times. The level of termite infestation was determined during two seasons. Termites were sampled from 30cm x 30cm quadrats laid at an interval of 5m along the transect. Additionally, five plants from each plot were also randomly selected for assessment of termites' infestation. Effect of bio-control agents was determined by treating *Macrotermes subhyalinus* and *Odontotermes badius* with biocontrol agents under laboratory conditions. There were five treatments replicated four times. The treatments were *Azadirachta indica*, *Metarhizium anisopliae*, ants predating on termites (*Megaponera analis* and *Dorylus gribodoi*), termidor (fipronil 9.1%) and distilled water as control. Termite diversity in Machakos and Embu counties was assessed by Renyi diversity analysis. Analysis of variance using R Software was used to compare the efficacy of various biological control methods and the effect of intercropping maize on infestation levels of termites. The relationship between termite functional diversity and soil properties was assessed using Canonical correspondence analysis. *Trinervitermes gratiosus* was only found in Machakos county and occurred in significantly greater numbers in natural vegetation macrohabitat compared to other macrohabitats. The abundance of termite species and functional groups varied between seasons and macrohabitats. Group II and IV were positively correlated to sand and silt, respectively while group IIf was negatively associated with sand. There was a low percentage of lodged plants in maize-sorghum intercrop which also had low population densities of *M. herus* and *Odontotermes badius* in both seasons. In the bio-control experiment, the mean percentage mortality caused by *M. anisopliae* in both *O. badius* and *M. subhyalinus* were significantly lower compared to the rest of the treatments. The information obtained from this study can be used in designing integrated termite control strategies.

CHAPTER ONE

1.0 GENERAL INTRODUCTION

1.1 Background information

Termites (Class: Insecta; Order: Isoptera) are among the most successful groups of insects on earth colonizing most land masses (Tasisa and Gobena, 2013). This group of insects live in colonies that range in size from a few thousands individuals to huge colonies with millions of termites (Jouquet *et al.,* 2011). Termite species in African agro-ecosystems mainly belong to the sub-family Macrotermitidae of which *Microtermes, Macrotermes* and *Odontotermes* are the prominent genera (Sileshi *et al.,* 2009). In Kenya, several termite species (e.g *Microtermes pusillas, Microtermes* spp., *Macrotermes herus, Pseudacanthotermes spiniger*) have been reported to be pests in natural agro-ecosystems and artificial forests (Ayuke, 2010; Yusuke, 2010).

Among the soil organisms in tropical regions, termites perform significant ecosystem roles such as decomposition and nutrient cycling (Jouquet *et al.,* 2011). Plant and organic material can be in different forms and particular termite species are involved in the decomposition process **(**Dahlsjo *et al*., 2014). Termite species composition and diversity data give an insight into their role in nutrient availability and distribution, physical alterations of the habitat, and functioning of the ecosystem **(**Ilse *et al*., 2009). As pests, termites impact negatively on the economy by causing damage to various agricultural crops, range lands, wooden houses, construction poles and fences in several parts of world (Mitchel, 2002; Cox, 2004). In agricultural crops and various domestic products, termites have been reported to cause up to 100% loss (Michael, 2000; UNEP and FAO, 2000; Sekamatte, 2002; Nyeko, *et al.,* 2010). In Africa, damage due to termites varies between crops, trees and grasslands. For instance, in Ethiopia, serious damage with losses of up to 100% were reported on Eucalyptus two years after transplanting (Khaenje *et al.,* 2013).
In Uganda and Kenya, the loss caused to various crops and tree species due to termites, range between 50% and 100% (Sekamatte, 2002; Nyeko, *et al.,* 2010). In Kenyan semi-

arid savannah, termites were reported to damage > 800-1500 kg/ha of pasture per year (Nyeko, *et al.,* 2010). Damage of up to 50 % in maize crop has been reported (Gitonga, 1996). In a study in Kenya on distribution and diversity of foraging patterns of groups of different species that build large mounds, the main genera were found to be *Macrotermes* and *Odontotermes*. Mound-building termites show evidence of intra-specific competition (Pomeroy, 2005). Examples of mound building termites in Taita in Kenya include *Macrotermes, Odontotermes* and *Amitermes* (Akoth, 2017). Kagezi *et al.* (2011) studied decomposition of tissue baits and termite density along a gradient of human land-use intensification in Western Kenya and found that the abundance of termites was not significantly affected. However, as expected, the relative abundance of soil-feeders decreased from primary forests to farmlands. In a study on diversity of termites and fungi in semi-arid Tsavo ecosystem in Kenya, Vasela *et al* (2017) demonstrated that the fungal community associated with *Macrotermes subhyalinus* and *Macrotermes michaelseni* consisted of three species of *Termitomyces* symbionts.

Control of termites in Kenya has largely relied on broad spectrum and persistent organo-chlorine insecticides (Abonyo *et al.,* 2016). However, serious limitations and increasing legal restrictions associated with the application and efficacy of these chemicals (Tasisa and Gobena, 2013) necessitates the need for environmentally friendly methods. Some of these methods include use of resistant crops, cultural techniques, application of botanical extracts and biological control agents (Sekamatte, 2002; Ayuke, 2010). These are ecologically sustainable methods with no adverse effects on humans and biodiversity; locally available materials which are cheap can be used (Abonyo *et al.,* 2016).

1.2 Problem statement and justification

In eastern region of Kenya general microfauna diversity analyses have been done but no study has focused on the diversity of termites (Ayuke, 2010). Apart from the crop damage that termites cause, they are important drivers of key ecosystem processes. Species composition and abundance of termite assemblages varies between bio-geographical regions (Dahlsjo¨ *et al*., 2014) and it determines the ecosystem processes that they perform (Jones and Prasetyo, 2002).

In East Africa, severe losses (50-100%) due to termites have been reported in maize (Sekamatte, 2002; Nyeko and Olumbayo, 2005). Termites cause serious damage in different agro-ecosystems in Kenya (Gitonga, 1996; Nyeko, *et al*., 2010). Maize is a staple crop for millions of people in Africa (ECAMAW, 2005). In Kenya, maize is predominantly grown by small-scale farmers and a few large-scale growers in north rift region of Kenya (Ministry of Agriculture and Livestock Development- Kenya, 2005). Losses caused to such staple crops directly impinge on the livelihoods of smallholder farmers. Termites infestation in maize contribute to low maize yields in Kenya (Sileshi *et al.,* 2008 and Nyeko *et al.,* 2010).

Kenyan subsistence farmers use various traditional termite control methods, including removal of the termite colony queen, crop rotation and use of plant extracts, but often with limited success (Khaenje *et al.,* 2013). As a result, control methods heavily depend on synthetic chemicals especially organo-chlorines which are currently banned in most regions of the world due to their persistent toxicity (Khaenje *et al.,* 2013; Tasisa and Gobena, 2013). Botanicals such as Neemroc (Addisu *et al.,* 2013) and bio-control agents such as *Metarhizium anisopliae* (Maniania *et al*., 2002; Osbrink *et al.,* 2001), *Megaponera analis* and *Dorylus molestus* (Garcia *et al.,* 2013; Akutse *et al.,* 2012) have been used as alternatives to chemical control.

Metarhizium anisopliae in the recent past has shown to be highly pathogenic to many insect species including termites in both temperate and tropical regions (Maniania *et al*., 2002). Although these control methods have been reported to control termites in other parts of Africa, their use and comparative efficacy has not been evaluated in Kenya.

Intercropping is a practical way to improve plant diversity in agro-ecosystems (Dassou *et al.,* 2015), and several studies have shown that intercropping tends to favour natural enemies of pests and thus enhance biological control (Berndt *et al.,* 2006; Hooks and Johnson, 2003; Song *et al.,* 2010). Maize intercropped with soybean, groundnut and common beans are effective in suppressing termite attack, suggesting the necessity to identify suitable legumes for each cropping situation (Sekamatte, 2003).

1.3 Objectives

1.3.1 General objective

To determine the distribution and diversity of termites in Embu and Machakos Counties and the efficacy of biocontrol agents against termites.

1.3.2 Specific objectives

i. To determine the effects of natural vegetation, maize-beans intercrop and maize monocrop on diversity of termite species in Embu and Machakos Counties.
ii. To assess the effect of seasons and soil properties on functional diversity of termites in Embu and Machakos Counties.
iii. To evaluate the effect of intercropping maize with soybean, common beans and sorghum on infestation levels of termites.
iv. To determine the effect of *Azadirachta indica*, *Metarhizium anisopliae*, *Megaponera analis* and *Dorylus gribodoi* on mortality of *Macrotermes subhyalinus* and *Odontotermes badius.*

1.4 Null hypotheses

1. Diversity of termite species in natural vegetation, maize-beans intercrop and maize monocrop in Embu and Machakos Counties is similar.
2. Soil properties and seasons do not affect functional diversity of termites in Embu and Machakos Counties.
3. Intercropping maize with soybean, common beans and sorghum does not influence the infestation levels of termites.
4. *Azadirachta indica*, *Metarhizium anisopliae*, *Megaponera analis* and *Dorylus gribodoi* have no effect on *Macrotermes subhyalinus* and *Odontotermes badius.*

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Termites distribution and diversity

Termites (Class: Insecta; Order: Isoptera) are diverse (Figure 2.1) and distributed throughout the world (Yusuke, 2010). Species diversity of termite assemblages is influenced by bio-geographical regions (Dahlsjo¨ *et al.*, 2014). In America, there are 494 known termite species found in different habitats. (Bignell and Jones, 2014). In South East Asia, 43 termite species from 17 genera (1–10 species per genus) have been described. Most of the species belong to the genera *Macrotermes*, *Odontotermes*, and *Pericapritermes* (Neoh *et al.*, 2015). In Africa, 660 out of 2600 known termite species are restricted to tropical and subtropical regions (Eggleton, 2000; Yusuke, 2010).

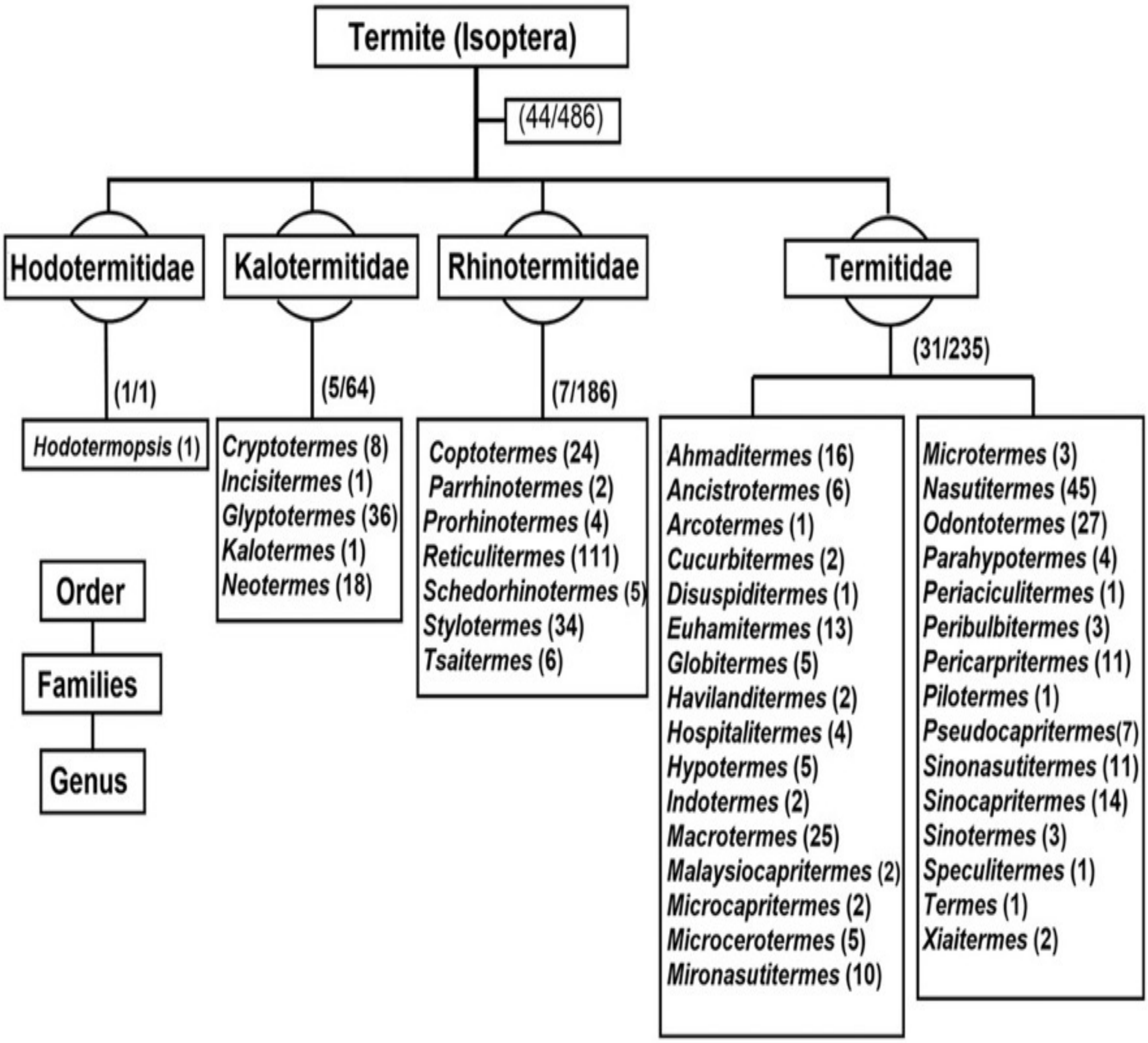

Figure 2.1: Example of termite diversity in China (Ahmad *et al*., 2021).

In Ghana, 86 species belonging to 38 genera of mound building and dry wood termites were recorded (Maayiem *et al*., 2012). Eggleton (2000) reported that in Ghana, some species of *Macrotermes, Microtermes, Ancistrotermes* and *Odontotermes* genera cause widespread damage to seedlings whilst others (e.g. *Ancistrotermes*, *Allondotermes* and *Pseudacanthotermes* genera) cause localized damage to forest trees, rangelands and food crops. In western Kenya, termite species found in maize agro-ecosystems include *Microtermes* spp., *Macrotermes herus, Macrotermes* spp., *Odontotermes kibarensis*, *Pseudacanthotermes spiniger,* and *Pseudacathotermes militaris* (Nyeko *et al.,* 2010). Among the species found in western Kenya, *Macrotermes herus*, *Microtermes pusillas*, *Microtermes* spp., and *Pseudacanthotermes spiniger* have been classified as pests (Ayuke, 2010).

During their lifecycle, termites undergo incomplete metamorphosis (Figure 2.2). They are four termite feeding groups and the functional diversity varies depending on the ecosystem (Donovan *et al.,* 2001). The criterion of classification is based on morphological characters of the digestive system of termite workers and the mandibles which relate to feeding preferences along a humification gradient (Eggleton, 2011). Functional diversity represents the functions that organisms perform in communities and ecosystems (Owen and Kevin, 2006). It predicts the impact of organisms in ecosystems and its microhabitat (Ilse *et al*., 2009).

2.2 Economic and ecological importance of termites

Termites are diverse (Figure 2.3) social organisms in the soil and they perform key ecological functions (Figure 2.4). Termites improve soil structure with the original micro-aggregates produced by the termites being preserved. These aggregates owe their stability to impregnation with saliva or other body fluids excreted by the termites (Pennisi, 2015). As termites forage, they decompose complex plant cellulose and other substances from different sources (Whitford and Duval, 2019; Figure 2.5). In tropical and subtropical regions, termites are abundant, and recycle plant nutrients in the presence of moisture (Jouquet *et al*., 2011).

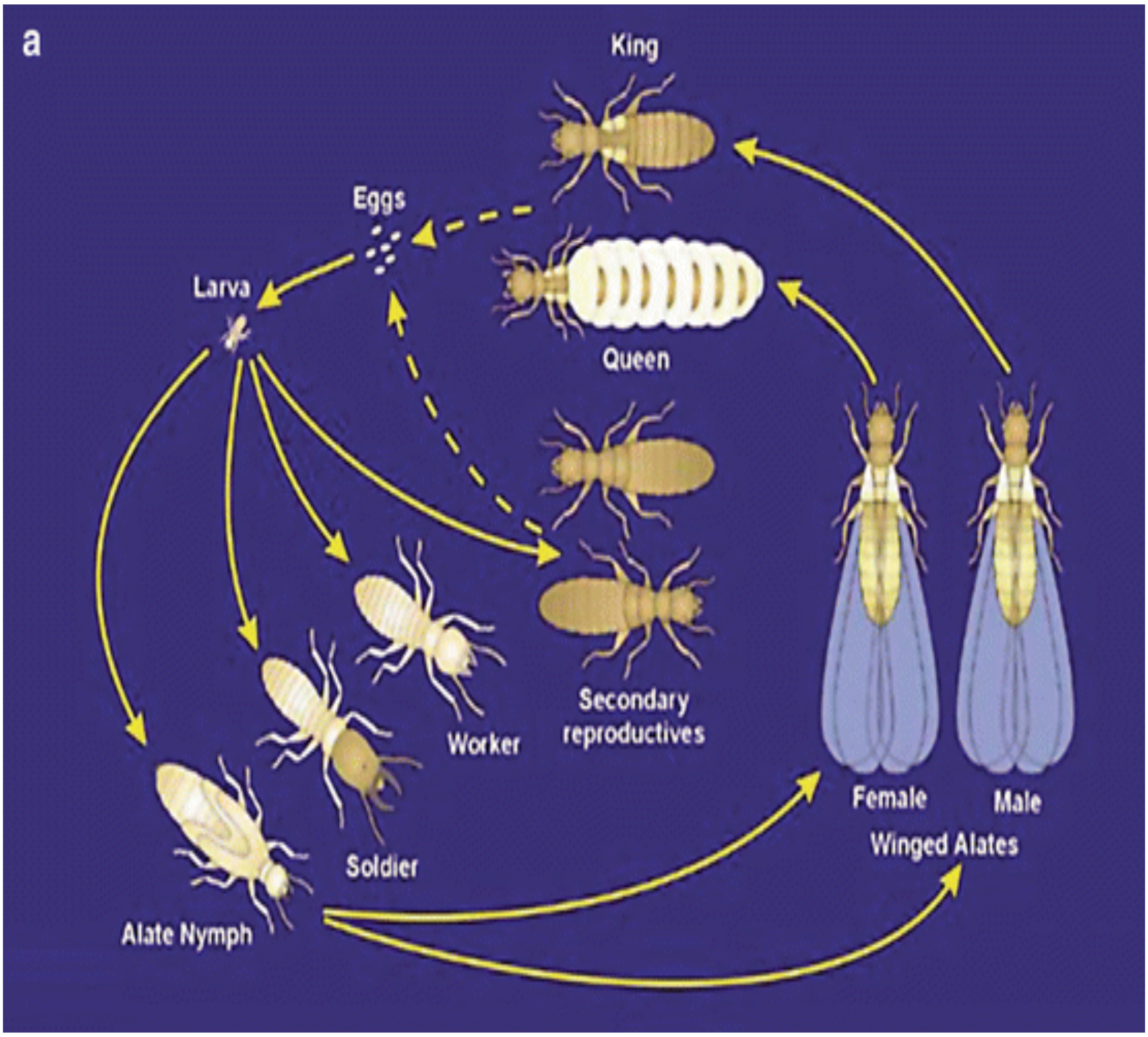

Figure 2.2: Life cycle of *Coptotermes formosanus* (Khan and Ahmad 2018a)

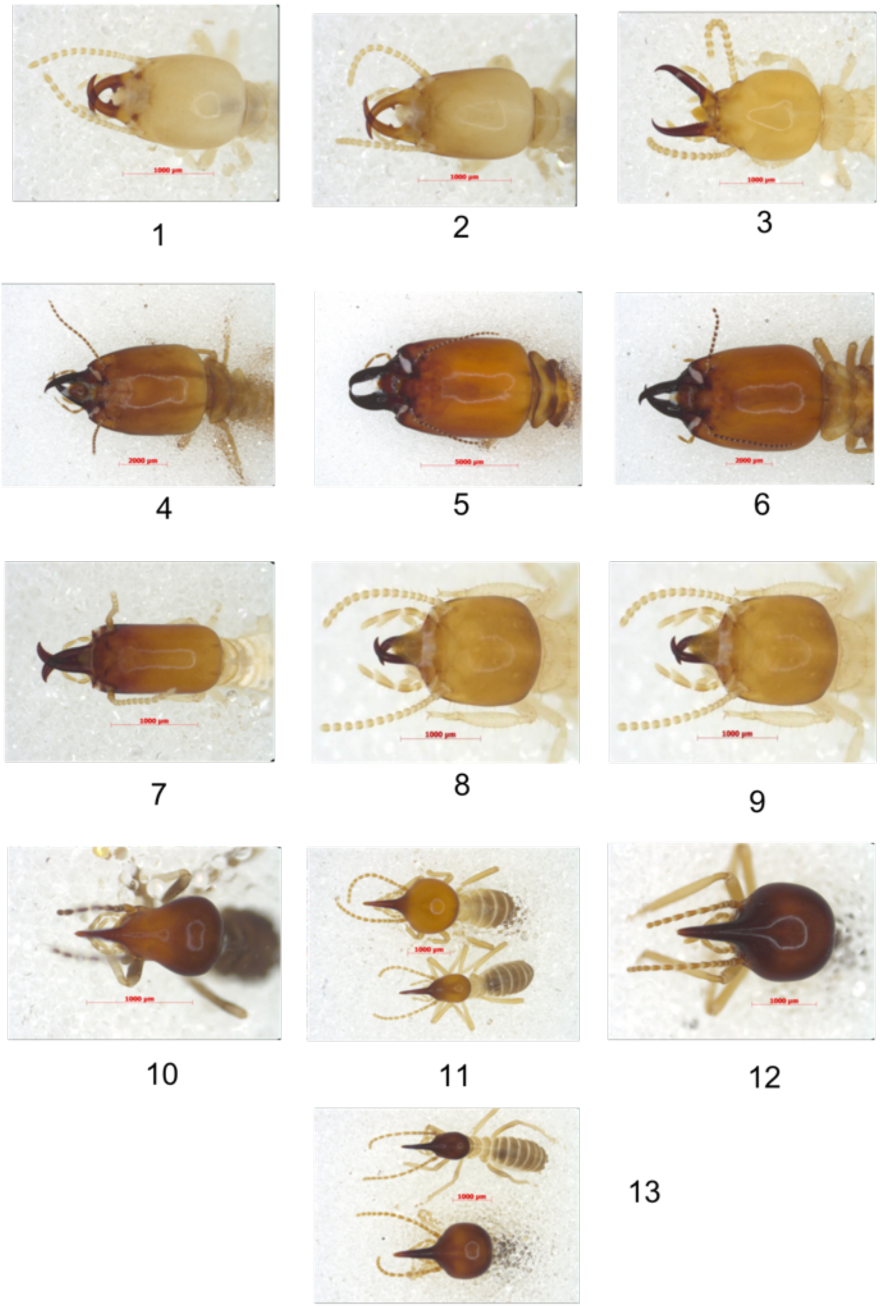

Figure 2.3: Examples of termite species diversity. ***Amitermes*** **spp. (1-2),** ***Coptotermes*** **spp. (3),** ***Macrotermes*** **spp. (4-6),** ***Microtermes*** **spp. (7),** ***Pericapritermes*** **spp. (8),** ***Ancistrotermes*** **spp. (9),** ***Fulleritermes*** **spp. (10) and** ***Trinervitermes*** **spp. (11-13) (Loko** ***et al.*****, 2019).**

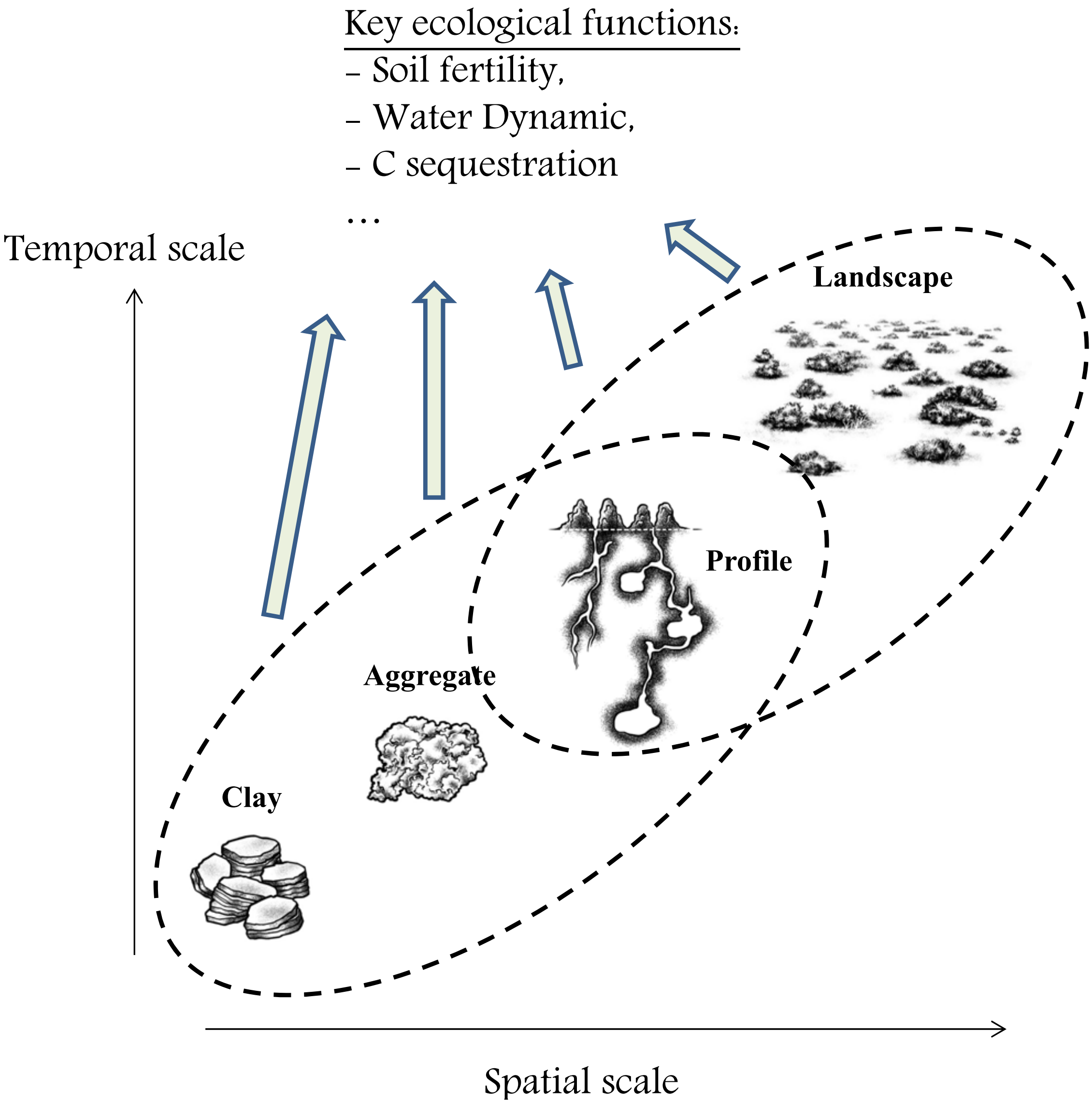

Figure 2.4: Ecosystem functions performed by termites (Jouquet *et al*., 2018)

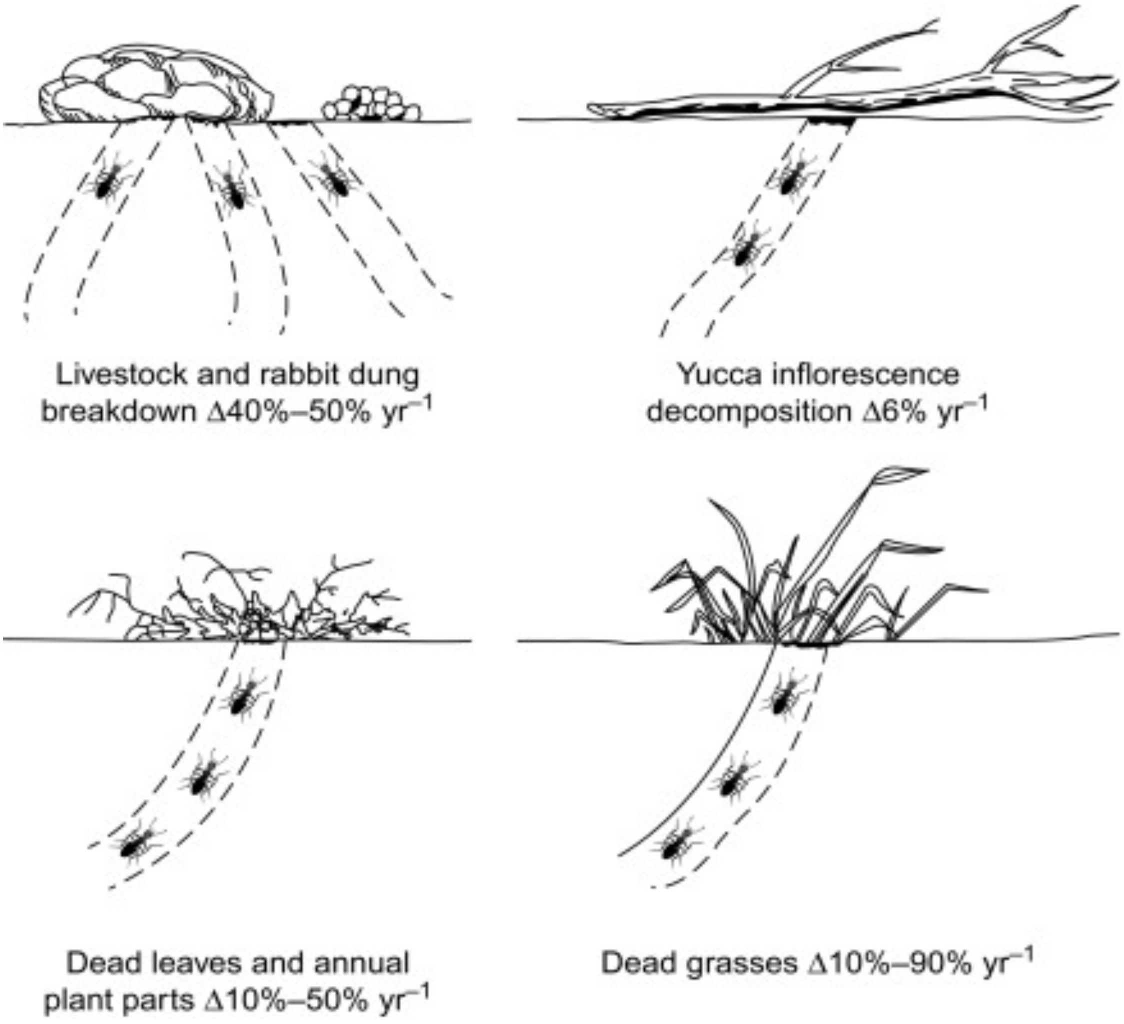

Figure 2.5: Decomposition of different materials by termites in a desert ecosystem (Whitford and Duval, 2019)

Termite mounds act as islands of soil fertility with a sample of soil originating from mounds having approximately 75% clay, 16% Carbon, 42% total Nitrogen, 23.2% Calcium, 30.6% Potassium and 15.4% Magnesium compared to soils that have not been inhabited by termites (Huis, 2017). However, as they forage their populations increase beyond economic injury levels to become pests. As pests they destroy products made of wood, building materials, trees and pasture (Meyer, 2005). Across the world termites cause huge damage to crops, products and structures that amount to billion dollars (Table 2.1).

Table 2.1: Estimated yearly economic losses due to termites (Ahmad *et al.*, 2021)

Country/Region	**Estimated losses ($)**
Australia	1.5 billion
Fiji Islands	1.0 million
China (mainland)	1.0 billion
France	0.5 billion
India	35.12 million
Indonesia	1.0 billion
Japan	0.8–1 billion
Malaysia	10–12 million
Philippine	100 million
Taiwan China	4 million
Thailand	0.5 billion
USA	11 billion
World	40 billion

In Kenya, temites damage crops such as maize, which is the key staple crop consumed in most regions in the country (Ochungo *et al.*, 2016; Figure 2.6). Suszkiw (1998), found that management of termites and replacement costs of products damaged by Formosan subterranean termites in New Orleans was estimated at 300 million dollars annually.

Despite their negative effects, termites are among the most consumed insects in Africa. Kinyuru *et al*., (2013) found that *Macrotermes* spp., *Pseudacanthotermes* spp., *Macrotermes bellicosus* and *Pseudacanthotermes spiniger* were used as food in western Kenya.

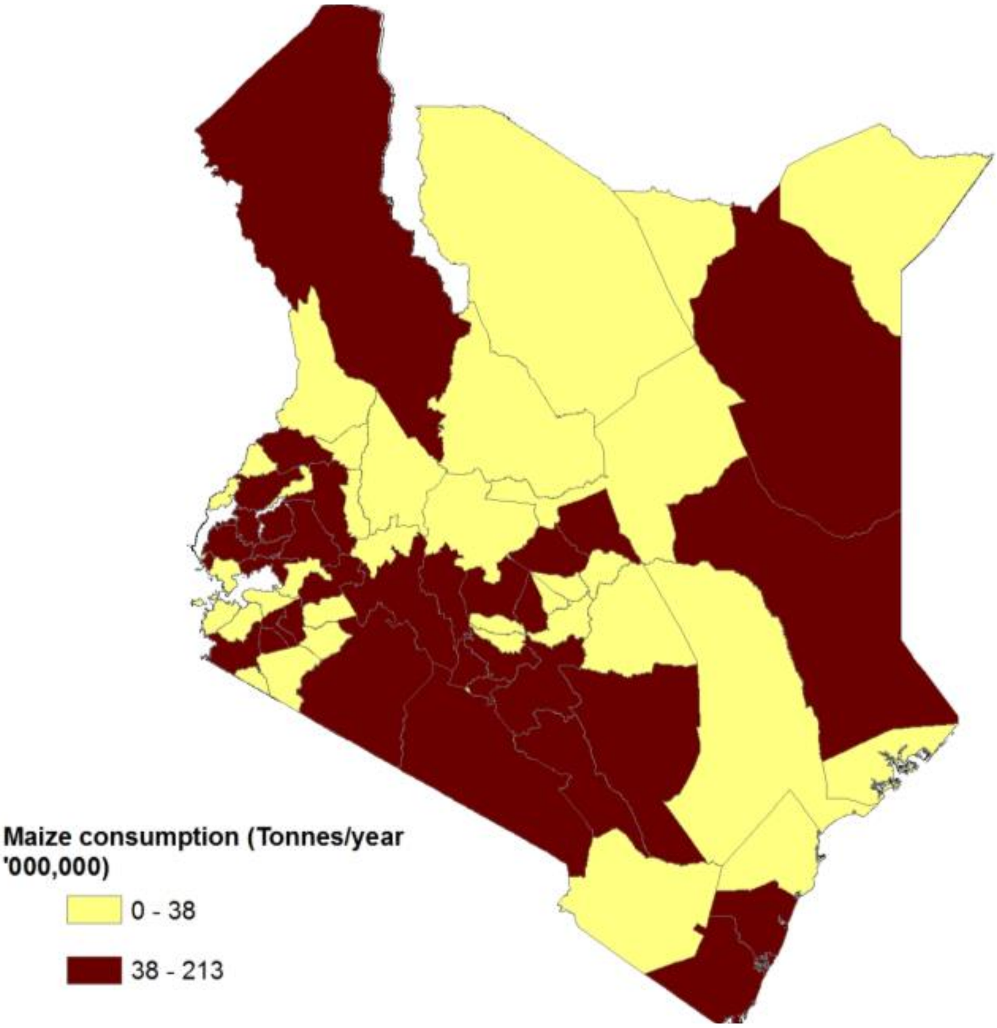

Figure 2.6: Consumption of maize (tonnes/year) in Kenya (Ochungo *et al.*, 2016).

Termites have an array of nutrients such as fats, proteins, carbohydrates, Iron and Zinc. Termites provide high-quality diets especially in the developing countries, which have been plagued by Iron and Zinc deficiencies as well as poor supply of dietary polyunsaturated fatty acid sources (Huis, 2017). In ecosystems, termites interact with other fauna such as insects which affect key functions like decomposition and nutrient cycling (Tuma *et al*., 2020; Figure 2.7). Fungus growing termites have a mutualistic association with *Termitomyces* fungi (Ahmad *et al*., 2020; Figure 2.8)

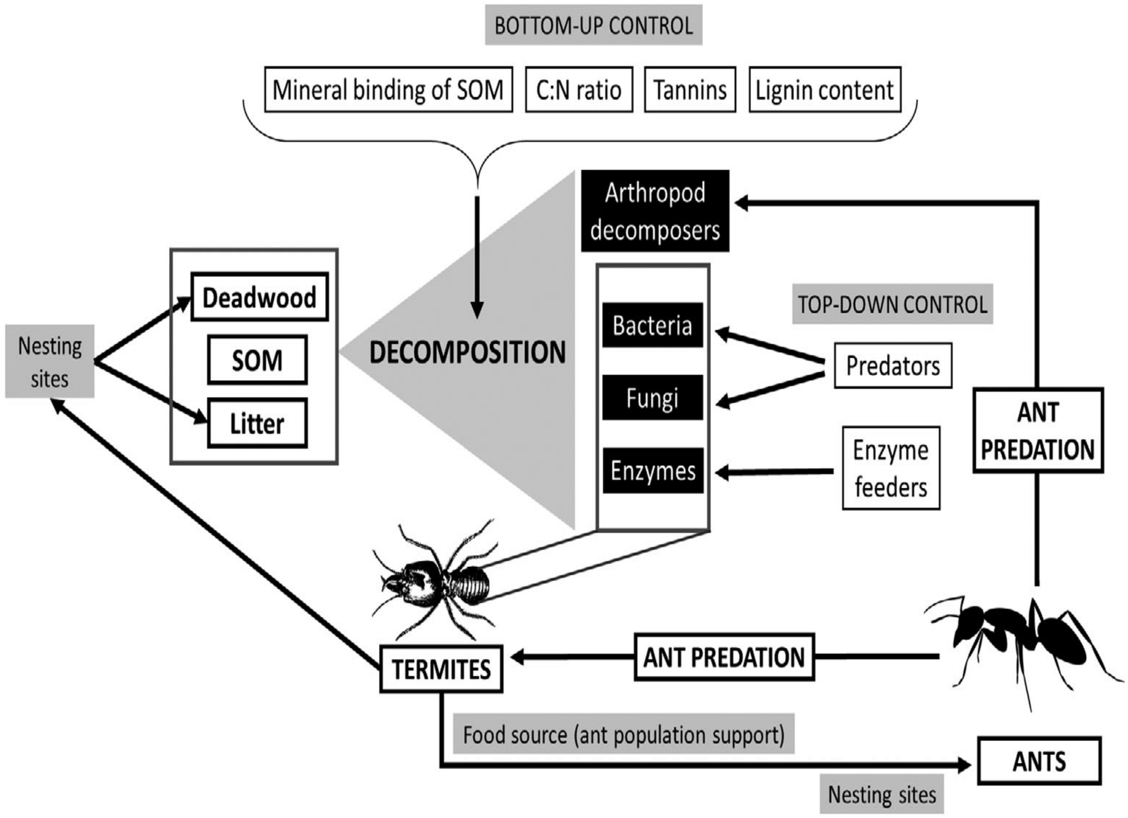

Figure 2.7: Interaction of termites with other organisms (Tuma *et al.*, 2020).

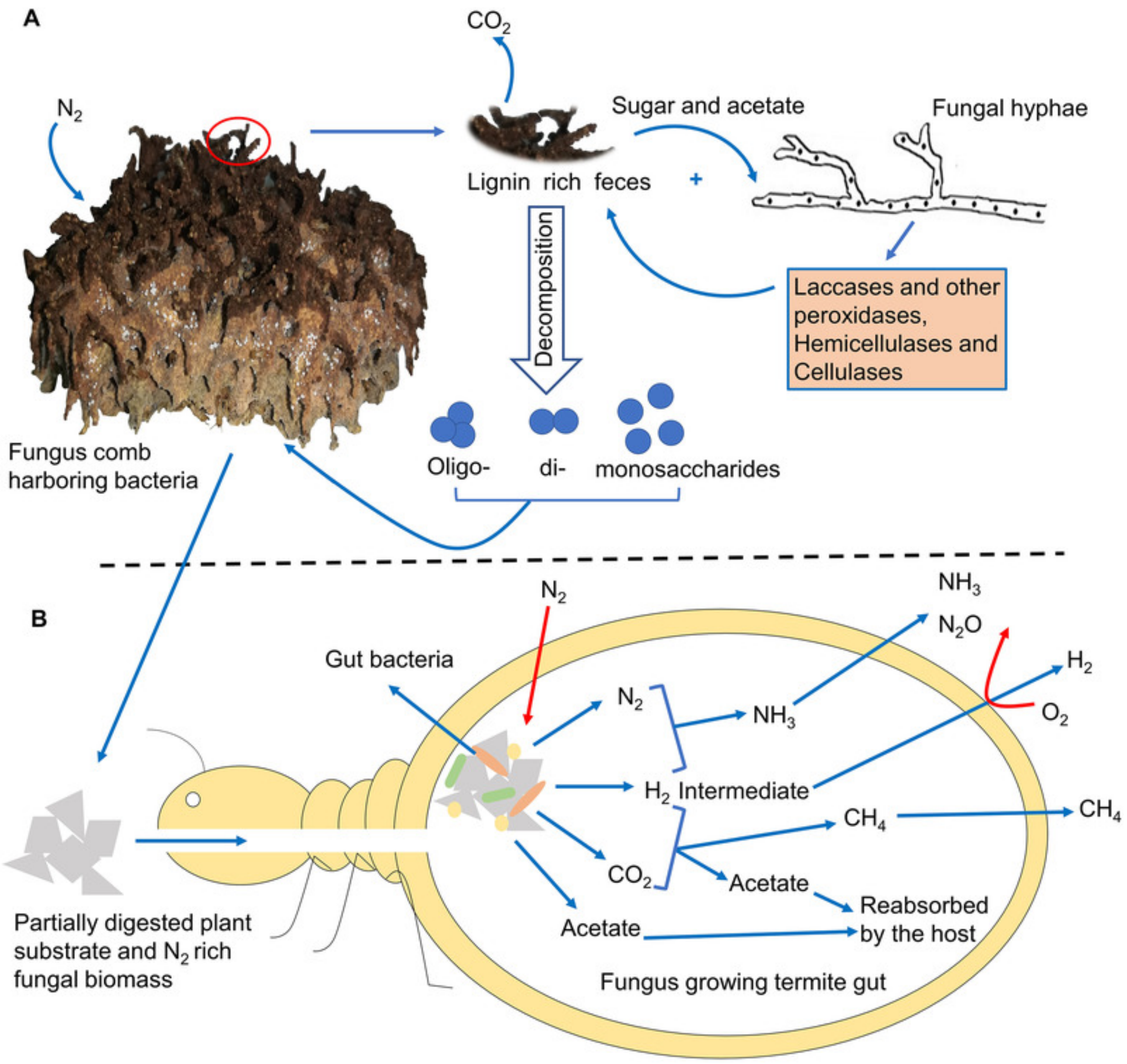

Figure 2.8: Association of termites and fungi A) Fungi and B) termites (Ahmad *et al.*, 2020).

2.3 Effects of soil properties on distribution and diversity of termites

Soil chemical and physical properties largely depend on the moisture content and mechanical properties of soil such as consistency, plasticity and aggregate strength (Nandika *et al.,* 2015). Termites modify soil structure (Figure 2.9) and soil properties affect taxonomic and functional diversity in an ecosystem.

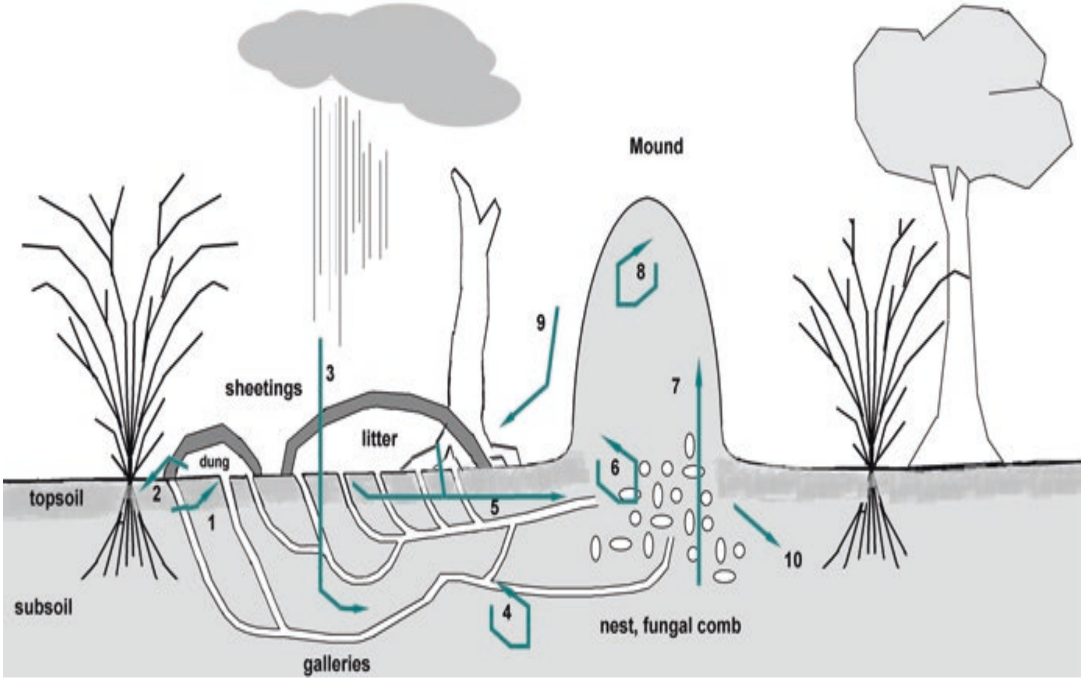

Figure 2.9: Soil modification by *Macrotermes* spp. and related processes (1-10) (Khan *et al.,* 2018b).

In a study on diversity of termites in south Jarkarta, Arinana *et al.* (2016) reported that most termite species prefer to nest in silt with more clay compared to loamy sand soil. The amount of soil organic matter influences termite interactions in an ecosystem (Figure 2.10). Axelsson and Anderson (2012) reported that there were more termite species in soils with high amount of organic matter compared to mineral soil without organic matter. Organic matter forms the bulk of termites' food and its quantity and quality can affect termite abundance and diversity (Donovan *et al.,* 2001).

Termites consume plant material in several stages of decomposition (Bourguignon *et al.,* 2011), but termites foraging can be limited by the amount of Nitrogen in the soil (Morales-Ramos and Rojas 2003).

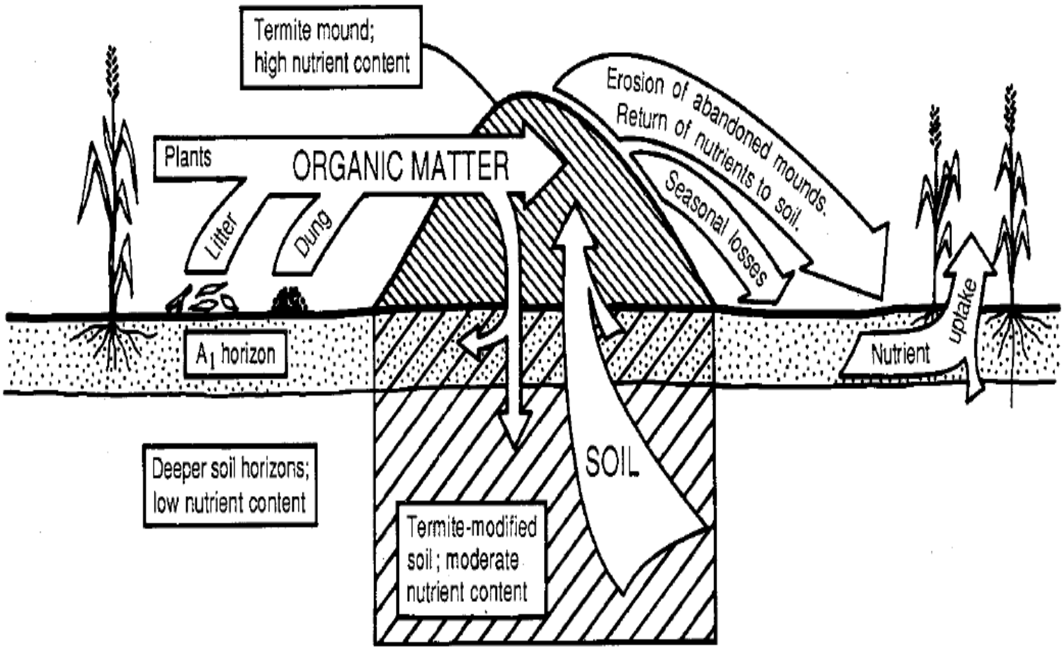

Figure 2.10: Interaction of termites with soil organic matter (Coventry *et al.*, 1988)

Phosphorous limits growth and development of consumers and decomposers (Anderson *et al.,* 2005). Phosphorus is particularly scarce in tropical forests soils and its concentration has been associated with the distribution of termites (Boelter *et al.*, 2014). Soil acidity or alkalinity affects the diversity of termites. Arinana *et al.* (2016) reported that soils with neutral pH ranging between 6.36 and 7.30 had more termite species compared to soils with pH higher than 8.00 and less than 5.00. High Carbon content is found at a depth of

15–20 cm below the soil surface and has a positive correlation with termite species abundance (Arinana *et al.,* 2016)

2.4 Management of termite infestation

A number of control measures are used to prevent termite attack on buildings as well as on crops and plants (Figure 2.11). These methods include; cultural, chemical and biological methods. The methods can be used in combination for effectiveness, efficiency and for lowering the cost of termite control programmes. The choice of the method also depends on the effect to the environment (Tasisa and Gobena, 2013).

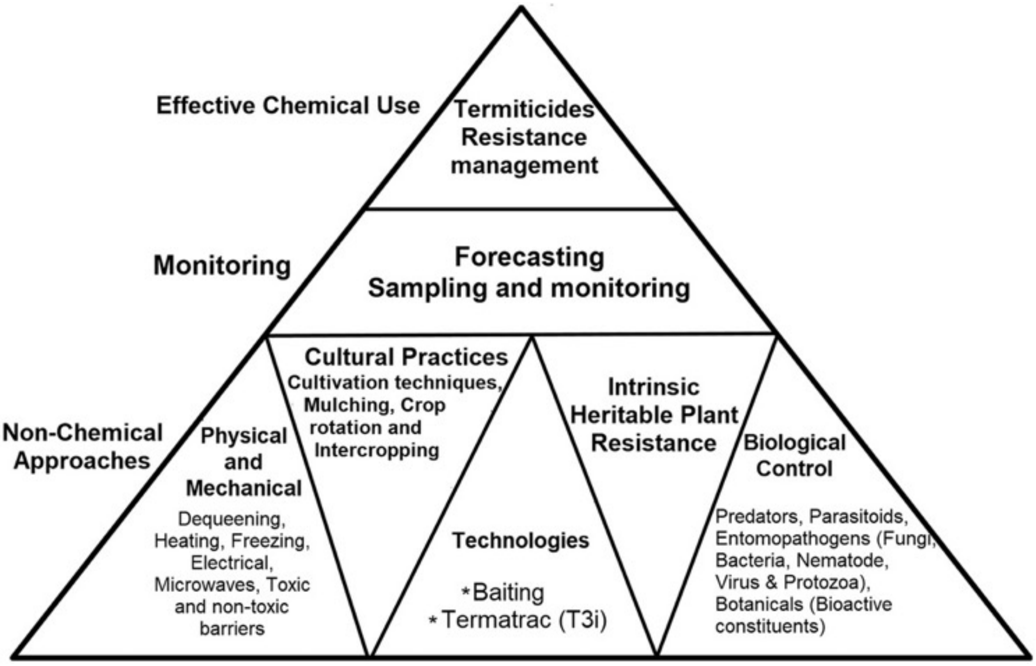

Figure 2.11: Methods for management of termites (Ahmad et al., 2021)

2.4.1 Cultural control

Farmers use several indigenous cultural methods to prevent and control termites in Africa. Akutse *et al.* (2012) reported that wood ash, sand, destruction of mounds and removal of the queen from mounds was used in the control of termites on crop farms in Ghana. In Zambia, Sileshi *et al.* (2009) reported cultural control methods such as flooding water into the mounds and crop rotation but with limited success. In Kenya, small-scale farmers use different traditional control methods of termites ranging from flooding and digging to remove the queen, excavation of mound tops, burning of straw, suffocating and killing the colony, using wood ash, dried and ground pepper, cattle urine and addition of organic manure (Gitonga, 1996). However, results are often unsatisfactory and the techniques are labour intensive (Sekamatte, 2003).

2.4.2 Intercropping

Maize monocrop systems use more nutrients compared to intercrop systems. In supplementation of nitrates in maize-beans intercrop by use of nitrogen fertilizer, beans use the inorganic nitrogen without using its natural ability to fix nitrogen from the air, thus competing with maize for nitrogen (Adu-Gyamfi *et al.*, 2007). Other than improving soil fertility, crop diversity on the same field reduces pests' infestation. Intercrops provide diverse dwelling places of predatory insects and increases the distance between plants of the same crops, thus reducing the spread of diseases. In smallholder farming systems in Africa, intercropping is used as a form of agriculture that increases yield of different crops and serves as a control for some insect pests (Sekamatte, 2002). Intercrops have been reported to reduce pest incidence and damage to the principal crops (Dassou *et al.,* 2015). Although little is known about possible preference of termites for particular crops, Sekamatte *et al.,* (2003) reported that intercropping might reduce termite damage in maize. In parts of northern Uganda, maize intercropped with sorghum had lower termite damage compared to pure stands (Sekamatte *et al.,* 2002).

2.4.3 Chemical control

Chemical control is the most widely used technique to reduce the infestation of termites. Most commonly used chemicals are broad-spectrum and persistent organo-chlorine insecticides, but there are serious limitations and increasing legal restrictions associated with their application (Tasisa and Gobena, 2013). Several termitocides are registered for termite control across the world under various brand names (Ewart, 2000). In Ethiopia, Tasisa and Gobena (2013), reported effective control of termites when mounds were treated with diazinon 60% Emulsifiable Concentrates (EC) at a rate of 20 ml and 25 ml. In Kenya and Uganda, Nyeko *et al.* (2010) demonstrated the effective control of termites by use of lindane. Khaenje *et al*. (2013) reported that although chemical insecticides were very effective in termite control in Kenya, they had negative environmental effects. Organo-chlorine insecticides also known as chlorinated hydrocarbons have been banned. These chlorinated hydrocarbons include DDT, aldrin, dieldrin, heptachlor, and chlordane. They have residual effects in the environment and accumulate in different trophic levels in food chains. A good example is chlordane which was banned and withdrawn from the market. It was found to have residue in the soil long after it was used. Othe negative impacts of organo-chlorine compounds include resistance, insect pest resurgence, secondary insect pest outbreaks and direct hazards to users (Khaenje *et al.*, 2013).

2.4.4 Biological control

There are a range of pathogenic organisms which have been isolated from termites (Osbrink *et al.,* 2001). Investigations on the effect of pathogenic organisms on termites have to a higher degree been on two entomopathogenic fungi. In the last two decades, *Beauveria bassiana* and *Metarhizium anisopliae* have been evaluated for their ability to regulate termites, but recently *Paecilomyces fumosoroseus* and entomopathogenic nematodes have been reported to infect termites (Osbrink *et al.,* 2001). The entomopathogenic fungus, *M. anisopliae*, has been developed into a product for control of termites in buildings in the USA, Brazil and Australia (Khaenje, 2013). *Metarhizium* species produce different proteins during the infection process (Figure 2.12; Kimberly and Seow, 2017). The fungus when formulated as granules and applied as seed treatment, results in reduction of plant lodging and a subsequent increase in maize yield comparable to that obtained with the use of the chemical insecticide lindane (Nyeko *et al.,* 2010; Khaenje *et al.,* 2013). The effectiveness of *M. anisopliae* in control of termites in maize cropping systems was demonstrated for the first time in Uganda (Maniania *et al.,* 2002).

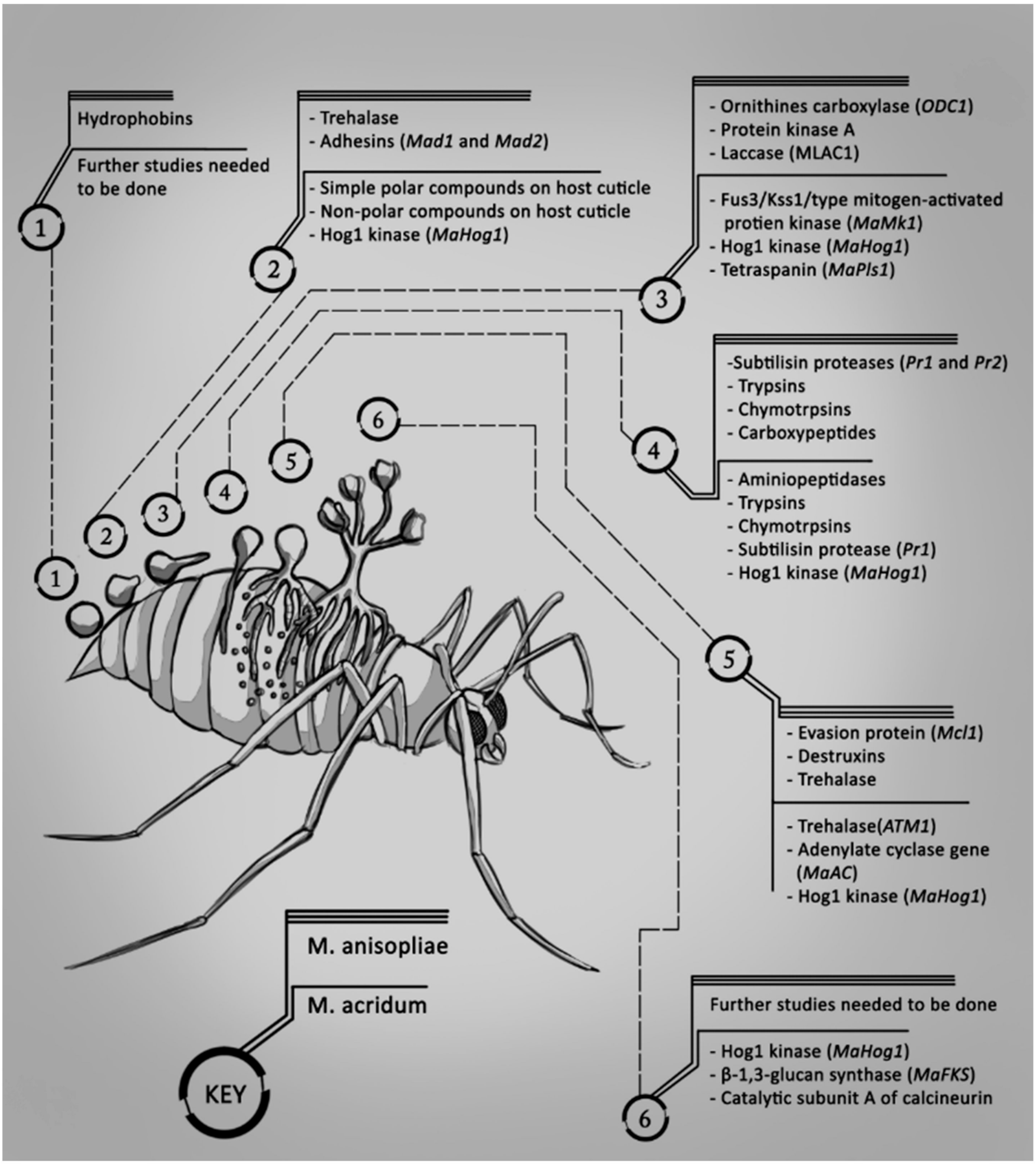

Figure 2.12: Substances that are produced by *Metarhizium* species during infection of termites (Kimberly and Seow, 2017).

Entomopathogenic nematodes attack insects and are naturally found in soil. Although laboratory experiments have shown high efficacy of these nematodes in controlling termites, trials have not been done in termite infested farms and homes. Furthermore, the nematodes have not been formulated to usable forms that can be used by the farmers to effectively control termites (Osbrink *et al.,* 2001). Soil-dwelling ant species in the Order Hymenoptera and family Formicidae are predatory on other invertebrates or arthropods participating in the cycle of litter and wood degradation such as termites (Eggleton, 2011). Luke *et al.* (2014) demonstrated that most of the ant species prey on termites opportunistically (by raiding) and several ant genera (*Leptogenys*, *Termitopone*, *Dorylus* and *Megaponera*) are specialized termite predators (Garcia *et al.,* 2013). Ants in the genus *Dorylus*, known as driver or safari ants, are natural enemies of termites and are used as a form of pest control in Cameroon and Ghana (Akutse *et al.,* 2012). Termites are attractive prey for predatory ants because they provide exceptionally concentrated and protein rich food and are relatively sessile (Buczkowski and Bennett, 2007).

Botanical pesticides (bio-pesticides) possess many desirable properties, such as insecticidal activity, repellency to pests, deterrent to feeding, insect growth regulation and toxicity to agricultural pests (Dhaliwal and Ramesh, 2013). Addisu *et al.* (2013) found that botanicals such as neem (*Azadirachta indica*), garlic (*Allium sativum*) and physic nut (*Jatropha* spp.) can be used in insect pest management and successfully demonstrated their efficacy in termite control in Ethiopia. Furthermore, Dhaliwal and Ramesh (2013) reported that Azadirachtin-based insecticide had low mammalian toxicity and could be applied as foliar spray or soil drench. Plant extracts are natural pesticides known to control insect pests. The plant extracts are made to liquid concentrate formulation similar to synthetic insecticides (Dhaliwal and Ramesh, 2013). Botanical insecticides are environmentally friendly compared to synthetic insecticides (Addisu *et al.,* 2013).

CHAPTER THREE

Termite diversity in natural vegetation, maize-beans intercrop and maize monocrop in Embu and Machakos Counties

3.0 ABSTRACT

Termites perform key ecological functions and also cause crop damage. Land use change resulting from agricultural intensification can result in changes in termite species diversity and abundance. Termite species occurring in natural vegetation, maize monocrop and maize-beans intercrop macrohabitats were investigated in Embu and Machakos Counties, Kenya. Across the two Counties, seven termite species were recorded with Machakos County having the highest number. Additive diversity partitioning of species richness and Simpson diversity showed that, α component contributed to 98.3% and 99.1% of the total diversity, respectively. Population densities of three termite species significantly varied between land use types in Machakos County but there were no differences in termite species abundance in Embu County. In addition, the species richness did not differ significantly between macrohabitats within each County. In Embu, season significantly influenced the abundance of *Macrotermes subhyalinus*, *M. herus*, and *Coptotermes formosanus* which occurred in greater numbers during the wet season. There was a significant influence of land use on *Trinervitermes gratiosus* and *C. formosanus* in Machakos with both species occurring in higher numbers in natural vegetation. These findings provide an insight into the effects of land use change from natural vegetation to maize agro-ecosystems on termite diversity. It also provides a baseline for further studies on termite diversity in Kenya and their ecological significance.

3.1 INTRODUCTION

Termites form an important component of the soil invertebrate community and they contribute to different ecosystem services (Jouquet *et al*., 2011). Like most biodiversity, they are threatened by agricultural intensification (Zabel *et al*., 2019) which is on the rise in sub-Saharan Africa (SSA) (Haggar *et al*., 2020). In the last decade, conversion of natural ecosystems to agricultural land has been observed in SSA in order to cater for the increased demand in supply of key staple crops (Kuyah *et al*., 2021). In Kenya, maize is widely consumed by both rural and urban population and the area of production has increased in the last decade (FAOSTAT, 2021). Loss of biodiversity, including termites, that results from unsustainable agricultural production can have implications on functioning of agro-ecosystems (Jouquet *et al*., 2011).

Termite populations can be high, reaching up to 15,000 individuals/m^2. They play an important role in ecosystem functioning through their involvement in organic matter decomposition, soil pedogenesis and nutrient cycling. They also influence microbial, plant and animal diversity through landscape modifications in water and nutrient distribution (Jouquet *et al*., 2011). In Uasin Gishu plateau, Kenya, Jungerius *et al*. (1999) reported that termites improved soil structure by producing stable microaggregates in the subsoil. Importance of termites in key ecosystem functions was demonstrated in a study in the Kenyan Laikipia plateau whereby subterranean termites influenced nitrogen fixation by *Acacia drepanolobium* and subsequently affected spatial distribution of the *Acacia* which had ecological implications on the entire community (Fox-Dobbs *et al*., 2010). At the same site, Pringle *et al*. (2010) observed that mounds built by *Odontotermes* species improved plant productivity while Baker *et al*. (2020) reported that *Odontotermes montanus* affected the diversity of fungi and bacteria at localized points within mounds. The effect was scaled up to the entire savanna community at regular spatial points which increased fungal and bacterial diversity with implications for ecosystem functioning.

In tropical agro-ecosystems, termites are perceived as pests with no consideration for the important ecosystem services that they provide; exploring potential utilization of these ecosystem services in cropping systems is proposed (Jouquet *et al*., 2011). In some African countries, farmers have utilized the ecosystem engineering function of termites in improving productivity of farmland and restoration of degraded land through the use of Zaï pits (Kaiser *et al*., 2017; Nyantakyi-Frimpong, 2020; Roose *et al*., 1999). Apart from the ecological role that they perform, termites can also reduce crop yields (Govorushko, 2019) and damage their quality (Black and Okwakol, 1997). Maize production by smallholders in SSA is largely rainfed (Prassana *et al*., 2021) which makes it susceptible to termite damage (Govorushko, 2019). In western Kenya, farmers reported damage of their crops and trees by termites (Adoyo *et al*., 1997) while in Zimbabwe, Mutsamba et al. (2016) observed a high prevalence of Macrotermitinae termites in maize under conservation agriculture.

Different termite species have been identified in Kenya (Anyango *et al*., 2020; Ayuke *et al*., 2011; Kagezi *et al*., 2011; Makonde *et al*., 2013; Vesala *et al*., 2017). However, there are limited studies on the influence of macro-habitats and seasons on their diversity. Land use change through agricultural intensification can affect termite diversity and the ecosystem services that they provide. Soil macrofauna in Zambia varied across land use systems whereby termite abundance was higher in miombo woodland relative to maize monoculture and maize intercropped with trees (Sileshi and Mafongoya, 2006). Black and Okwakol (1997) posits that land use change from natural vegetation to agricultural land can affect termite diversity which can consequently affect nutrient cycling, energy flow, gas fluxes and vegetation diversity. In Cameroon, agricultural land that was converted from a tropical forest had a lower number of soil-feeding termite species which the authors argued could negatively affect crop yields (Eggleton *et al*., 2002). Similarly, anthropogenic disturbance in a West African savannah resulted in reduced population densities of termite species relative to a protected national park (Hausberger and Korb, 2016).

In addition to the influence of land use change on termites, climatic variables can also affect their diversity (Eggleton, 2000; Bourguignon *et al.*, 2015; Davies *et al.*, 2015). Temperature and moisture variations across seasons affect termite diversity (Davies *et al.*, 2015) warming and rainfall influences the distribution and architecture of mounds (Korb and Linsenmair, 1998; Shanbhag *et al.*, 2017). Knowledge on how termite species distribution and diversity is affected by the intensification of land use change in Kenyan maize agro-ecosystems and natural systems is crucial since it forms a basis for understanding their ecological role and potential economic impact which will consequently inform sustainable crop production that taps into the ecosystem services that they provide. Such information will also be important in designing species-specific integrated termite management programmes that are ecologically sustainable.

3.2 MATERIALS AND METHODS

3.2.1 Study sites

The study was conducted in Kithimani (Mamba), Matuu, and Ndalani (Kambi ya mawe) locations of Machakos county and Kangaru, Kamiu and Ena of Embu county, Kenya (Figure 3.1). Study sites in Machakos and Embu were at an average altitude of 1240m and 1600 m above sea level, respectively. The rainfall pattern in both counties is bimodal, with the first rainy season (long rains) starting from March to June while the second (short rains) starts in mid-October and ends in December. In each location, three macrohabitats comprising of maize monocrop farms, maize intercropped with beans and natural vegetation were purposively sampled from farmers established farms and uncultivated natural vegetation. Three replicates of each macrohabitat in each county were sampled. The replicates were 20km apart from each other. In both counties, natural vegetation comprised of grass, *Lantana camara* and *Acacia* species. The maize monocrop and maize-bean intercrop macrohabitats had been converted from adjacent natural vegetation and had been under cultivation for 20 years.

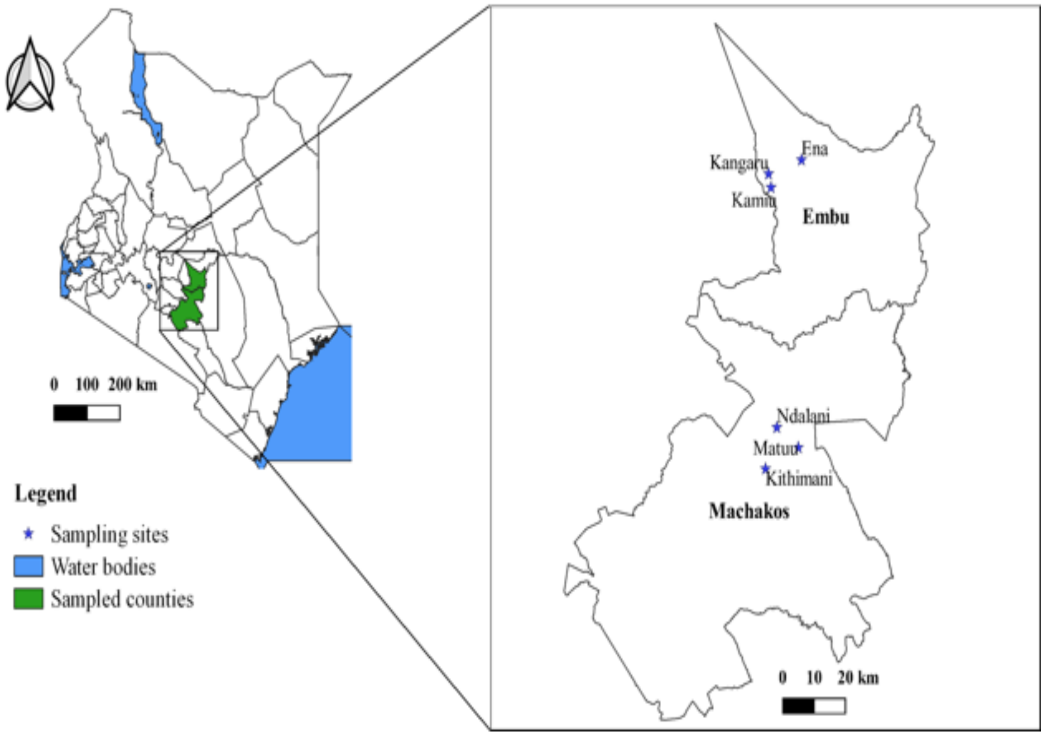

Figure 3.1: Study sites at Kithimani (Mamba), Matuu, and Ndalani (Kambi ya mawe) locations of Machakos county and Kangaru, Kamiu and Ena of Embu county, Kenya

3.2.2 Termite sampling and identification

Three 100m × 2 m belt transects separated by 100m were laid out at each macrohabitat as described by Jones et al. (2003). Twenty 5m × 2 m sections from each transect were sampled (one-person hour) from different microhabitats that included dead wood, soil, mounds, leaf litter, sheeting and runways. From each section, termites were also collected from twelve (12cm × 12 cm, 10 cm deep) pits. Sampling across all sites was done during dry and wet seasons for two consecutive years (dry season one -July to September 2018, dry season two – Jan to March 2019, wet season one – Oct to Dec 2018 and wet season two – March to May 2019). During each season, samples were collected at monthly intervals and stored in 80% ethanol. Collections of soldier and/or worker castes were identified to species levels using taxonomic guides (Webb, 1961; Sands, 1998) and through reference collections of National Museums of Kenya. The average rainfall and minimum temperature data were obtained from the Kenya Meteorological Department.

3.2.3 Data analysis

Termites species abundance data were checked for normality and log(x+1) transformed where necessary. The data from the two dry seasons (dry season one -July to September 2018, dry season two – Jan to March 2019) was pooled and the average was used for subsequent analyses. The same was done for the two wet seasons (wet season one – Oct to Dec 2018 and wet season two – March to May 2019). Data was checked for differences before pooling. To assess the influence of season (dry and wet) and macrohabitats (maize monocrop, maize intercropped with beans and natural vegetation) on termite species and diversity indices in Embu and Machakos Counties, a two-way analysis of variance was performed with subsequent Tukey's Honestly Significant Difference (HSD) post hoc tests. Simple main effects tests for significant season x macrohabitat interactions were also performed. Species richness, Pielou's evenness, Shannon-Weaver and Simpson diversity indices were analyzed using vegan package version 2.5-7 in R statistical software (Oksanen *et al*., 2020). Contribution of α (diversity within fields) and β diversity (diversity between fields in different sites) to the total termite diversity ($\gamma=\alpha+\beta$), was assessed by additive diversity partitioning (Lande, 1996) using the *adipart* function (Crist *et al*., 2003) in R package vegan version 2.5-7 (Oksanen *et al*., 2020). This function considers that mean alpha (α) and beta (β) diversities add up to gamma (γ) diversity. The six sites were Kangaru, Kamiu, Ena (Embu county), Kithimani (Mamba), Matuu, and Ndalani (Kambi ya mawe) (Machakos county). The additive partitioning of diversity was based on species richness, Shannon-Weaver and Simpson indices. Permutation analyses was used to determine the expected diversity.

Non-metric multidimensional scaling (nMDS; Clarke, 1993) using Jaccard index was used to present the spatial patterns of termite species populations in Embu and Machakos counties and the differences were analyzed using permutational multivariate analysis of variance (PERMANOVA) (Anderson, 2001), followed by permutational multivariate analysis of dispersion (PERMDISP) (Anderson, 2006). The most influential species and their contribution to site dissimilarities were evaluated using similarity percentage analysis (SIMPER). The vegan functions *simper, metaMDS, adonis* and *betadisper* in R version 2.5-7 were used in the analyses (Oksanen *et al*., 2020). Relationships between climate variables and termite abundance were examined through canonical correspondence analysis (CCA) in vegan package (Oksanen *et al*., 2020).

3.3 RESULTS

Across the two counties, *Trinervitermes gratiosus, Macrotermes subhyalinus*, *Macrotermes herus*, *Coptotermes formosanus*, *Odontotermes badius, Odontotermes longignathus* and *Cubitermes ugandensis* were recorded with Machakos county having the highest number—seven due to the presence of *Trinervitermes gratiosus*. In Embu county, season significantly influenced the abundance of *Macrotermes subhyalinus*, *Macrotermes herus*, and *Coptotermes formosanus*. *Odontotermes badius* was the only species whose abundance was influenced by the interaction of season and macrohabitat (Table 3.1; Figure 3.2 and 3.3). A test of simple main effects showed that interaction between dry season and natural vegetation was significant ($P = 0.01$).

In Machakos county, the abundance of one species (*C. ugandensis*) was affected by season x macrohabitat interaction. Specifically, there was a significant interaction of both seasons with maize monocrop ($P < 0.001$). The number of *M. herus*, and *O. longignathus*, was affected by season. Abundance of *T. gratiosus*, and *C. formosanus*, was influenced by both season and macrohabitat. *Trinervitermes gratiosus* which was only recorded in Machakos county occurred in greater numbers in the natural vegetation macrohabitat. In Embu and Machakos counties, *C. formosanus* occurred in greater numbers during the wet season (Table 3.1; Figure 3.2 and 3.3). Machakos county had the highest number of termite species; however, the species richness did not vary across macrohabitats within each of the two counties. However, Pielou'evenness was significantly lower, in the maize-beans intercrop relative to natural vegetation in Embu county (Table 3.2). In Machakos county, the Simpson diversity index was greater during the wet season.

Table 3.1: Two-way analysis of variance of season, macrohabitat and their interaction on termite species in Embu and Machakos Counties

	Season		Macrohabitat		Season x macrohabitat	
	F	*P*	*F*	*P*	*F*	*P*
Embu						
Macrotermes subhyalinus	9.0	0.011*	0.1	0.895	0.3	0.723
Macrotermes herus	12.0	0.005**	2.3	0.139	1.0	0.397
Odontotermes badius	16.3	0.002**	1.0	0.397	4.3	0.038*
Cubitermes ugandensis	2.0	0.183	0.5	0.619	0.5	0.619
Odontotermes longignathus	3.2	0.099	0.2	0.821	0.2	0.821
Coptotermes formosanus	36.0	<0.001***	3.3	0.074	2.3	0.148
Machakos						
Macrotermes subhyalinus	4.5	0.055	0.7	0.537	0.1	0.911
Macrotermes herus	5.6	0.036*	0.1	0.946	0.4	0.686
Trinervitermes gratiosus	17.3	0.001**	8.6	0.004**	2.8	0.102
Odontotermes badius	0.9	0.361	1.3	0.308	0.3	0.746
Cubitermes ugandensis	196.0	<0.001***	19	<0.001***	7.0	<0.001***
Odontotermes longignathus	8.0	0.015*	0.9	0.441	0.1	0.883
Coptotermes formosanus	14.3	0.003**	8.1	0.006**	1.9	0.198

*** = P < 0.001, ** = P < 0.01, * = P < 0.05

Table 3.2: Species richness, Pielou's evenness, Shannon-Weaver and Simpson diversity indices of three macrohabitats in Embu and Machakos Counties during wet and dry seasons

County	Index	Maize-beans intercrop		Maize monocrop		Natural vegetation	
		Mean	SE	Mean	SE	Mean	SE
Embu	Shannon-Weaver	1.32a	0.04	1.37a	0.05	1.45a	0.02
	Simpson diversity	0.67a	0.02	0.69a	0.02	0.73a	0.01
	Species richness	5.83a	0.17	5.83a	0.17	5.83a	0.17
	Pielou's evenness	0.75b	0.01	0.78ab	0.02	0.83a	0.02
Machakos	Shannon-Weaver	1.37a	0.06	1.2a	0.10	1.42a	0.08
	Simpson diversity	0.68a	0.02	0.61a	0.04	0.68a	0.03
	Species richness	6.33a	0.33	5.67a	0.42	6.67a	0.33
	Pielou's evenness	0.74a	0.02	0.69a	0.04	0.75a	0.03

Different letters across the row indicate significant differences. SE-Standard error.

Table 3.3: Two-way analysis of variance of season, macrohabitat and their interaction on species richness, Pielou's evenness, Shannon-Weaver and Simpson diversity indices in Embu and Machakos Counties

County		Season		Macrohabitat		Season X macrohabitat	
		F value	P value	F value	P value	F value	P value
Embu	Shannon-Weaver	0.19	0.67	2.89	0.09	0.25	0.79
	Simpson diversity	0.46	0.51	3.59	0.06	0.41	0.67
	Species richness	3.00	0.10	0.10	1.00	0.10	1.00
	Pielou's evenness	3.61	0.08	5.53	0.02*	0.39	0.69
Machakos	Shannon-Weaver	3.27	0.10	2.68	0.11	2.40	0.13
	Simpson diversity	5.07	0.04*	1.93	0.19	1.70	0.22
	Species richness	0.31	0.59	2.15	0.16	2.15	0.16
	Pielou's evenness	4.31	0.06	1.24	0.32	1.60	0.24

* = $P < 0.05$

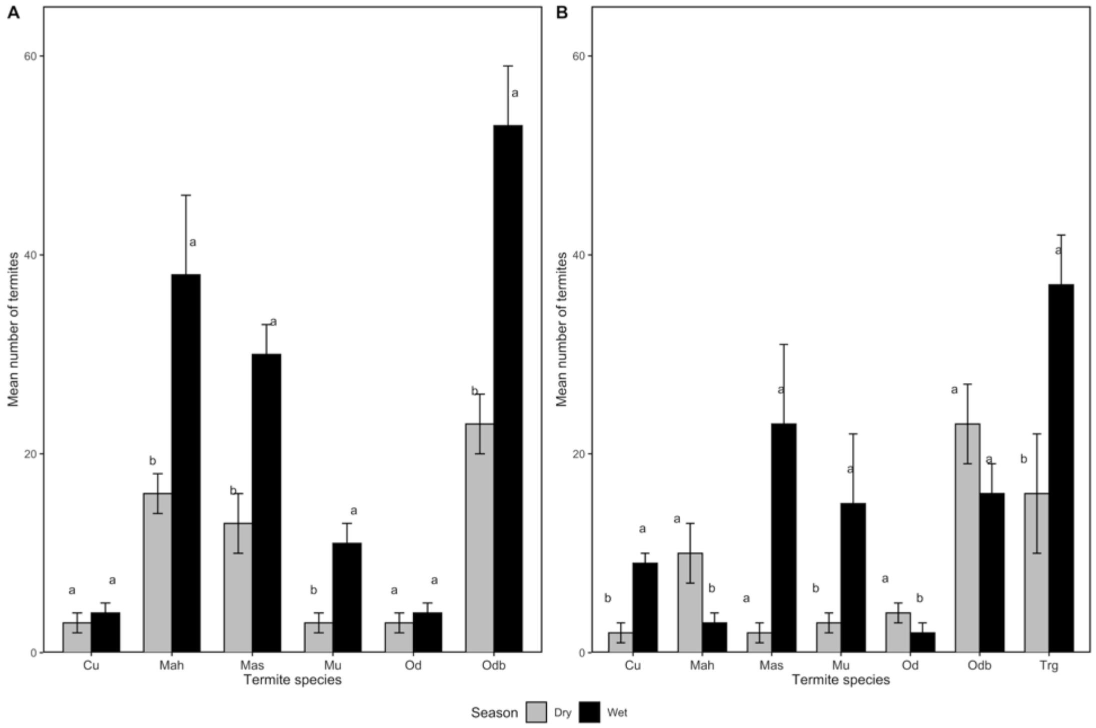

Figure 3.2: Abundance (mean ± standard error) of termite species during dry and wet season in A) Embu and B) Machakos Counties. Different letters indicate significant differences in abundance of termite species. Mas- *Macrotermes subhyalinus,* Mah- *Macrotermes herus,* Trg- *Trinervitermes gratiosus,* Odb- *Odontotermes badius,* Cu- *Cubitermes ugandensis*, Od- *Odontotermes longignathus* and Mu- *Coptotermes formosanus*.

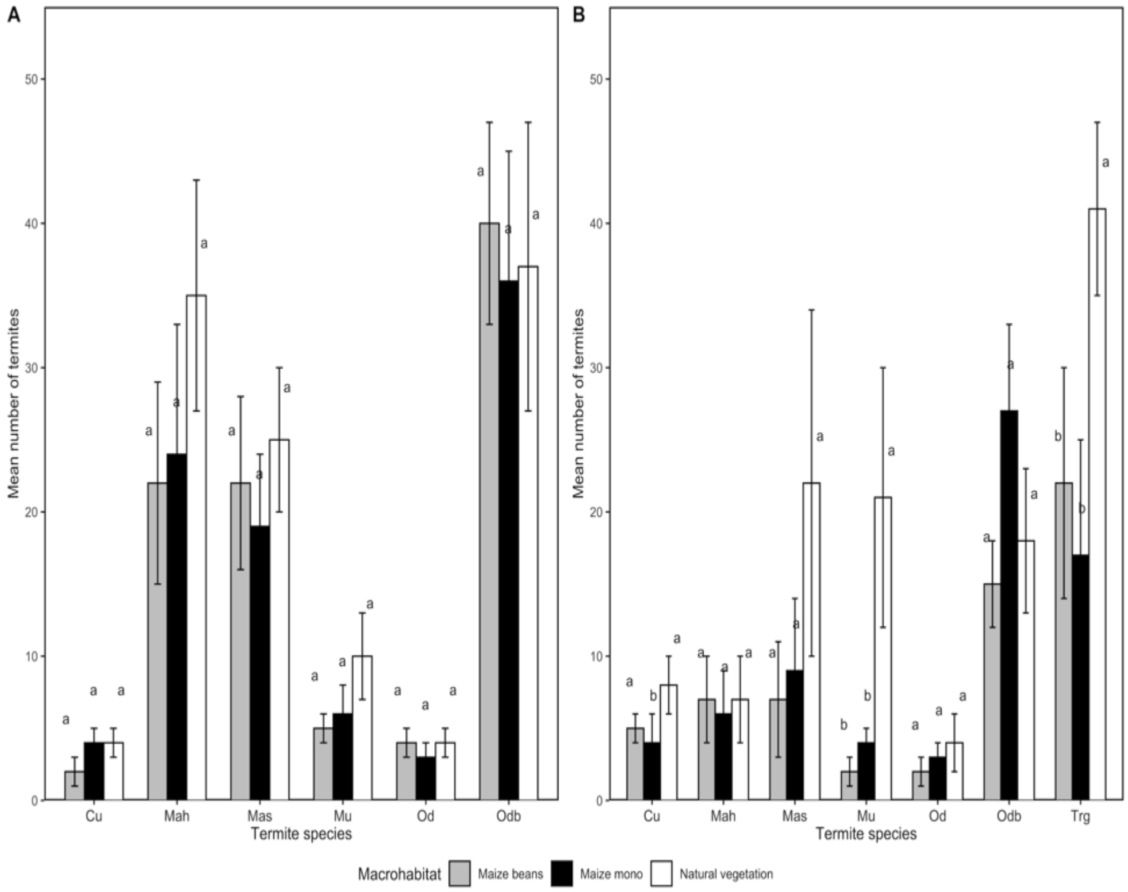

Figure 3.3: Abundance (mean ± standard error) of termite species in maize-beans, maize monocrop and natural vegetation macrohabitats in A) Embu and B) Machakos Counties. Different letters indicate significant differences in abundance of termite species. Mas- *Macrotermes subhyalinus,* Mah-*Macrotermes herus,* Trg- *Trinervitermes gratiosus,* Odb- *Odontotermes badius,* Cu- *Cubitermes ugandensis*, Od- *Odontotermes longignathus* and Mu- *Coptotermes formosanus*.

Additive diversity partitioning was conducted for species richness, Shannon-Weaver and Simpson indices in Kangaru, Kamiu, Ena (Embu county), Matuu, Mamba and Kambi ya Mawe (Machakos county) sites. From the diversity partitioning of richness, 98.3% of the total diversity was contributed by α component which was significantly lower than expected (P = 0.0001). On the other hand, contribution of β diversity was higher than expected by chance (P = 0.0001). Within fields, α Simpson diversity was greater (99.1%) than β diversity but lower than expected (P = 0.0001; Figure 3.4).

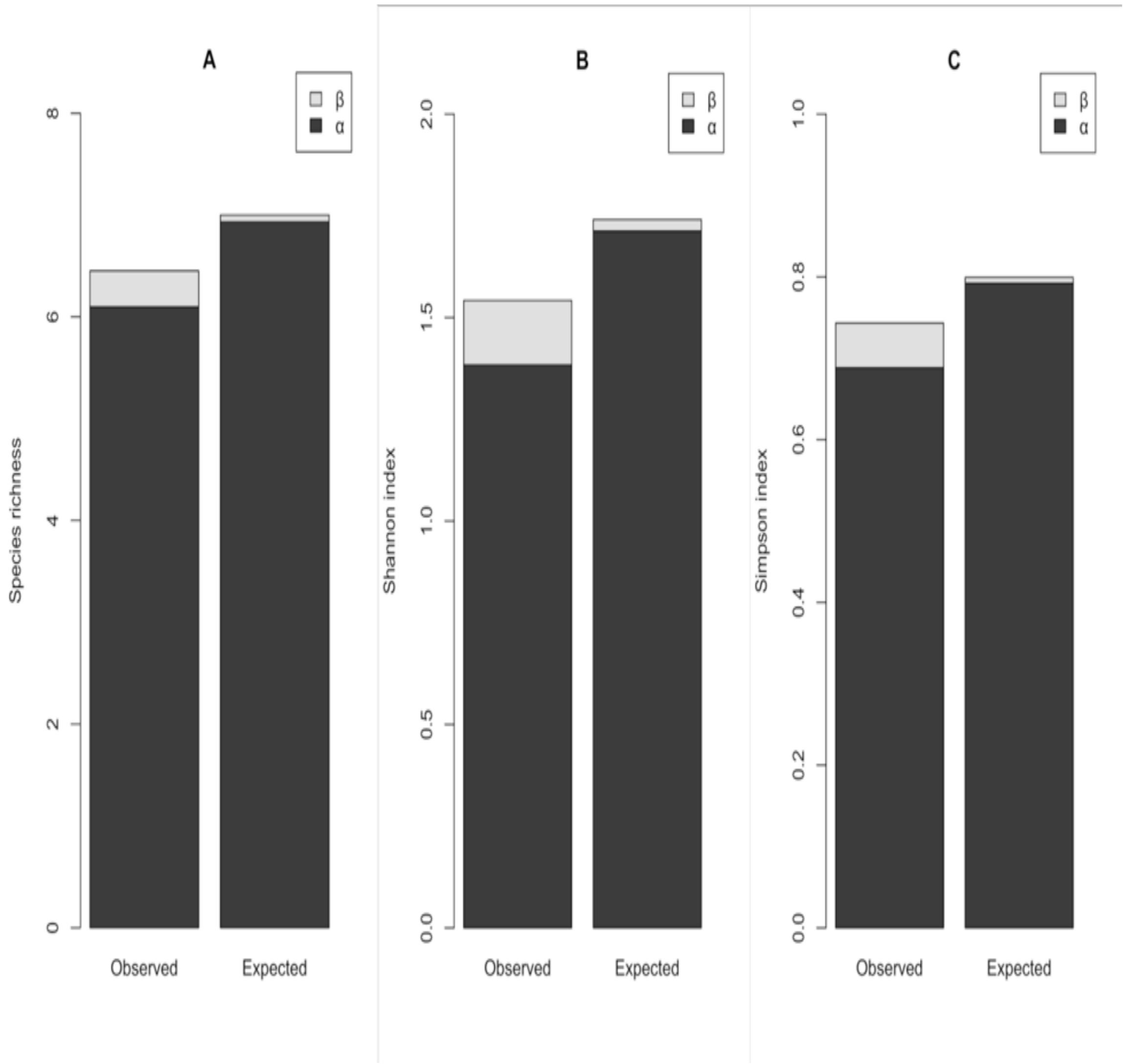

Figure 3.4: Additive partitioning of a) species richness b) Shannon-Weaver diversity and c) Simpson diversity for fields in Kangaru, Kamiu, Ena (Embu County), Matuu, Mamba and Kambi ya mawe (Machakos County) sites. Total diversity (γ) is partitioned into (α) and beta (β) components.

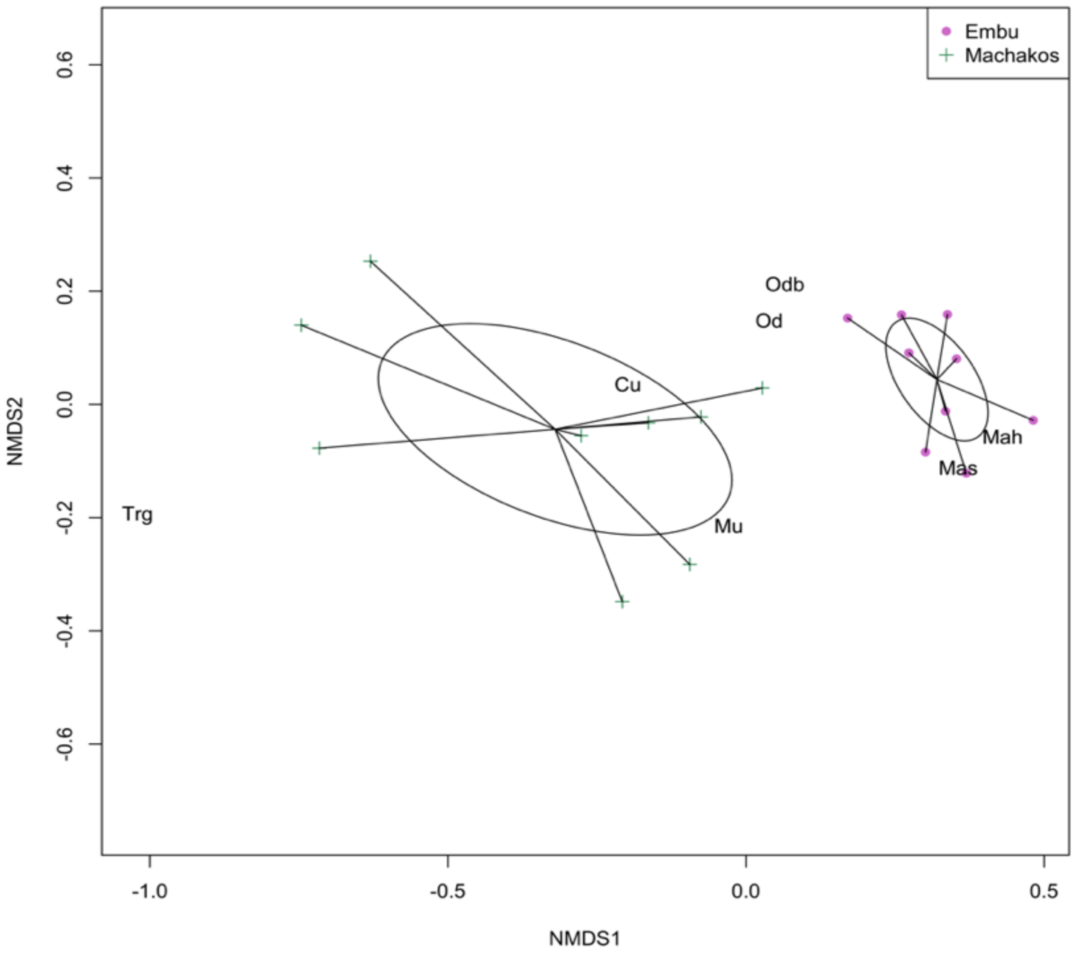

Figure 3.5: Non-metric multidimensional scaling (nMDS) ordination of maize-beans, maize monocrop and natural vegetation macrohabitats in Kangaru, Kamiu, Ena (Embu County), Matuu, Mamba and Kambi ya mawe (Machakos County) sites based on distribution of termite species. (PERMANOVA: P = 0.001, NMDS; Stress = 0.06). Mas- *Macrotermes subhyalinus,* Mah-*Macrotermes herus,* Trg- *Trinervitermes gratiosus,* Odb- *Odontotermes badius,* Cu- *Cubitermes ugandensis*, Od- *Odontotermes longignathus* and Mu- *Coptotermes formosanus*.

In the NMDS analysis, there was distinct differentiation of termite species in Machakos and Embu counties (PERMANOVA, $R^2 = 0.4$, $F = 12.7$, $P = 0.001$; PERMDISP, $F = 9.91$, $P = 0.006$) (Fig. 3.5) with an average dissimilarity of 50.5%. The most influential species contributing to the dissimilarity were *M. herus, T. gratiosus,* and *O. badius.*

The minimum temperature and rainfall during the study period is provided in Table 3.4. Minimum temperature (°C) in Embu County during both seasons ranged from 12.7±0.2 to 15.6±0.68 while rainfall (mm) was 30.2±8.17 to 117.8±49.67. The lowest minimum temperature and rainfall in Machakos County was 11.5±0.78 and 5.6±5.07, respectively. Based on the CCA analysis of climatic variables and termite species, 23.1 and 1.4% of the variance was explained by the first and second axis, respectively. *Trinervitermes gratiosus* showed a negative correlation with rainfall and minimum temperature while *M. subhyalinus* and *M. herus* were positively associated with rainfall (Figure 3.6).

Table 3.4: Minimum temperature and mean rainfall during dry and wet seasons in Embu and Machakos Counties

County	Season	Minimum temperature (°C)	Rainfall (mm)
Embu	Dry season one	12.7±0.2	36.3±9.51
	Dry season two	14±0.2	30.2±8.17
	Wet season one	14.9±0.28	86.9±17.91
	Wet season two	15.6±0.68	117.8±49.67
Machakos	Dry season one	11.5±0.78	5.6±5.07
	Dry season two	14±0.21	9.7±3.81
	Wet season one	14.7±0.09	124.5±54.16
	Wet season two	15±0.47	26.7±13.61

Dry season one - July to September 2018, Dry season two – Jan to March 2019, Wet season one – Oct to Dec 2018 and Wet season two – March to May 2019

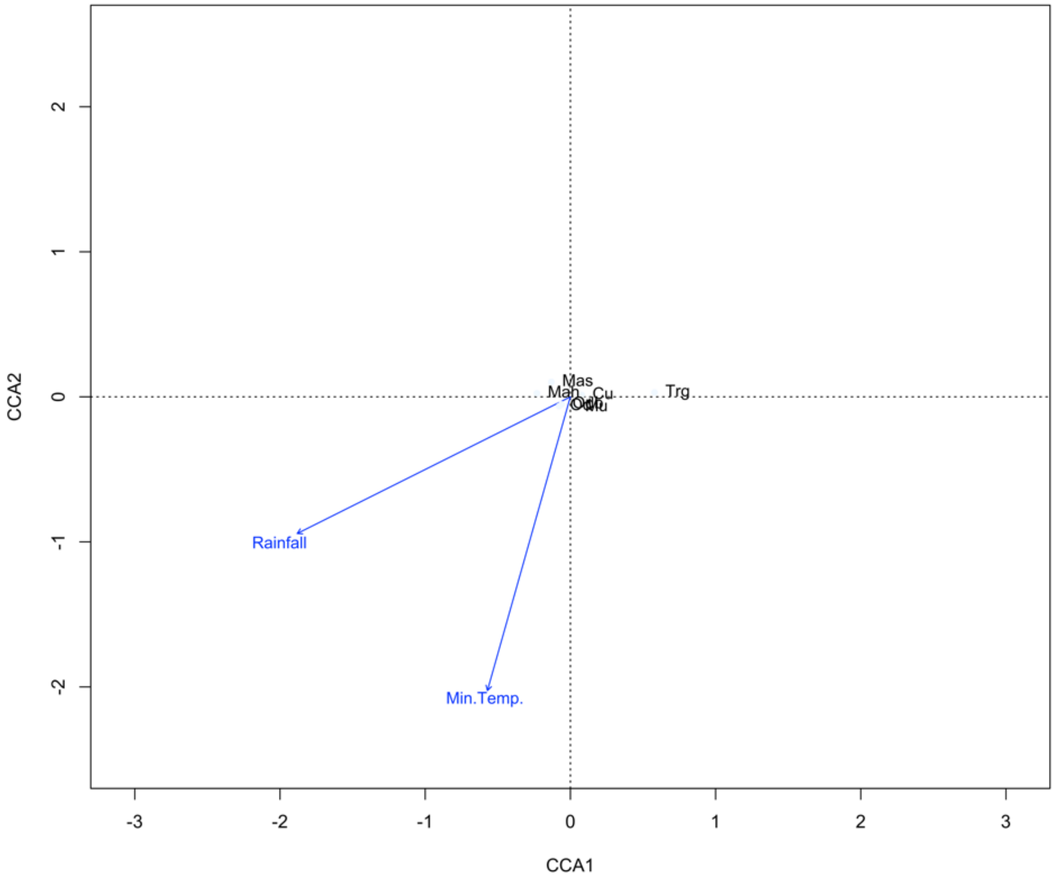

Figure 3.6: Canonical correspondence analysis of seven termite species in Embu and Machakos Counties using minimum temperature and rainfall marked by arrows. The first and second axes explain 24.5% of the observed variance. Odb- *Odontotermes badius,* Od- *Odontotermes longignathus* and Mu- *Coptotermes formosanus* (overlapping labels), Mas- *Macrotermes subhyalinus,* Mah-*Macrotermes herus,* Cu- *Cubitermes ugandensis*, Trg- *Trinervitermes gratiosus.*

3.4 DISCUSSION

Several factors including anthropogenic disturbances resulting from land use change affect termite diversity (Muvengwi *et al.*, 2017; Netshifhefhe *et al.*, 2019). In this study, seven termite species were observed across the two counties with Embu having six and Machakos county having seven due to the presence of *T. gratiosus*. Presence of *T. gratiosus* in Machakos county may have been due to region-specific factors. Termite species observed in this study have been reported in Kenya and the number is within that observed in other studies (Anyango *et al.*, 2020; Ayuke *et al.*, 2011; Kagezi *et al.*, 2011; Makonde *et al.*, 2013; Vesala *et al.*, 2017). Additive diversity partitioning of species richness and Simpson diversity showed that α component contributed 98.3% and 99.1% of the total diversity, respectively; an indication that most species were similar within fields in the two counties. The low beta diversity within each county may be an indication of lack of significant differences in macrohabitats which resulted in homogenization of the termite communities (Liu *et al.*, 2019).

Population densities of three termite species significantly varied between macrohabitats in Machakos county but there were no differences in termite species abundance in Embu county. In addition, the species richness did not differ significantly between macrohabitats within each county. Contrary to the observations made in this study, loss of termite species due to agricultural activities has been reported in several studies. For instance, in Uganda 40% reduction in termite species richness was observed after a forest was cleared and the numbers reduced further when banana was cultivated (Okwakol, 2000). An agricultural field in Zimbabwe had lower termite species richness compared to a woodland and grazing area (Muvengwi *et al.*, 2017). Application of fertilizers, liming and tillage— which led to termite habitat changes — were farming practices that contributed to low number of termite species in Colombia. Furthermore, cultivation of annual crops such as maize was considered as the most unfavorable land use type for termite species (Sanabria *et al.*, 2016). Supporting the observations of low termite abundance in Embu County, Kagezi et al. (2011) reported that termite species populations did not vary between forested land and agricultural fields in Kenya. This was attributed to the study site altitude and the fact that moderate levels of disturbance did not affect species abundance. This is further corroborated by

Muvengwi et al. (2017) in Zimbabwe where there were no differences in species richness between farmland and woodland habitats.

In Embu, *O. badius* which occurred in greater numbers during the wet season was influenced by season x macrohabitat interaction. Similar interaction in Machakos affected the abundance of *C. ugandensis* which was lower in the maize monocrop. Natural vegetation had a higher number of the species although it was not significantly different from maize beans intercrop. *Odontotermes* spp. whose foraging activity increases during the wet season (Sattar *et al*., 2013) causes considerable damage in maize and a study in Kenya demonstrated that they were associated with lodging in the crop (Anyango *et al*., 2019). Corroborating the observations made in this study, Okwakol (2000) observed a reduction in abundance of C*ubitermes* spp. and *Trinervitermes* spp. after clearance of a forest and subsequent banana cultivation which was attributed to mound destruction. Similarly, in West Africa, *Cubitermes* spp. occurred in lower numbers in agricultural plots due to high levels of disturbance (Eggleton *et al*., 2002). This species improves soil quality and fertility (Donovan *et al*., 2001), influences availability of nutrients to plants and the indirect contribution of symbiotic microorganisms to nutrient acquisition (Diaye *et al*., 2003). Reduced densities of *Cubitermes* spp. may therefore negatively affect crop yields (Eggleton *et al*., 2002).

In addition, there was a significant influence of habitat on *T. gratiosus* and *C. formosanus* in Machakos with both species occurring in higher numbers in natural vegetation. Occurrence of *Coptotermes* spp. in natural vegetation consisting of *Acacia* spp. has been previously reported (Intachat and Kirton 1997; Kirton *et al*., 1999). On the other hand, *Trinervitermes* has also been observed in undisturbed land in other studies (Hausberger and Korb 2016; Schyra and Korb, 2019). Compared to other termite species, *Trinervitermes* spp. is highly susceptible to disturbances because it is specialized in how it feeds and nests (Schyra and Korb, 2019). *Coptotermes* is among the invasive termite species (Evans, 2021) with potential ecological consequences. They colonize dead or living trees (Lee *et al*., 2015) in large colonies causing considerable damage to trees (Evans, 2021).

NMDS analysis clearly differentiated termite species in Machakos and Embu County probably due to regional differences related to climatic variables among other factors. In Embu County, season significantly influenced the abundance of *M. subhyalinus*, *M. herus*, and *C. formosanus* with all the species occurring in greater numbers during the wet season. From the CCA analysis of climatic variables, there was a negative correlation between *T. gratiosus*, minimum temperature and rainfall while *M. subhyalinus* and *M. herus* were positively associated with rainfall. However, the variance explained by the first two axes was low. Woon et al. (2019) demonstrated that moisture which determines the rate of desiccation also influences distribution of termite species which may affect ecological roles that they perform. In addition, temperature also influences dispersal of termites and their foraging behavior; species have different thermal tolerance levels (Smith and Rust, 1994; Woon *et al.*, 2019). Cao and Su (2016) observed that *Reticulitermes* spp. was found in areas with lower temperatures compared to *Coptotermes* spp. and the authors argued that temperature preferences of termite species can be used in prediction of invasion patterns to new regions. In the tropics, average and very high temperature have direct and indirect relationships with termite species richness (Cerezer *et al.*, 2020). For *Trinervitermes* spp., temperature is important in providing ideal conditions in the nest that allow decomposition of plant material and survival of termites (Aiki *et al.*, 2019). Foraging activity of fungus-cultivating termites increases during the wet season (Schuurman, 2006) and in some species, such as *M. gilvus*, flight is positively correlated with rainfall (Neoh and Lee, 2009). This could be a possible explanation of the high population densities of *Macrotermes* spp. that were observed in this study during the wet season which corroborates findings by Dangerfield and Schuurman (2000). Similarly, Korb and Linsenmair (2001) reported that the activity of *M. bellicosus* increased during the rainy season in a savanna in Cote d'Ivoire. In Botswana, occurrence of termite species was linked to seasons with *M. subhyalinus* preferring the wet season (Séré *et al.*, 2018). *Macrotermes* spp. prefer to construct their mounds in areas of high moisture levels due to the fact that they need to provide optimal humidity conditions for their symbiotic *Termitomyces* fungi (Bardunias et al., 2020; Aanen and

Eggleton, 2005). *Coptotermes* spp. occurrence is also largely dependent on rainfall (Lee *et al*., 2017).

In this study, habitat type, physico-chemical properties of soil and climatic variables influenced abundance of certain termite species. However, influence of other factors such as predator-prey interactions (Sanabria *et al*., 2016) and competence cannot be ruled out and requires further investigations. Land use change can result in shifts of termite species which contribute to both beneficial ecosystem functions and also cause damage to plants. As put forward by Jouquet et al. (2020) benefits and risks attributed to termites are mutually exclusive and there is therefore need to design programmes that can achieve an ecological balance between the two extremes. Maize farming systems in Kenya should therefore consider maintaining an appropriate number of termite species in the field by using cropping practices that do not have detrimental effects on the soil engineers. Control strategies of termite species that attack maize should also consider non-target effects on beneficial termites. There should also be continuous monitoring to assess the long-term impact of land use change on termites. Additional information on effect of soil properties and seasons on functional groups of termites is also required.

CHAPTER FOUR

Effect of seasons and soil properties on functional diversity of termites in Embu and Machakos Counties

4.0 ABSTRACT

Termites (Insecta: Blattodea: Isoptera) are soil ecosystem engineers with ecological functions that influence the formation of microhabitat heterogeneity that affects growth and survival of plants. Termites species can be identified into four feeding groups using the various food materials that they consume and the habitats of their nesting and foraging sites. Soil chemical and physical properties affect functional diversity of termites. Termite functional groups are also strongly affected by human agricultural activities and intensification of land-use. There is dearth of information on how land use through agricultural intensification and soil physico-chemical properties affects functional diversity of termites. Therefore, the study objective was to evaluate effects of change in utilization of land through agricultural intensification and soil properties on termite functional groups in three macro-habitats namely; natural vegetation, maize-beans intercrop and maize monocrop. The study was conducted in Kithimani, Matuu, and Ndalani locations of Machakos County and Kangaru, Kamiu and Ena of Embu County, Kenya. Three 100 × 2 m belt transects separated by 100m were laid out at each macrohabitat. Twenty 5 × 2 m sections from each transect were sampled (one-person hour) from different microhabitats that included dead wood, soil, mounds, leaf litter, sheeting and runways. From each section, termites were also collected from twelve (12 × 12 cm, 10 cm deep) pits. Sampling across all sites was done during dry and wet seasons for two consecutive years. Collections of soldier and/or worker castes were identified to species levels using taxonomic guides and through reference collections of National Museums of Kenya. For soil physico-chemical analysis, samples were collected from each point in the macrohabitats and a composite sample of 500g was used for analysis at the Kenya Agricultural and Livestock Research Organization, National Agricultural Research Laboratories. To identify indicator species in macro habitats within each County, an analysis of indicator values was performed. To check for association between species and macro habitats within the Counties, Pearson Phi coefficient was determined. Contribution of nestedness and turnover was assessed by partitioning overall β diversity of termite assemblages in each macro habitat in the two counties. Termite species assemblage in maize-beans intercrop, maize monocrop and natural vegetation in Embu and Machakos were ordered using Renyi diversity profiles. Two-way analysis of variance was performed to test the effect of season and macrohabitats on termite functional groups. Relationships between termite functional groups, soil properties and climatic variables were inferred through Canonical correspondence analysis. Four termite functional groups were identified across the two regions. Nestedness accounted for total beta diversity in maize sole crop, maize-beans mixed cropping and natural vegetation macrohabitats in Embu. Similarly, in Machakos County, termite assemblages in natural vegetation were driven by nestedness, while turnover shaped communities in maize sole crop and maize-beans mixed cropping macrohabitats. In Embu, there was a significant influence of season on abundance of group IIf while season x habitat interaction influenced group I. Season and macrohabitat affected the abundance of group I and II in Machakos while group IV was influenced by season x habitat interaction. There was a difference in group IV termite population densities across all macrohabitats in Machakos. Group II and IV were positively correlated to sand and silt, respectively while group IIf was negatively associated with sand. The observed shifts in termite functional groups across disturbance gradients necessitates that measures are put in place to protect the soil engineers through farming practices that conserve biodiversity.

4.1 INTRODUCTION

Termites (Insecta: Blattodea: Isoptera) are important organisms in terrestrial ecosystems and are soil ecosystem engineers whose ecological functions influences the formation of microhabitat heterogeneity that influences plant growth (Beaudrot et al. 2011). Particularly, termites cause bioturbation covering large areas and modify physical, chemical, and biological characteristics of soils (Garba *et al.*, 2011; Jouquet *et al.*, 2015; Van der Plas *et al.*, 2013; Sugimoto et al. 2000; Lavelle *et al.*, 2006). Furthermore, termites' activities lead to ecosystem stabilization by decomposing complex plants and animals remains and providing important nutrients in the soil for plants (Bonachela *et al.*, 2015; Veldhuis *et al.*, 2017).

A wide range of plant materials form the diet of termites at different levels of chemical breakdown. (Bignell and Eggleton, 2000; Donovan *et al.*, 2001). In a study on the contents of termites' digestive systems, Donovan et al. (2001) identified four feeding groups using various food materials that they consume and the habitats of their nesting and foraging sites. The study revealed that, termites that feed on wood, dwell in wood or galleries of wooden litter belong to group I. Termites that were found foraging on grass and leaves litter were Group II termites. Termites that were found feeding on highly decomposed wood materials with particles of soil (wood/soil interface or pure humus) were assigned Group III while Group IV fed on mineral soil. Group I and II termites are abundant and found in most ecosystems and they perform critical ecosystem functions (Bignel and Eggleton, 2000).

Activities of termite functional groups can be influenced by both living and non-living factors of an ecosystem (Gosling *et al.*, 2016). Climatic variables, especially temperature and rainfall influences soil formation process (Binkley and Fisher, 2012), furthermore, variation of vegetation and plants species composition as well as soil chemical and physical properties are affected by temperature and rainfall (Kardol *et al.,* 2010). Therefore, by extension, climatic variables affect functional groups of termites, chemical and physical properties of soil and type of vegetation in various parts of the world (Eggleton 2000; Bourguignon *et al.* 2015; Davies *et al.*, 2015). Occurrence of six termite species was influenced by 11 soil physico-chemical properties across different land use types in Colombian Llanos (Sanabria *et al.*, 2016).

Different termite species prefer soil with particular properties for construction of mounds and sheetings (Jouquet *et al.*, 2007). Shape and physicochemical properties of mounds constructed by group IIf, *Odontotermes obesus* varied with soil properties in Ferralsol and Luvisol soil in India (Jouquet *et al.*, 2015). In addition, termite functional groups are strongly affected by human agricultural activities and intensification of land-use and often, the number of termites per area and the importance of group IV termites decrease along a land use gradient. Alteration of functional groups of termites results to decline in ecosystem processes mediated by termites.

Kagezi et al. (2011) studied breakdown of tissue baits and termites per unit area along a gradient of intensification of agricultural activities in Western region of Kenya and found that there was no significance variation of abundance of termites a land-use gradient. However, there was significant reduction in-group IV termites from the primary forests to the agroecosystems.

In Kenya, there are various termite species (Anyango *et al.*, 2020; Ayuke *et al.*, 2011; Kagezi *et al.*, 2011; Makonde *et al.*, 2013 Vesala *et al.*, 2017 that belong to different functional groups (Donovan *et al.*, 2001). Nevertheless, there is dearth of information on how land use through agricultural intensification and soil physico-chemical properties affect the diversity of termite functional groups. Therefore, the study objective was to evaluate effects of land utilization due to agricultural intensification and soil properties on termite functional groups in natural vegetation, maize-beans intercrop and maize monocrop in Embu and Machakos Counties.

4.2 MATERIALS AND METHODS

4.2.1 Study sites and sampling

Termites were collected at monthly intervals from three locations each in Machakos and Embu county, Kenya. Three replicates each of maize sole crop, maize and beans intercrop and natural vegetation were sampled from each location. Sampling was carried out during dry (dry season 2018 - July to September and dry season 2019 - January to March) and wet (wet season 2018 - October to December and wet season 2019 - March to May) seasons. Three belt transects (100m × 2 m) separated by 100m were laid out at each macrohabitat (Jones et al. 2003). From each transect 20 (5m × 2 m) sections were sampled from different microhabitats. In addition, samples were collected from 12cm × 12 cm, 10 cm deep pits (12) in each section. Termites were identified to species level at the National Museums of Kenya using identification keys and assigned to functional groups. Termites species feeding on dead wood and grass that is less decayed were designated Group I while group II can be divided into termites that feed on more decayed leaves, wood, micro-epiphytes and grass and group IIf which are fungus cultivators. True soil feeders are classified as group IV (Donovan *et al.*, 2001; Inward *et al.*, 2007). Soil physico-chemical characteristics analysis was done at the Kenya Agricultural and Livestock Research Organization and climate data was obtained from Kenya Meteorological Department. Soil texture was determined using the hydrometer method (Klute, 1986) while the Mehlich double acid method was used to assess Phosphorus, Sodium, Potassium, Calcium, Magnesium and Manganese (Mehlich *et al*., 1962). Nitrogen content was analyzed using the Kjeldahl digestion method (Bremner and Mulvaney 1982) and soil pH was determined in a 1:1 (w/v) water extract as described by Mehlich et al. (1962). For analyses of Copper, Iron and Zinc, 0.1 M HCL in 1:10 (w/v) ratio was used for extraction before Atomic Absorption Spectrophotometer readings were taken (Mehlich *et al*., 1962). Carbon was determined colorimetrically following Anderson and Ingram (1993).

4.2.2 Data analysis

Termite abundance data was checked for normality and log(x+1) where applicable. Data from two wet and dry seasons were pooled before analysis. To identify indicator species in macrohabitats within each county, an analysis of indicator values (Dufrêne, and Legendre 1997) was performed using indicspecies package; function *multipatt* in R software. In addition, association (Pearson Phi coefficient) between species and macrohabitats (De Cáceres and Legendre 2009) within each County, was analyzed using the same function and R package. Contribution of nestedness (β_{sne}; gain or loss of termite species) and turnover (β_{sim}; replacement of termite species) was assessed by partitioning overall β diversity (β_{sor}) of termite assemblages in each macrohabitat in the two Counties. Sørensen index and *beta.multi* function were applied in betapart package (Baselga *et al*., 2018) in R. Termite species assemblage in maize-beans intercrop, maize monocrop and natural vegetation in Embu and Machakos were ordered using Renyi diversity profiles. Vegan package (Oksanen *et al*., 2019) in R software was used by applying the *renyi* command. The scale parameter α at 0, 1, 2, and infinity represent species richness, Shannon index, logarithm of the reciprocal Simpson index and Berger–Parker index, respectively. Two-way analysis of variance was performed to test the effect of season and macrohabitats on termite functional groups. Where there were significant differences in means, separation was carried out using Tukey honestly significant difference post hoc test. Significant season x habitat interactions were further evaluated using simple main effects tests. All analyses were done in R version 4.0.2 (R Core Team 2020). Cluster analysis based on Bray-Curtis dissimilarity matrix and Ward's clustering algorithm was used to determine the spatial structure of termite functional groups in different locations in Embu and Machakos county using *heatmap.2* function in R. Relationships between termite functional groups, soil properties and climatic variables were inferred through Canonical correspondence analysis (CCA) using vegan package (Oksanen *et al*., 2019).

4.3 RESULTS

Four termite functional groups were identified in both Counties. Group II (*Trinervitermes gratiosus*; grass feeder) was only recorded in Machakos while Group I (*Coptotermes formosanus*; wood feeder), IIf (*Macrotermes subhyalinus*, *M. herus*, *Odontotermes badius*, *O. longignathus*; fungus cultivators) and IV (*Cubitermes ugandensis*; soil feeder) were recorded in Machakos and Embu. In Machakos, there was no indicator species for maize monocrop and maize-bean intercrop; however, *Coptotermes formosanus* was the indicator species (0.76; *P*=0.001) in the natural vegetation. Pearson's phi coefficient of association showed that *Trinervitermes gratiosus* (r=0.302; *P*=0.001), *Cubitermes ugandensis* (r=0.251; *P*=0.001) and *C. formosanus* (r=0.302; *P*=0.001) were significantly associated with natural vegetation. In Embu, there was no indicator species for all three macrohabitats.

Nestedness accounted for observed beta diversity (β_{sor}=0.08) in maize mono crop, maize-bean intercrop and natural vegetation in Embu. Similarly, in Machakos County, termite assemblages in natural vegetation (β_{sor}= 0.13) were driven by nestedness while turnover shaped communities in maize monocrop (β_{sor}=0.4; β_{sim}=0.25; 62.5%; β_{sne}= 0.15; 37.5%) and maize-beans intercrop (β_{sor}=0.22; β_{sim}=0.06; 27%; β_{sne}=0.16; 73%) macrohabitats (Fig. 4.1). Renyi diversity ordering was not unequivocal due to intersecting of the profiles in both counties. However, the profiles showed that in Embu, maize-beans intercrop had the highest frequency of the dominant species while natural vegetation had the most even species distribution which was also observed in Machakos (Fig. 4.2).

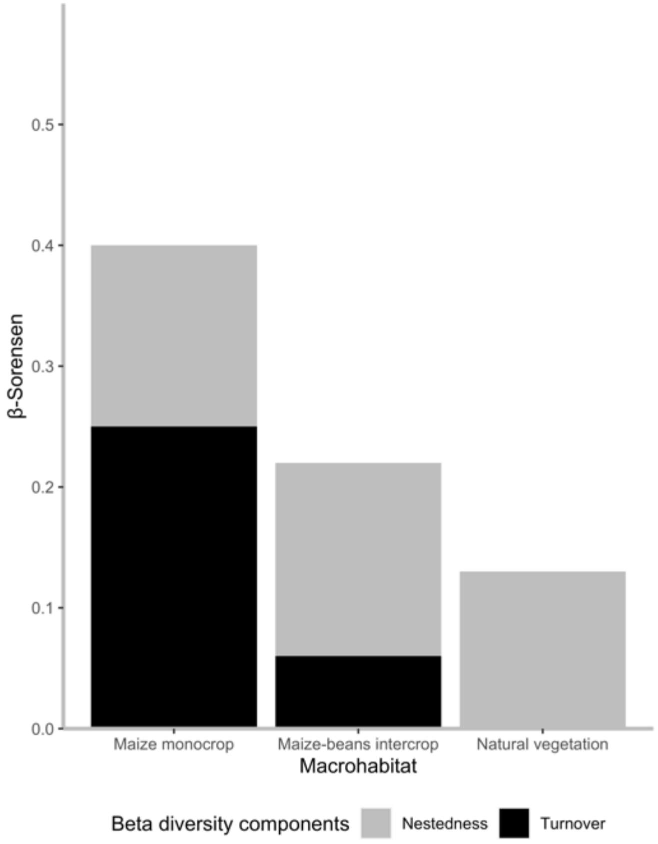

Figure 4.1: Nestedness and turnover contribution to beta diversity in maizeβ monocrop, maize-beans intercrop and natural vegetation macrohabitats in Machakos County

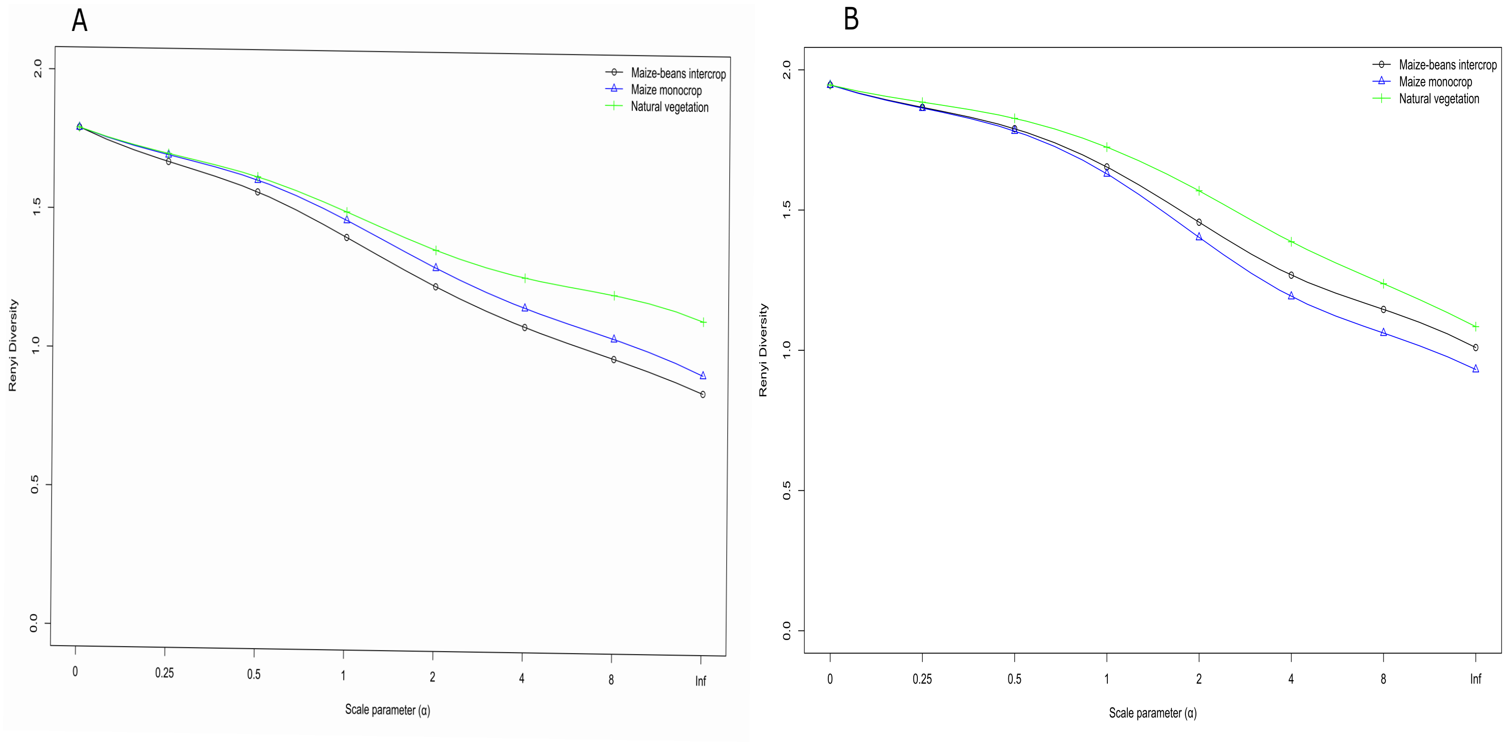

Figure 4.2: Renyi diversity profiles of termite assemblages in maize-beans intercrop, Maize monocrop and natural vegetation in A) Embu B) Machakos county. The alpha values 0, 1, 2, and infinity represent species richness, Shannon index, logarithm of the reciprocal Simpson index and Berger–Parker index, respectively.

In Embu, there was a significant influence of season on abundance of group IIf ($F_{1,12}$ =71.3 P <0.0001) while season x habitat interaction influenced group I ($F_{2,12}$ =4.9; P =0.028). Simple main effects showed that for group 1 the interaction was significant for wet season and all macrohabitats, and the dry season with natural vegetation. Season and macrohabitat affected the abundance of group I ($F_{1,12}$ =14.6, P =0.002; $F_{2,12}$ = 10.4, P =0.002) and II ($F_{1,12}$ =12.5, P = 0.004; $F_{2,12}$ =4.7; P = 0.032) termite functional groups in Machakos while group IV was influenced by season x habitat interaction ($F_{2,12}$=11.0; P=0.002). From simple main effects analysis, interactions between dry season and maize monocrop, and wet season and all macrohabitats were significant. There was no influence of macrohabitat on group IIf in both counties. In Machakos, group I, II and IV abundance were highest during the wet season while group I and IIf were also present in high numbers during the same season in Embu. There was a difference in group IV termite population densities across all macrohabitats in Machakos (Fig. 4.3 and 4.4).

Table 4.1: Effect of season, macrohabitat and their interaction on termite functional groups in Embu and Machakos counties

	Season		Macrohabitat		Season x Macrohabitat	
	F	P	F	P	F	P
Embu						
I	41.4	<0.0001***	5.7	0.018*	4.9	0.028*
IIf	71.3	<0.0001***	1.9	0.193	2.1	0.164
IV	1.4	0.263	0.8	0.452	1.1	0.357
Machakos						
I	14.6	0.002**	10.4	0.002**	1.1	0.355
II	12.5	0.004**	4.7	0.032*	2.1	0.167
IIf	0.1	0.818	1.1	0.380	1.0	0.387
IV	242.9	<0.0001***	27.7	<0.0001***	11.0	0.002**

*** = $P < 0.001$, ** = $P < 0.01$, * = $P < 0.05$. Group I -wood feeders, group II-grass feeders, group IIf-fungus cultivators and group IV-soil feeders.

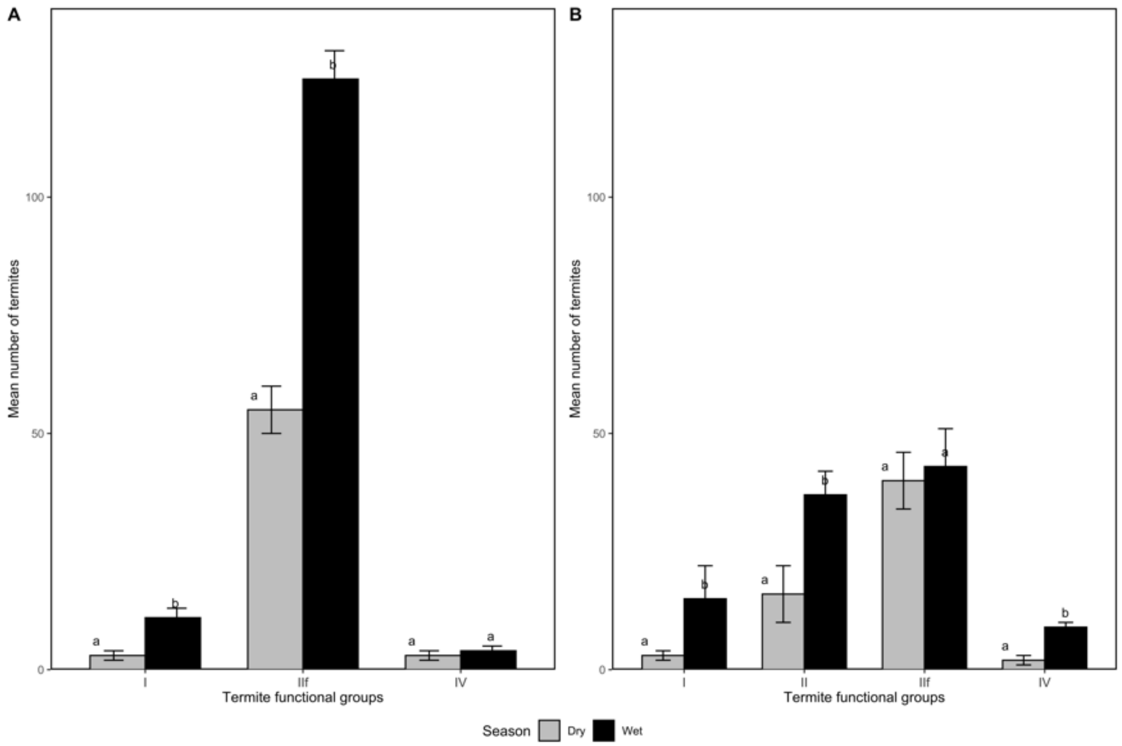

Figure 4.3: Abundance (mean ± standard error) of termite functional groups during dry and wet season in A) Embu and B) Machakos counties. Different letters indicate significant differences in abundance of termite functional groups. Group I -wood feeders, group II-grass feeders, group IIf-fungus cultivators and group IV-soil feeders

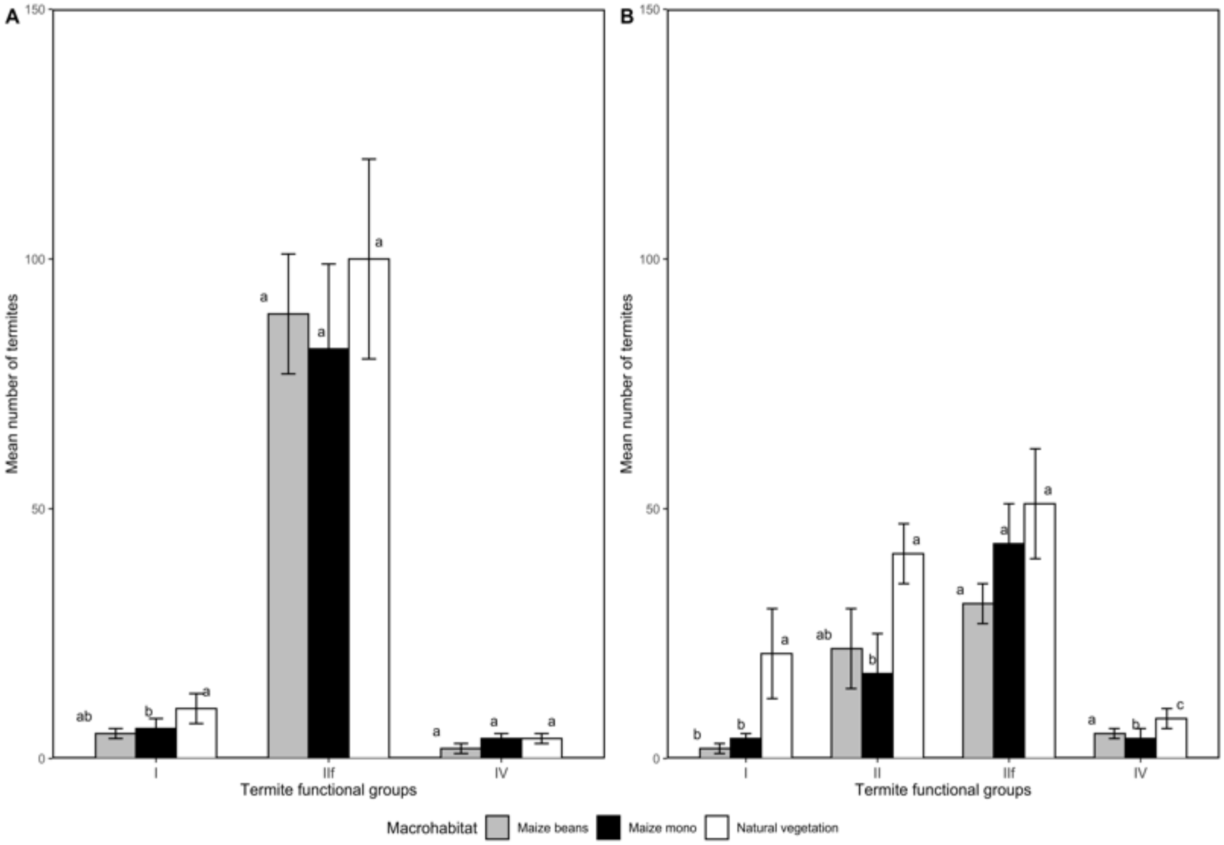

Figure 4.4: Abundance (mean ± standard error) of termite functional groups in maize-beans intercrop, maize monocrop and natural vegetation macrohabitats in A) Embu and B) Machakos counties. Different letters indicate significant differences in abundance of termite functional groups. Group I -wood feeders, group II-grass feeders, group IIf-fungus cultivators and group IV-soil feeders.

Termite functional groups in different locations were clearly separated according to county (Fig. 4.5). Soil from Embu and Machakos showed significant variations in pH, P, Ca, Mg, Mn, Zn, sand and clay (Table 4.2). From the CCA analysis of soil properties and termite species, the first and second axes accounted for 79.9% of the variance. *Trinervitermes gratiosus* was negatively associated with Mn but positively correlated to pH and sand. *Macrotermes subhyalinus* and *M. herus* showed a positive association with

P and silt while *C. formosanus* was positively correlated to Ca and Mg. There was a positive correlation between *O. badius* and Cu (Fig. 4.6).

Table 4.2: Physical and chemical properties of soil collected from Embu and Machakos Counties.

Soil property	*Embu*		*Machakos*		*P value*
	Mean	SE	Mean	SE	
pH	4.79a	0.07	7.26b	0.28	<0.001***
Total Nitrogen %	0.21a	0.07	0.17a	0.06	0.648
Total organic Carbon %	1.52a	0.18	1.2a	0.23	0.297
Phosphorous ppm	20.11a	1.42	15.44b	1.26	0.026*
Potassium meq%	0.44a	0.07	0.56a	0.11	0.362
Calcium meq%	0.84a	0.25	15.73b	5.83	0.021*
Magnesium meq%	0.83a	0.13	2.29b	0.63	0.039*
Manganese meq%	0.93a	0.08	0.33b	0.1	<0.001***
Copper ppm	0.5a	0.3	0.5a	0.11	0.99
Iron ppm	17.58a	2.97	17.58a	3.5	1
Zinc ppm	12.09a	3.26	1.54b	0.16	0.005**
Sodium meq%	0.47a	0.05	0.66a	0.12	0.151
Sand	47.11b	0.48	72a	4.18	<0.001***
Clay	47.33b	1	23.11a	3.7	<0.001***
Silt	5.56a	0.73	5.11a	0.75	0.68

Means with the same letter across the row are not significantly different. *** = P < 0.001, ** = P < 0.01, * = P < 0.05. SE-Standard error.

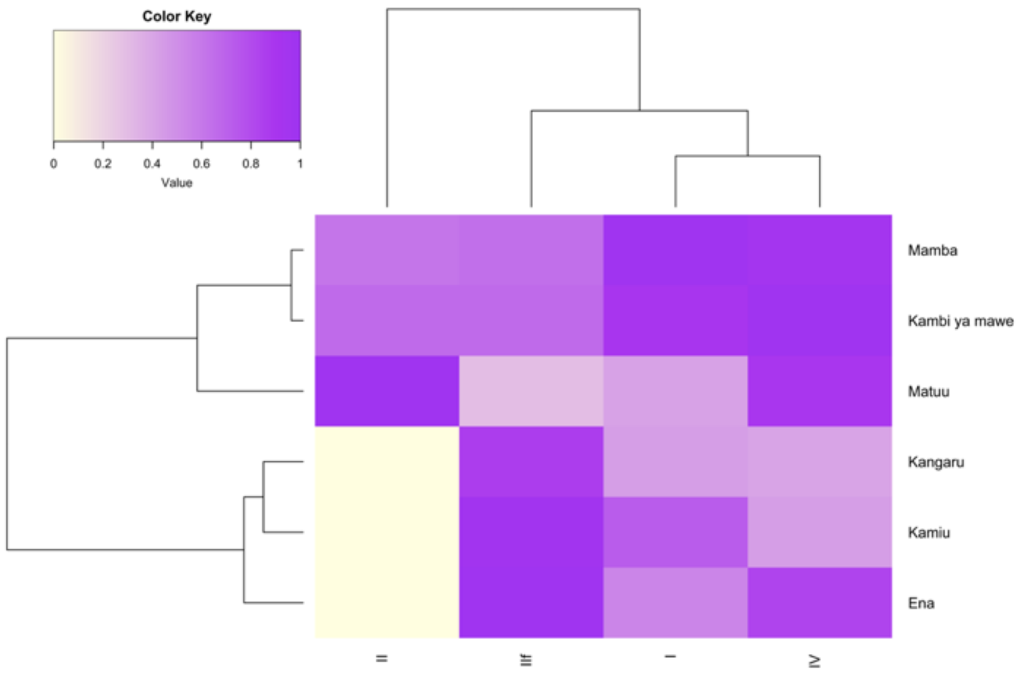

Figure 4.5: Heatmap of termite functional groups in maize monocrop, maize-bean intercrop and natural vegetation macrohabitats in Mamba, Ndalani, Matuu (Machakos county), Kangaru, Kamiu and Ena (Embu county). Field locations are represented by the dendrogram along the left axis and functional groups are indicated by the dendrogram in the upper part. The color key scale represents abundance of functional groups with high intensity representing high abundance. Group I -wood feeders, group II-grass feeders, group IIf-fungus cultivators and group IV-soil feeders

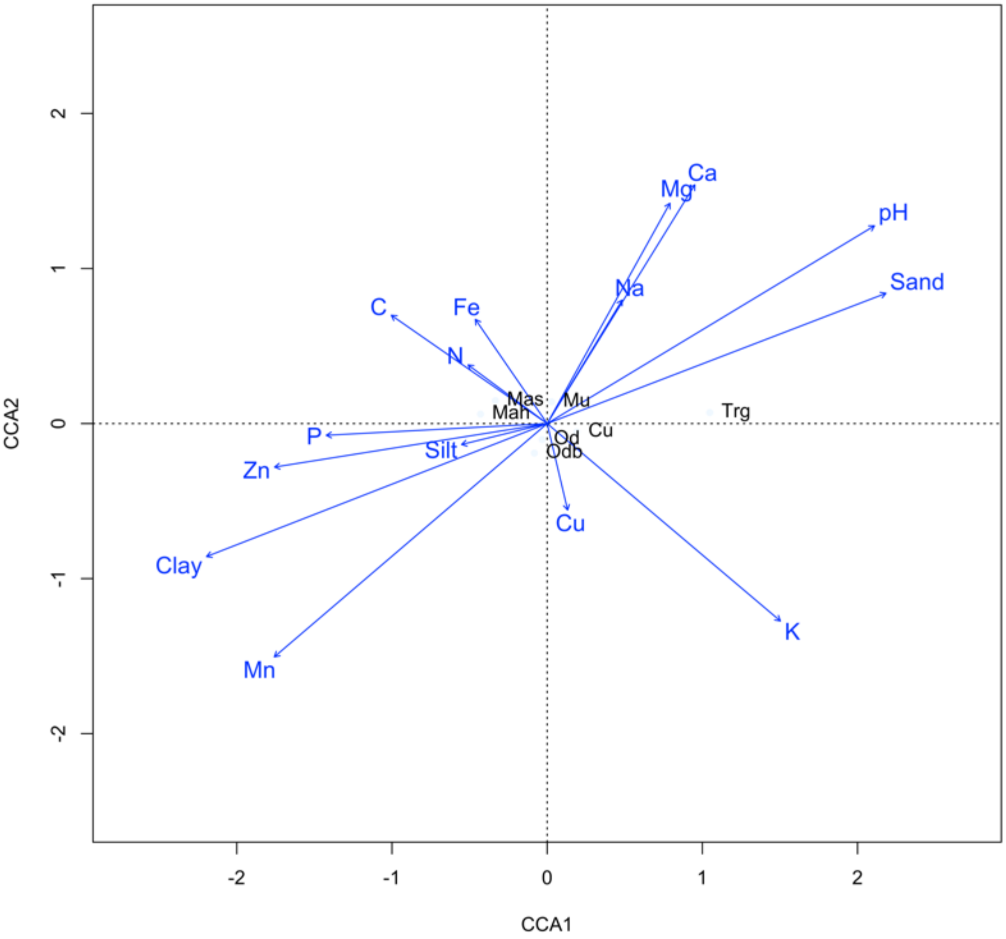

Figure 4.6: Canonical correspondence analysis of seven termite species in Embu and Machakos counties using soil physico-chemical properties (pH, N, C, P, K, Ca, Mg, Mn, Cu, Fe, Zn, Na, sand, clay and silt) marked by arrows. The first and second axes explain 79.8% and 0.07%, of the variance, respectively. Mas- *Macrotermes subhyalinus,* Mah- *Macrotermes herus,* Trg- *Trinervitermes gratiosus,* Odb- *Odontotermes badius,* Cu- *Cubitermes ugandensis*, Od- *Odontotermes longignathus* and Mu- *Coptotermes formosanus.*

In CCA of soil properties and termite functional groups, first and second axes accounted for 89.7 and 0.06% of the observed variance, respectively. Group II was positively correlated to sand and K and negatively associated with clay and Zn. There was a positive correlation between group IV and silt and group I and N. Group IIf showed a negative association with sand, Ca and Mg. Occurrence of group IIf, I and IV was negatively correlated with pH (Fig. 4.7). For the climatic variables, the first and second axes accounted for 30% of the variance with a positive correlation between rainfall, group I, IIf and IV. Group II was negatively correlated to rainfall and minimum temperature (Fig. 4.8).

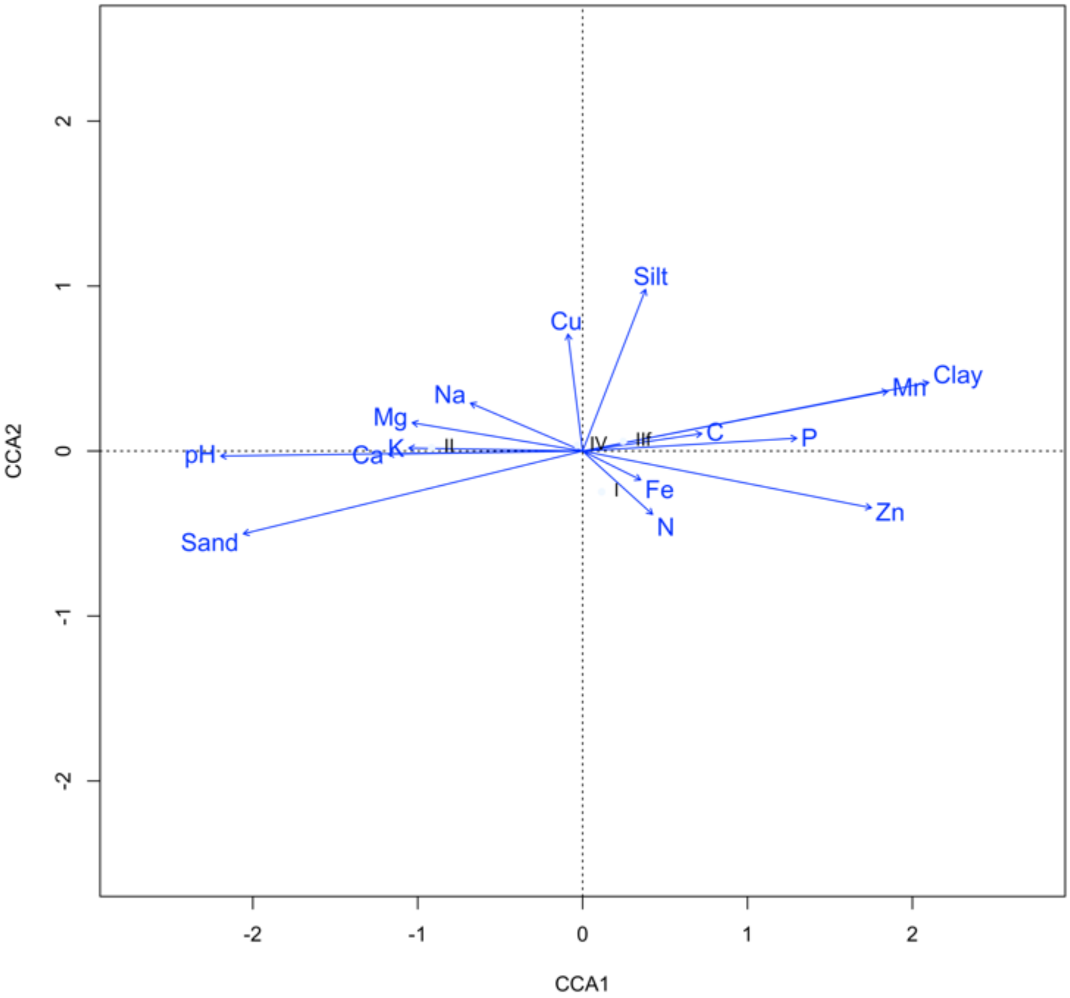

Figure 4.7: Canonical correspondence analysis of termite functional groups in Machakos and Embu Counties using pH, N, C, P, K, Ca, Mg, Mn, Cu, Fe, Zn, Na, sand, clay and silt marked by arrows. The first (eigen value =0.17) and second (eigen value =0.01) axes account for 89.8% of the variance. Group I -wood feeders, group II-grass feeders, group IIf-fungus cultivators and group IV-soil feeders

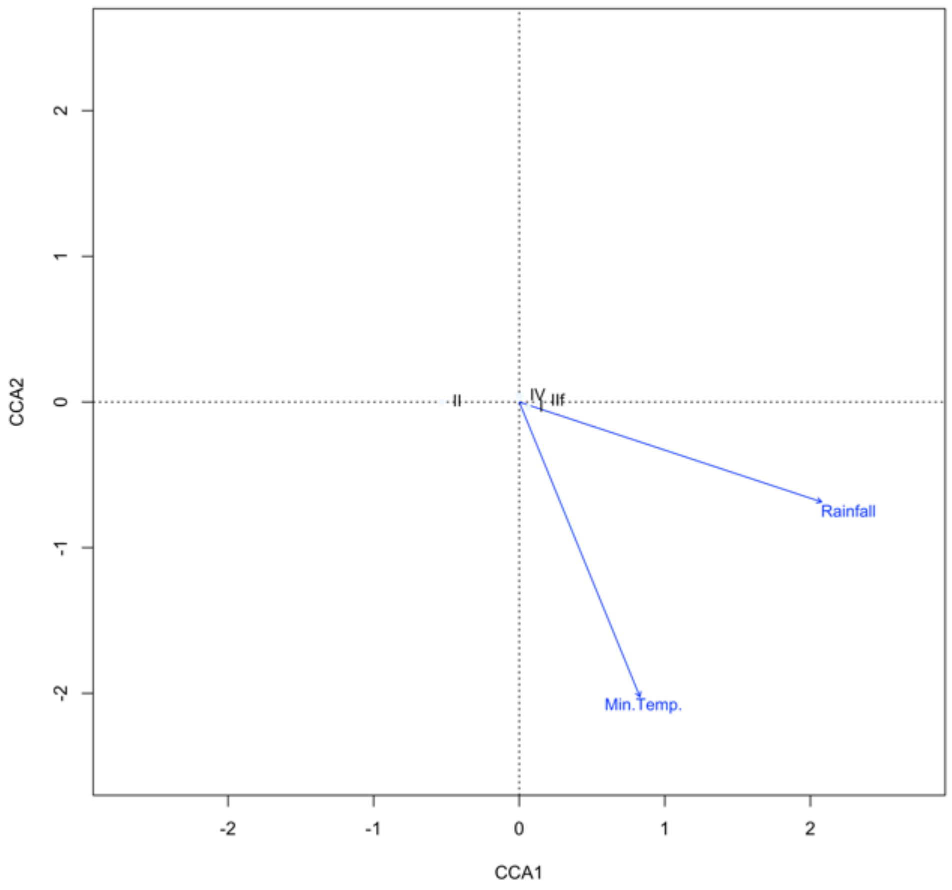

Figure 4.8: Canonical correspondence analysis of termite functional groups in Machakos and Embu counties using rainfall and minimum temperature marked by arrows. The two axes account for 30% of the variance. Group I -wood feeders, group II-grass feeders, group IIf-fungus cultivators and group IV-soil feeders

4.4 DISCUSSION

In Machakos county, *Cubitermes ugandensis* (group IV) population was significantly higher in natural vegetation. Natural vegetation is composed of a variety of trees and grass cover that controls the fluctuations in soil water content and climatic variable such as temperature, hence providing group IV termites a conducive environment to inhabit the soil (Eggleton *et al*., 1996, 2002). Different forms of disturbance affect termite species diversity and functional groups (Eggleton *et al*., 1996). *Coptotermes formosanus* was the indicator species in the natural vegetation in Machakos which may be due to availability of suitable food resources. Disturbance in the maize monocrop and maize-bean intercrop macrohabitats in Machakos may have led to the lack of indicator species (Muvengwi *et al*., 2017). The observed association of *Trinervitermes* spp., *Cubitermes* spp. and *Coptotermes* spp. with natural vegetation is as previously reported in other studies (Muvengwi *et al*., 2016; Schyra and Korb 2019; Effowe *et al*., 2021). Intersecting of Renyi diversity profiles was due to similar species richness across macrohabitats within each County. The observed species richness is within the range that is reported in Kenya (Ayuke *et al*., 2011; Kagezi *et al*., 2011; Anyango *et al*., 2020). Beta diversity across all macrohabitats in Embu and in natural vegetation in Machakos was driven by nestedness — an indication that the species-poor macrohabitats were sub-sets of sites with greater richness (Nunes *et al*., 2017). On the other hand, in Machakos, turnover was a major contributor to diversity in maize monocrop and maize-beans intercrop which may have been due to ecological differences in the macrohabitats that acted as filters for specific termite species (Nunes *et al*., 2020). The high level of disturbance in the two macrohabitats may have also led to the high contribution of species turnover to the dissimilarity (Hausberger and Korb 2016).

Differences in functional groups in Embu and Machakos as indicated in the heatmap (Figure 4.5) may have been due to regional environmental factors that differentially affected the ecological requirements and physiology of the termite functional groups (Eggleton *et al*., 2002). Group I, II and IV occurred in high numbers during the wet season in Machakos while group I and IIf were also present in high numbers during the same season in Embu. The CCA analysis revealed a positive correlation between rainfall, group I, IIf and IV while group II was negatively correlated to rainfall and minimum temperature. During wet seasons, increase in abundance of Group IIf species, *Odontotermes* spp. (Korb and Linsenmair 2001) and *Macrotermes* spp., has also been observed and in field trials in Kenya, their abundance was affected by seasons (Anyango et al. 2020). Although group IIf abundance increase during the wet season, their foraging activity also persists during the dry season (Schuurman 2006). Niche range of group I, *Coptotermes* spp., is influenced by rainfall which is also positively correlated with swarming activity in *C. formosanus* (Tong *et al*., 2017). However, wind has also been reported as a key factor that influences swarming (Leong *et al*., 1983). Physiological requirements of Group IV termites explain their association with moist soils (Eggleton *et al*., 2002). In addition, mound density increases with high rainfall but the size decreases (Muvengwi *et al*., 2018). For, *Trinervitermes* spp., the role of temperature in chemical breakdown of grass cannot be over emphasized as it is the main food source (Aiki *et al*., 2019).

Soil properties affected termite species whereby *T. gratiosus* was negatively associated with Mn but positively correlated to pH and sand. *Macrotermes subhyalinus* and *M. herus* showed a positive association with P and silt while *C. formosanus* was positively correlated to Ca and Mg. Soil properties influence termite abundance and diversity (Dosso *et al*., 2010) and mound properties (Jouquet *et al*., 2015). *Trinervitermes* spp. is adapted to a wide range of soil types (Brossard *et al*., 2007) and can tolerate pH levels above 4 as observed in the current study (Mugerwa *et al*., 2011). Mills et al. (2009) observed that clay content in the top soil around *Trinervitermes* spp. nests was much lower compared to *Macrotermes* mounds. Soil physical characteristics coupled with environmental conditions affects the survival and body hydration levels in termites (Jin *et al*., 2020). Contrary to the findings in this study, *Macrotermes* spp. did not show a significant correlation with silt in Ghana (Usher, 1975). The positive association of *Macrotermes* with P may be related to phosphorus adsorption dynamics during mound construction (Seymour *et al*., 2014). Similarly, for the mound outer casing, *Coptotermes* spp. uses clay which is rich in inorganic ions such as Ca and Mg (Wang and Henderson, 2014). At the functional level, group II and IV were positively correlated to sand and silt, respectively while group IIf was negatively associated with sand. According to Muvengwi et al. (2018), group IV termites prefer soil with low amounts of clay during mound construction due to the high permeability and reduced chances of inundation. Contrary to our observations, Nduwarugira et al. (2020) reported a positive correlation between the soil-feeder *Cubitermes* spp. and clay content. On the other hand, clay and soil organic matter are important to group IIf termites during mound construction. Clay is also preferred over sand due to the high stability of clay-sheetings (Jouquet *et al*., 2007). The negative correlation that was observed in the current study between pH, Ca, Mg, Zn and some termite feeding groups may be due to physiological disruption of the gut by sub-optimal pH levels (Muvengwi *et al*., 2016) and toxicity of micronutrients (Jones *et al*., 2010; Nduwarugira *et al*., 2020).

From the observations made in this study, species richness did not vary within macrohabitats in each county and beta diversity was largely driven by nestedness, although replacement occurred in two disturbed macrohabitats in Embu. There was a clear separation of termite functional groups based on the county. Season and macrohabitat differentially affected termite functional groups based on the level of disturbance. Loss of key functional groups such as soil feeders could have implications on crop productivity due to their role in improving soil fertility. Shifts in functional groups that cause crop losses could also have implications for productivity in maize based agro-ecosystems in Kenya. Based on these findings, there is need for further assessment on ecological implications of disturbance on diversity and abundance of termite functional groups. However, with the increasing rate of agricultural intensification in Kenya, immediate measures are required to protect soil engineers through use of farming practices that conserve biodiversity.

CHAPTER FIVE

Effect of intercropping maize with soybean, common beans and sorghum on infestation levels of termites maize lodging due to termites

5.0 ABSTRACT

Termites perform major ecological functions in the tropics but certain species in cause damage to economically important crops. This study evaluated the effect of intercropping maize with soybean, common bean and sorghum on the level of termite damage, abundance of termite species and functional groups in Machakos county, Kenya during two cropping seasons. In both seasons, *Macrotermes herus, M. subhyalinus, Coptotermes formosanus, Odontotermes badius, O. longignathus* and *Cubitermes ugandesis* were recorded. There was a low percentage of lodged plants in maize-sorghum intercrop which also had low population densities of *M. herus* and *O. badius* in both seasons. There was no difference in the number of *C. formosanus* in both seasons. The lowest number of fungus-cultivators was in the maize-sorghum intercrop while soil feeders occurred in low populations. Intercropping maize and sorghum can be further explored alongside other integrated termite management techniques. The observed low populations of soil feeders necessitate adoption of farming practices that conserve them in order to improve crop productivity.

5.1 INTRODUCTION

In the tropics, termites are among the major invertebrates that perform key ecological functions such as decomposition of organic matter, nutrient cycling and soil pedogenesis (Jouquet *et al*., 2011; Law *et al*., 2019). Termites species also serve as indicator organisms for ecosystem services (Duran-Bautista *et al*., 2020). In agro-ecosystems, certain termite species cause damage to economically important crops (Black and Okwakol, 1997; Govorushko, 2019); however, some termite species may lead to increased crop yields particularly in dry environments (Evans *et al*., 2011). Globally, termites cause a loss of USD 40 billion necessitating the need for their management through, among other techniques, agricultural techniques that reduce the level of termite infestation (Ahmad *et al*., 2021). Crops in rainfed agro-ecosystems are prone to greater damage by termites which can occur during different growth stages (Govorushko, 2019). In addition, termite activity and farming practices such as application of organic and inorganic manure can also influence the damage level (Anyango *et al*., 2019).

Maize is among several crops that are affected by termites and in Africa >50% damage has been reported (Maniania *et al*., 2002). Termite infested plants cannot efficiently transport water and nutrients thereby affecting yields (Mutsamba *et al*., 2016). In addition, lodged plants may be damaged further by fungi and rodents (van den Berg and Riekert, 2003). Apart from the damage that termites cause on maize, disturbances that are created during cultivation also affect certain termite functional groups that perform key ecosystem services. Disturbances such as agricultural intensification lead to loss of biodiversity which is often not recovered even after restoration; a deficit of 27-33% in species diversity across the globe has been reported (Moreno-Mateos *et al*., 2017). Agriculture is a major form of disturbance that leads to biodiversity loss (Tsiafouli *et al*., 2015); yet, soil diversity plays a critical role in agro-ecosystem sustainability through enhanced resilience and resistance to different forms of stress (Brussaard *et al*., 2007). According to Bengtsson (2002) organisms can be affected by press, frequent pulse or large infrequent disturbances. Neoh et al. (2018) reported that cultivation significantly affected specific termite functional groups. Termites that feed on soil showed a negative correlation with disturbance along a gradient consisting of primary and regenerating forests, fallows, farmland and tilled plots in Cameroon and Congo (Eggleton *et al*., 2002).

Direct and indirect contributions of agriculture to the Kenyan Gross Domestic Product are estimated at 26 and 25%, respectively. Since growth of the Kenyan economy is correlated to agricultural development, production of key staple crops such as maize will increase (GoK, 2010). In order to sustainably produce the crop, management of termites, which have been reported to cause damage in Kenyan maize (Anyango *et al*., 2020, 2019), is imperative. Management of these pests should be such that other ecologically important termite functional groups are not affected. Several termite management techniques have been proposed (Demissie *et al*., 2019; Mutsamba *et al*., 2016; Negassa and Sileshi, 2018;

Nyagumbo *et al*., 2015). For instance, intercropping maize with other plants reduces termite damage, number of lodged crops (Sileshi *et al*., 2005) and yield losses (Sekamatte *et al*., 2003).

In Kenya, there are limited studies on control of termites in maize through intercropping and the effect of intercrop systems on termite functional groups. Due to their contribution to ecosystem functions and enhancing productivity, additional studies on sustainable management of termites in maize are needed. This information will serve as a guide for integrated termite management that considers the ecological role of other termite functional groups that co-exist with the pests. Therefore, the objective of this study was to determine the effect of intercropping maize with soybean, common beans and sorghum on infestation levels of termites species and functional groups and maize lodging due to termites termites in Machakos county, Kenya.

5.2 MATERIALS AND METHODS

5.2.1 Study site

The experiment was carried out in Yatta sub-county in Machakos county, Eastern Kenya (1.2358° S, 37.5961° E). The region is within the arid and semi-arid lands at an elevation of 700-800 a.s.l. (Figure 5.1). Temperature range is between 29 ^{o}C and 36^{o}C and the rainfall pattern is bimodal, with annual rainfall ranging between 500 and 800mm. Soil type ranges from clay to sandy and the land is mainly used for agricultural activities with the main crops being cereals, pulses, roots and tubers (Eidt *et al*., 2020).

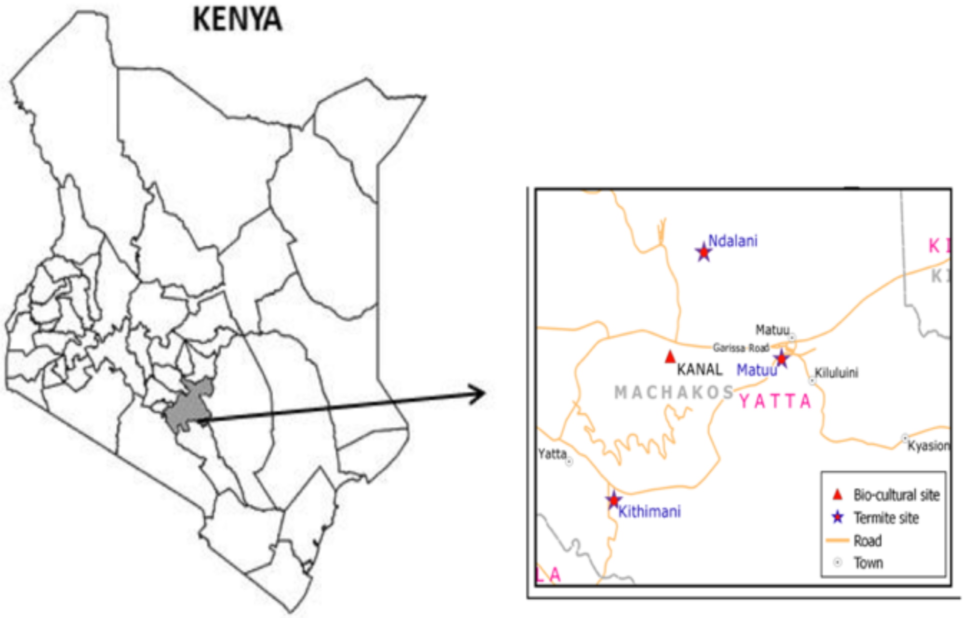

Figure 5.1: Map of study site at Yatta sub-county, Machakos county (Modified from Eidt *et al*., 2020).

5.2.2 Experimental design

There were three treatments consisting of maize-soybean (*Glycine max*; variety Nam 1), maize-sorghum (*Sorghum bicolor*; variety SDS 3220; 'macia') and maize-bean (*Phaseolus vulgaris*; variety K31) intercrops. In addition, maize (*Zea mays*) monocrop was established as a control. Each treatment was replicated four times and each replicate consisted of five plants. Choice of intercrops was based on the crops that are commonly grown in the area. The maize variety 511 hybrid was used because it is known to be susceptible to termite attack. The treatments were replicated four times in a completely randomized block design and the experiment was conducted in two seasons (long rains season one - October 2020 to February 2021; short rains season two- March to July 2021). Plots were 10 m x 10 m separated by 2 m alleys. Based on local practices, maize was planted at a spacing of 90 cm between rows and 30 cm between plants, with one seed per hole. Soybeans were planted at a spacing of 30 cm between rows and 15 cm between plants. Common beans were planted at a spacing of 45 cm between rows and 15 cm between plants. Two seeds each of soybeans and common beans were planted per hole. Sorghum was planted at a spacing of 75 cm between rows and 30 cm between plants with three seeds per hole. For all the intercrop treatments, two rows of the intercropped plants were planted between two maize rows. Diammonium phosphate was applied at planting at the rate of 150kg/ha. No other crop management activities were performed during the trials. In each treatment, number of termites and termite lodged plants were assessed at 42, 56, 70, 84 and 102 days after planting. Termite damage in lodged plants was confirmed and the plants were tagged after each count. Lodging was recorded on plants that were previously healthy and were then cut off at the base of the crop (Anyango *et al*., 2019). In each sampling session two belt transects (10m × 2 m) separated by 1m were laid out at each plot. From each transect, 30cm x 30cm quadrats were laid out at an interval of 2m within the transect. In each quadrat, all termites on the surface of the soil were sampled from different microhabitats. In addition, samples were collected from 12cm × 12 cm, 10 cm deep pits (Jones *et al*., 2003). Termites were identified to species level at the National Museums of Kenya using identification keys and assigned to functional groups. Termite species that feed on dead wood and grass that is less decayed are designated Group I while group II can be divided into termites that feed on more decayed leaves, wood, micro-epiphytes and grass and group IIf which are fungus cultivators. True soil feeders are classified as group IV (Donovan *et al*., 2001; Inward *et al*., 2007).

5.2.3 Data analysis

Data on number of lodged plants was expressed as the proportion (%) of lodged plants relative to the total number of plants per plot averaged across the sampling sessions. The data was square root transformed before one-way analysis of variance (ANOVA). To identify indicator species in different treatments, an analysis of indicator values (Dufrêne, and Legendre, 1997) was performed using indicspecies package; function *multipatt* in R software. In addition, association (Pearson Phi coefficient) between species and treatments (De Cáceres and Legendre, 2009) was analyzed using the same function and R package. To assess the influence of treatments on termite species and functional groups in the two seasons, a one-way ANOVA with subsequent Tukey honestly significant difference post hoc tests was performed. Termite species assemblage in different treatments across the two seasons were ordered using Renyi diversity profiles. Pearson correlation analysis was used to determine the relationship between number of lodged maize plants and termite species populations. Vegan package (Oksanen *et al*., 2019) in R software was used by applying the renyi command. The scale parameter α at 0, 1, 2, and infinity represent species richness, Shannon index, logarithm of the reciprocal Simpson index and Berger–Parker index, respectively. All analyses were done in R version 4.0.2 (R Core Team, 2020).

5.3 RESULTS

5.3.1 Lodged plants and termite population densities

There was a significant variation in the percentage of lodged plants between treatments in season one ($F_{3,12}$= 22.9; *P* <0.001) and two ($F_{3,12}$=13.9; *P* <0.001). In season one, maize-sorghum intercrop had a low number of lodged plants while in season two a similar observation was made (Fig. 5.2). In both seasons, *Macrotermes herus, M. subhyalinus, Coptotermes formosanus, Odontotermes badius, O. longignathus* and *Cubitermes ugandesis* were recorded. Across the two seasons, *O. longignathus* was the indicator species in the maize monocrop, maize-beans and maize-soybean intercrops. Pearson's phi coefficient of association showed that *M. herus* (r=0.195; *P*= 0.021) was significantly associated with maize-beans intercrop (r=0.304; *P*= 0.025) while *M. subhyalinus* was associated with maize-monocrop (r=0.24; *P*= 0.006).

Maize-sorghum intercrop in season one had the lowest number of *M. herus* ($F_{3,76}$=10.5; *P* <0.001) and *O. badius* ($F_{3,76}$=11.1; *P* <0.001). In the same season, there were no differences in the number of *C. formosanus* ($F_{3,76}$= 1.2; *P*=0.3) and *C. ugandesis* ($F_{3,76}$= 0.6; *P* =0.62) across the treatments. In maize-sorghum intercrop, *O. longignathus* occurred in low numbers compared to maize-beans and maize-soybean intercrops. In the second season, there were low populations of *M. herus* ($F_{3,76}$=8.2; *P* <0.001) and *O. badius* ($F_{3,76}$=6.8; *P* <0.001) in maize-sorghum intercrop. Populations of *O. longignathus* ($F_{3,76}$= 2.1; *P* = 0.1) and *C. formosanus* ($F_{3,76}$= 2.4; *P* = 0.07) were similar in all the treatments (Table 5.1). In maize-beans intercrop, populations of *M. herus* (r=0.72, P<0.001) and *M. subhyalinus* (r=0.455, P=0.04) were significantly correlated with increased number of lodged plants. A similar observation was made in the maize monocrop (*M. herus*; r=0.78, P<0.001 and *M. subhyalinus*; r=0.7, P<0.001). In maize-soybean intercrop (r=0.5, P=0.02), abundance of *O. badius* was positively correlated with percentage of lodged plants. There was no significant correlation between abundance of termite species and lodging of plants in maize-sorghum intercrop.

5.3.2 Termite functional groups

Abundance of fungus cultivators was lower in maize-sorghum intercrop compared to the other treatments in both seasons (season 1; $F_{3,76}$=36.2; *P* <0.001, season two; $F_{3,76}$=23.6; *P* <0.001). There were no differences in the abundance of group 1 termites in both seasons. Across all treatments in both seasons, there were low numbers of soil feeders (Table 5.2). Renyi diversity ordering was not unequivocal due to intersecting of the profiles in both seasons. However, the profiles showed that in season one, maize monocrop had the highest frequency of the dominant species (*M. herus*). Termite species were more evenly distributed in maize-sorghum intercrop in both seasons (Figure 5.3).

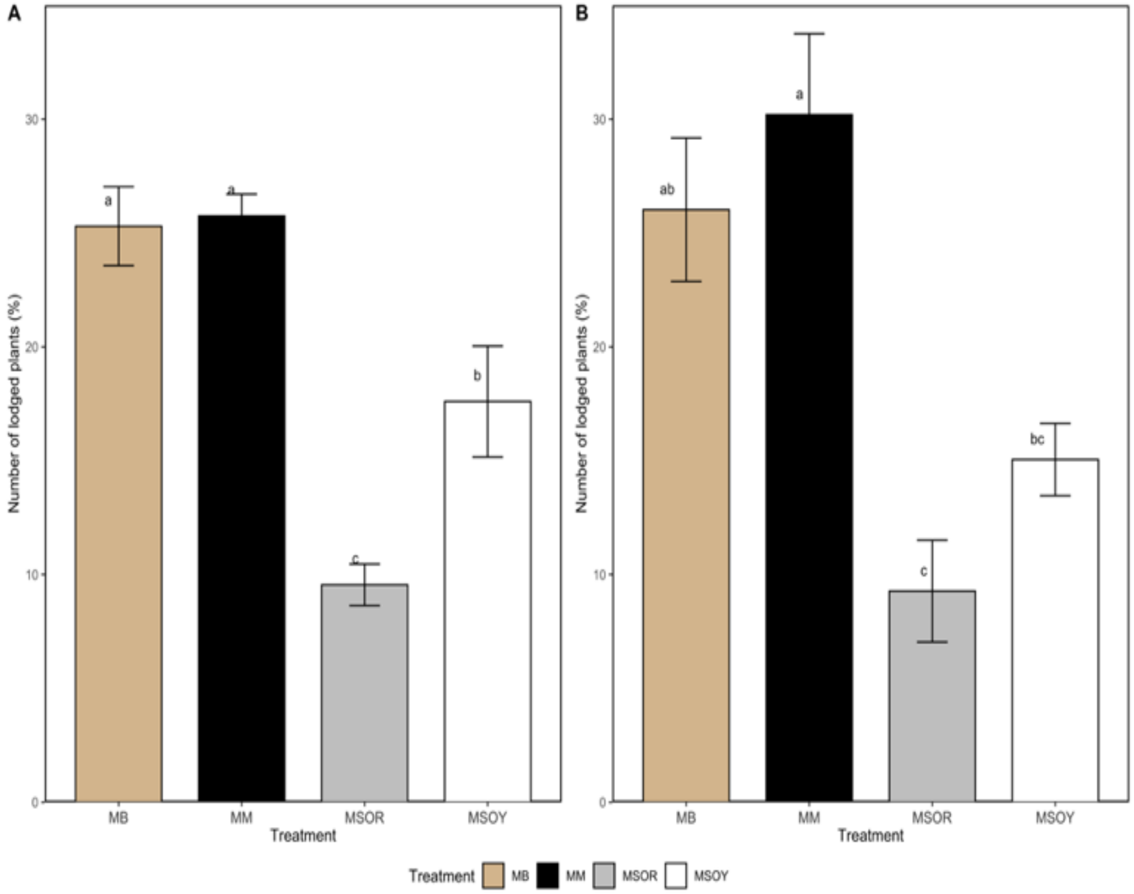

Figure 5.2: Number of lodged maize plants in maize-beans intercrop (MB), maize monocrop (MM), maize-sorghum intercrop (MSOR) and maize-soybean intercrop (MSOY) during A) season one and B) season two. Different letters indicate significant differences in number of lodged plants

Table 5.1: Abundance (mean ± standard error) of termite species in maize monocrop, maize-sorghum, maize-beans and maize-soybean intercrops during season one and season two (long rains season one - October 2020 to February 2021; short rains season two- March to July 2021).

Treatment	*Macrotermes herus*	*M. subhyalinus*	*Coptotermes formosanus*	*Odontotermes badius*	*O. longignathus*	*Cubitermes ugandesis*
Season one						
Maize monocrop	58.1±8.39a	10.4±1.77a	4.8±1a	32.2±6.9a	4±1.12ab	1.3±0.43a
Maize-beans intercrop	45.4±5.68a	3.5±0.98b	9.5±3.49a	31±4.2a	5.7±1.19a	1.6±0.43a
Maize-sorghum intercrop	7.6±1.87b	2.7±0.83b	3.4±1.32a	7.9±1.67b	0.7±0.38b	1±0.36a
Maize-soybean intercrop	33.1±5.44a	3.5±0.96b	5.2±1.54a	25.8±4.04a	4.8±1.06a	0.9±0.3a
F value	10.5	5.6	1.2	11.1	5.4	0.6
P value	<0.001	0.002	0.3	<0.001	0.002	0.62
Season two						
Maize monocrop	51.1±7.7ab	8.9±1.3a	4.8±1.9a	32.3±8.4a	5.9±1a	0.8±0.4ab
Maize-beans intercrop	42±4.8a	9.4±1.1a	4.1±1.1a	21.6±5.3ab	5.5±0.9a	2.1±0.6a
Maize-sorghum intercrop	11.5±1.9c	3.1±1b	6.9±2.6a	8±1.8b	3.2±1a	0.3±0.3b
Maize-soybean intercrop	25±5.3bc	5.6±1.3ab	0.6±0.4a	34.6±5.9a	6.6±1.6a	1.2±0.5ab
F value	8.2	5.9	2.4	6.8	2.1	4
P value	<0.001	0.001	0.07	<0.001	0.1	0.01

Means with the same letter along a column are not significantly different.

Table 5.2: Abundance (mean ± standard error) of termite functional groups in maize monocrop, maize-sorghum, maize-beans and maize-soybean intercrops during season one and season two (long rains season one - October 2020 to February 2021; short rains season two- March to July 2021).

Treatment	I- Wood feeders	IIf- Fungus cultivators	IV- Soil feeders
Season one			
Maize monocrop	4.8±1.0a	104.7±8.05a	1.3±0.43a
Maize-beans intercrop	9.5±3.49a	85.4±6.57a	1.6±0.43a
Maize-sorghum intercrop	3.4±1.32a	18.9±2.75b	1±0.36a
Maize-soybean intercrop	5.2±1.54a	67.1±6.68a	0.9±0.3a
F value	1.2	36.2	0.59
P value	0.3	<0.001	0.62
Season two			
Maize monocrop	4.8±1.91a	98.1±10.5a	0.8±0.37ab
Maize-beans intercrop	4.1±1.1a	78.5±6.92a	2.1±0.59a
Maize-sorghum intercrop	6.9±2.58a	25.7±2.37b	0.3±0.25a
Maize-soybean intercrop	0.6±0.38a	71.7±6.7a	1.2±0.45ab
F value	2.4	23.6	4.0
P value	0.07	<0.001	0.01

Means with the same letter along a column are not significantly different. Group I -wood feeders, group IIf-fungus cultivators and group IV-soil feeders

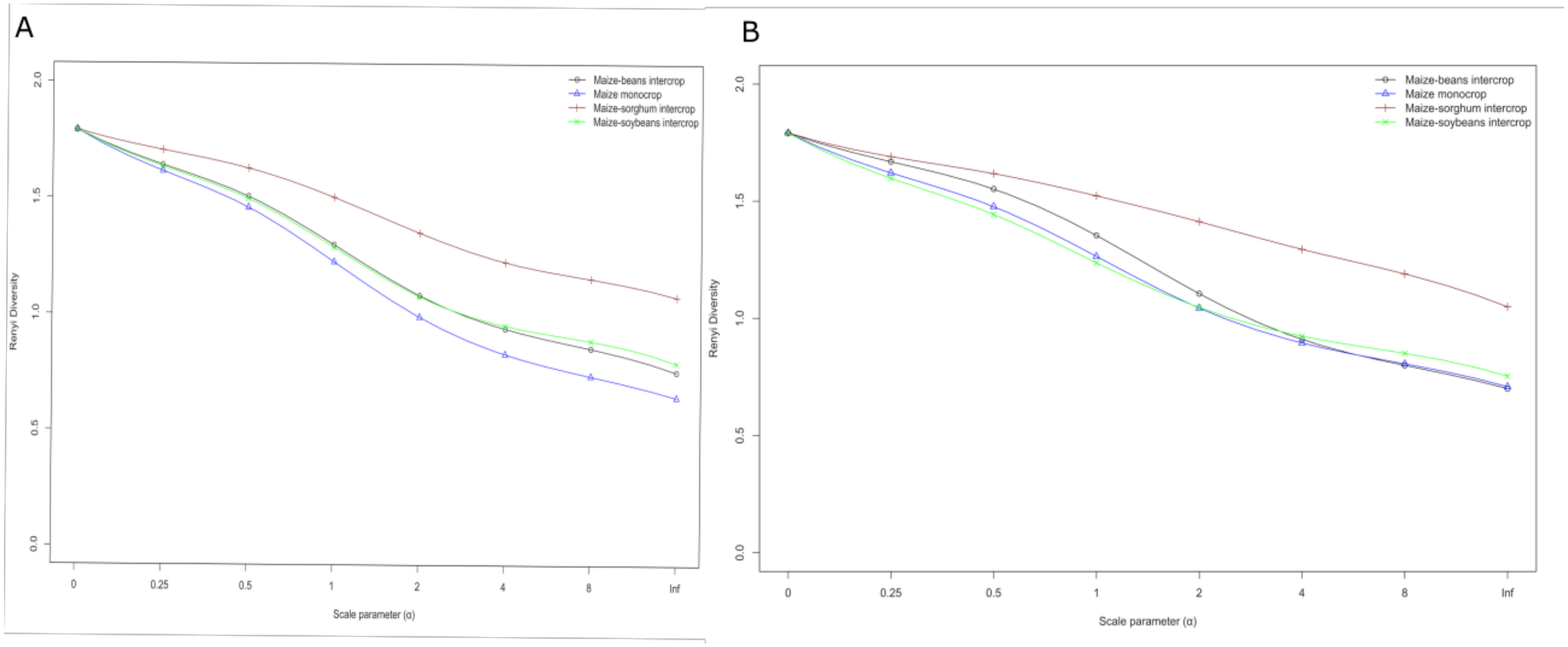

Figure 5.3: Renyi diversity profiles of termite assemblages in maize monocrop, maize-sorghum, maize-beans and maize-soybean intercrops during season A) one B) two. The alpha values 0, 1, 2, and infinity represent species richness, Shannon index, logarithm of the reciprocal Simpson index and Berger–Parker index, respectively

5.4 DISCUSSION

Termites cause considerable damage to maize and different forms of disturbances affect termite species diversity and functional groups (Anyango *et al*., 2019; Eggleton *et al*., 1996). The indicator species for all treatments except maize-sorghum intercrop was *O. longignathus*; however*, M. subhyalinus* was associated with maize-monocrop. *Macrotermes* spp. and *Odontotermes* spp. are among the most damaging species in maize (Nyagumbo *et al*., 2015). The species partially or completely cut off stems after they attack at the surface of the soil or slightly below (Wood, 1991). These two species have been observed in Kenyan maize fields and are associated with lodging of crops (Anyango *et al*., 2019). The termite species infestation was low in maize-sorghum intercrop in both seasons; this situation may explain the small percentage of lodged plants. In addition, predatory ants that feed on termites are common in maize-sorghum intercrops which reduces termite damage (Sekamatte *et al*., 2003). High percentage of lodged plants in maize-monocrop is similar to observations made by Sileshi et al. (2005) which they attributed to reduced water retention and low soil organic carbon in the maize monoculture compared to intercropped systems. Similarly, 65-56% of lodged maize in monoculture was recorded in South Africa (Riekert and van den Berg, 2003). As observed in this study, Sekamatte *et al*. (2003) reported that common beans do not effectively control termite damage; however, they observed that soybeans were more efficacious compared to beans. This was attributed to large amounts of soybean litter that served as food for termites.

Macrotermes herus, M. subhyalinus, C. formosanus, O. badius, O. longignathus and *C. ugandesis* were identified in the current study. Intersecting of Renyi diversity profiles was due to similar species richness across treatments during each season. The observed termite species are similar to those previously reported in Kenya (Anyango *et al*., 2020, 2019; Ayuke *et al*., 2011; Kagezi *et al*., 2011). Simplification of habitats that accompanies agricultural intensification can lead to loss of termite functional groups (Kaiser *et al*., 2015). Population densities of group IV was low across all treatments in both seasons. This may be due to the unstable conditions in cultivated land which are not ideal for group

IV termite species that show sensitivity to environmental disturbance. Disturbed sites modify the microclimate of soil feeders which reduces their reproductive fitness and population (Dosso *et al*., 2013). Furthermore, group IV soil feeders, which have short dispersal distances, occur in restricted ranges at the lower humification gradient where energy levels are limited due to low quality of substrates (Eggleton and Tayasu, 2001; Isra *et al*., 2008). The low abundance of soil feeders may have implications on soil fertility (Eggleton *et al*., 2002). In this study, all treatments except maize-sorghum intercrop, had a higher number of group IIf termites. Contrary to the observations made in this study, wood feeders were the dominant functional group in maize cropping systems in Benin but fungus-cultivators (*Macrotermes* spp. and *Odontotermes* spp.) were frequently encountered in roots and stems (Loko *et al*., 2021). However, association of maize with fungus-growers has also been reported (Sekamatte *et al*., 2003; van den Berg and Riekert, 2003).

The study results indicated that, there were a low percentage of lodged plants in maize-sorghum intercrop. The lowest number of fungus-cultivators was in the maize-sorghum intercrop while soil feeders occurred in low populations. Loss of key functional groups such as soil feeders could have implications on crop productivity due to their role in improving soil fertility. Although this study showed that intercropping maize and sorghum reduces termite infestation, there is need to further evaluate the impact of termite infestations on yield under the different treatments. Other factors that may also influence the level of termite damage such as tillage, seasons, application of fertilizers, rainfall and soil properties should also be evaluated. With the increasing rate of agricultural intensification in Kenya, immediate measures such as those proposed in this study are required to control termite infestation in maize and at the same time protect soil engineers.

CHAPTER SIX

Effect of *Azadirachta indica*, *Metarhizium anisopliae*, *Megaponera analis* and *Dorylus gribodoi* on mortality of *Macrotermes subhyalinus* and *Odontotermes badius*

6.0 ABSTRACT

Termites are ecological engineers that perform key ecological functions as they forage. However, they are destructive to various crops, forests, pasture land and farm structures in several parts of world. In Kenya, *Macrotermes* spp. and *Odontotermes* spp. are known to be important pests in maize causing between 50 -100% loss. Maize is a major staple food crop grown by small-scale and a few large-scale farmers in Kenya. Losses of maize on the farm or in store directly affect the livelihoods of small-scale maize farmers. There are various methods used in management of termite infestation. These methods include cultural, chemical and biological methods. However, the control of termites in Kenya to a higher degree depends on non-selective organo-chlorine insecticides. These chemicals impact negatively on the environment, some have limited efficacy and the target pests have also developed resistance. Entomopathogenic fungi, botanicals such as *Azadirachta indica* and use of predatory ants on termites have been used to control termites. However, comparative efficacy on these non-chemical control methods has not been widely evaluated in Kenya. Therefore, the aim this study was to evaluate the comparative efficacy of *Metarhizium anisopliae*, *Dorylus gribodoi*, *Megaponera analis*, and *Azadirachta indica* on the control of *Macrotermes subhyalinus* and *Odontotermes badius.* The treatments had four replicates each in a completely randomized experimental design. Distilled water was a control in the experiment. The experiment was carried out at 25±2°C and at 60% relative humidity under laboratory conditions. The mean mortality (%) caused by *M. anisopliae* in *O. badius* and *M. subhyalinus* was significantly lower compared to the rest of the treatments. *Macrotermes subhyalinus* showed significantly higher mean mortality caused by *D. gribodoi* and Termidor (Fipronil 9.1%) compared to *M. analis* and *A. indica*. In *D. gribodoi, A. indica* caused a mean mortality of 68.03% which was significantly higher than mean mortality caused by *M. anisoplae*. There was a significant time*treatment interaction ($P<0.0001$) in the mean mortality of *M. subhyalinus*, *O. badius, D. gribodoi*

and *M. analis* due to *A. indica* treatment. The information obtained from this study will help in development of environmentally friendly termite control methods.

6.1 INTRODUCTION

In Kenya, different termite genera are pests in agro-ecosystems, natural and artificial forests (Ayuke, 2010; Yusuke, 2010). Termites have been reported to cause high yield losses in crops (Michael, 2000; UNEP and FAO, 2000; Sekamatte, 2002; Nyeko, *et al.*, 2010). Termites show different levels of damage on crops, forests and grass in Eastern Africa. For instance, termites in Ethiopia caused losses of up to 100% on Eucalyptus, twenty-four months after trees establishment (Khaenje *et al.*, 2013). In Uganda and Kenya, greater than 50% loss has been reported on crops and forests (Sekamatte, 2001; Nyeko, *et al.*, 2010). In Kenya, damage of between 800-1500 kg/ha of grass pasture has been reported per year (Nyeko, *et al.*, 2010). Maize is a major food crop for the rural population in Africa (ECAMAW, 2005) and losses negatively affect livelihoods of small-scale farmers. Damage of maize caused by termites was previously reported to be between 50-100% in East Africa (Sekamatte, 2002; Nyeko and Olumbayo, 2005). Such termite infestation in maize contribute to low maize yields in Kenya (Sileshi *et al.*, 2008 and Nyeko *et al.*, 2010). Gitonga, (1996) reported 50 % loss on maize in the Eastern region of Kenya.

There are various methods of controlling termite damage either in farm structures, crops and/or forests. The methods include use of synthetic chemicals, cultural practices and use of other organisms. These methods can be used in combination for effectiveness, efficiency and for lowering the cost of termite control. The choice of the method also depends on the effect to the environment (Tasisa and Gobena, 2013). In Kenya, management of termites to a higher degree depends on non-selective residue effect of organo-chlorine chemicals (Abonyo *et al.,* 2016). There are a number of chemical brands used to control termites registered across the world (Ewart, 2000). In Kenya and Uganda, Nyeko et al. (2010) demonstrated the effective control of termites by use of lindane. Khaenje et al. (2013) reported that although chemical insecticides were very effective in termite control in Kenya, they had harmful environmental effects. The limitations associated with use of organo-chlorine chemicals necessitate the need for alternative non-chemical methods.

There are several environmentally safe methods for control of termites. These include cultural practices, destruction of termites' habitats (nests and mounds), use of biocontrol agents and growing resistant crops. (Sekamatte, 2002; Ayuke, 2010). Akutse et al. (2012) reported that wood ash, sand, damaging of termites' habitats (nests and mounds) and isolation of queen from the colony reduced termites on crop farms in Ghana. In Kenya, use of excess water on termites infested areas, removing the queen from the colony, damaging mounds, destruction of crop residues, application of wood ash or dried and grinded pepper, use of cattle urine and addition of organic manure are some of the methods that have been explored in controlling termites (Gitonga, 1996). However, these management methods have low efficacy and are labour intensive (Sekamatte, 2003). It is therefore important to explore alternative methods for management of termites in Kenya. The aim of this study was to assess the efficacy of *Azadirachta indica*, *Metarhizium anisopliae*, *Megaponera analis* and *Dorylus molestus* on *Macrotermes subhyalinus* and *Odontotermes badius*.

6.2 MATERIALS AND METHODS

6.2.1 Experimental design

The study was carried out in the University of Embu Botany laboratory. The treatments were *Azadirachta indica*, *Metarhizium anisopliae*, *Dorylus gribodoi*, *Megaponera analis* and Termidor EC (Fipronil 9.1%). Each treatment was replicated four times in a completely randomized design. Distilled water was used as a control. The experiments were carried out at 25±2°C and 60% relative humidity.

6.2.2 Collection of termites

Macrotermes subhyalinus and *Odontotermes badius* were collected from Kangaru, Embu. Termite mounds for both *M. subhyalinus* and *O. badius* were identified and dug up.

Termites were collected using a hair brush and placed in plastic boxes (polyethylene plastic boxes; 40cm x 30cm x30cm) (Gitonga *et al*., 1995). Wooden plant parts infested with *M. subhyalinus* and *O. badius* were added to the plastic boxes as food for the termites. The boxes were transported to University of Embu laboratory and placed in a cool and dark area until termites were used for the experiments. For both *M. subhyalinus* and *O. badius*, 100 termite workers were used in the experiments.

6.2.3 Trapping and collection of *Megaponera analis* and *Dorylus gribodoi*

A piece of fresh cattle meat weighing 250g was placed in plastic boxes measuring 40cm x 30cm x 30cm and placed next to swarming lines of ants as bait. A hole to fit the plastic box was dug in the ground next to the swarming lines of ants such that the edge of the top of the box was at the level of the ground. After two hours the ants had entered the boxes to forage on the meat. The boxes were covered with perforated covers for ventilation and transferred to University of Embu laboratory. One hundred ants of each species were used in the experiments. Data was collected after one hour.

6.2.4 Preparation of *Metarhizium anisopilae*, *Azadirachta indica* and Termidor EC

The entomopathogenic fungi *Metarhizium anisopilae*, ICIPE-69 (*M. anisopliae*) was obtained from International Center of Insect Physiology and Ecology in Nairobi. The *M. anisoplae* was in a liquid formulation which was a spore suspension with a concentration of 1.0 x 10^7 spores per ml. The *M. anisoplae* treatment was prepared by mixing one ml of the spore suspension in one liter of distilled water. *Azadirachta indica* was in a liquid formulation and had a concentration of 30% and was prepared by mixing one ml of the concentrate in 400ml of distilled water. Termidor EC (Fipronil 9.1%) was also in a liquid formulation and was prepared by mixing one ml in one liter of distilled water. *M. anisoplae, Azadirachta indica* and Termidor EC (Fipronil 9.1%) treatments were applied in the plastic boxes using a hand sprayer. Data was collected after 15 and 30 minutes (Termidor EC), 30 minutes and 1 hour (*Azadirachta indica*) and 48 hours for *M. anisoplae*.

6.2.5 Data analysis

Data on number of dead worker termites was expressed as the proportion of all the total number of termite workers in the plastic box in all the replicates. The data was square root transformed before analyses. One-way analysis of variance (ANOVA) with subsequent Tukey honestly significant difference (HSD) post hoc test was used to determine treatment effects. To assess the influence of time, *Azadirachta indica* and Termidor EC (Fipronil 9.1%) on termite and ant species two-way ANOVA with subsequent HSD post hoc test was performed.

6.3 RESULTS

Mean mortality of *O. badius* and *M. subhyalinus* varied significantly ($P<0.0001$) between different treatments. The mean percentage mortality caused by *M. anisopliae* in both *O. badius* and *M. subhyalinus* were significantly lower compared to the rest of the treatments. *Macrotermes subhyalinus* showed significantly higher mean mortality due *D. gribodoi* and Termidor (Fipronil 9.1%) compared to *M. analis* and *A. indica* (Table 6.1, Fig. 6.1).

Table 6.1: Percentage mortality (mean± standard error) of *Odontotermes badius* and *Macrotermes subhyalinus* caused by various treatments

Treatment	*Odontotermes badius*		*Macrotermes subhyalinus*	
	Mean	SE	Mean	SE
Azadirachta indica	94.05a	1.80	84.33b	1.25
Distilled water	0c	0.00	0d	0.00
Dorylus gribodoi	96.25a	0.67	94.6a	1.21
Megaponera analis	90.58a	1.10	81.5b	1.05
Metarhizium anisopliae	14.58b	1.52	13.15c	0.92
Termidor (Fipronil 9.1%)	99.08a	0.58	97.58a	0.84
F value	1829.2		3491.1	
P value	<0.0001		<0.0001	

Means with the same letter along a column are not significantly different. Data was collected at 30 minutes (Termidor EC), 1 hour (*Azadirachta indica*), 48 hours for *M. anisopliae* and 1 hour for *Megaponera analis* and *Dorylus gribodoi*.

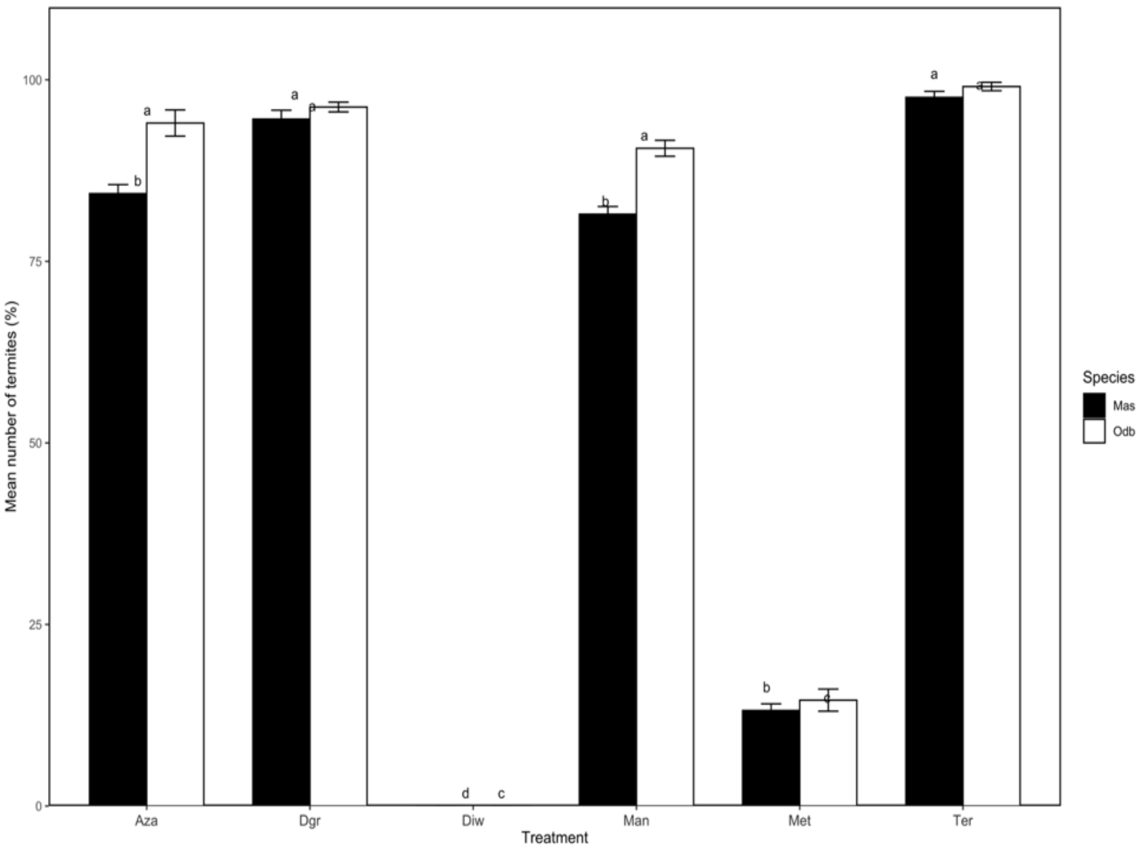

Figure 6.1: Mean (SE) number of dead termites (%) after exposure to different treatments. Aza- Azadirachta indica, Mas-*Macrotermes subhyalinus,* Odb- *Odontotermes badius,* Man- *Megaponera analis,* Met- *Metarhizium anisopilae*, Dgr-*Dorylus gribodoi,* Man-*Megaponera analis,* Diw-Distilled water, Ter-Termidol. Data was collected at 30 minutes (Termidor EC), 1 hour (*Azadirachta indica*), 48 hours for *M. anisopliae* and 1 hour for *Megaponera analis* and *Dorylus gribodoi*.

Mean mortality of *D. gribodoi* and *M. analis* due to the different treatments was significantly different. In *D. gribodoi, A. indica* caused a mean mortality of 68.03% which was significantly higher than mean mortality caused by *M. anisoplae*. In *M. analis,* mean mortality caused by *A. indica* (85.88%) was significantly higher than that caused by *M. anisoplae* (4.9%) (Table 6.2, Figure 6.2, 6.3 and 6.4).

Table 6.2: Percentage mortality (mean± standard error) of *Dorylus gribodoi* and *Megaponera analis* due to different treatments.

*Treatment**	*Dorylus gribodoi*		*Megaponera analis*	
	Mean	SE	Mean	SE
Azadirachta indica	68.03b	2.54	85.88b	1.03
Distilled water	0d	0.00	0d	0.00
Metarhizium anisopliae	6.78c	0.68	4.9c	0.58
Termidor EC (Fipronil 9.1%)	100a	0.00	100a	0
F value	2189		4991.2	
P value	<0.001		<0.001	

*Data was collected at 30 minutes (Termidor EC), 1 hour (Azadirachta indica) and 48 hours for *M. anisoplae.*

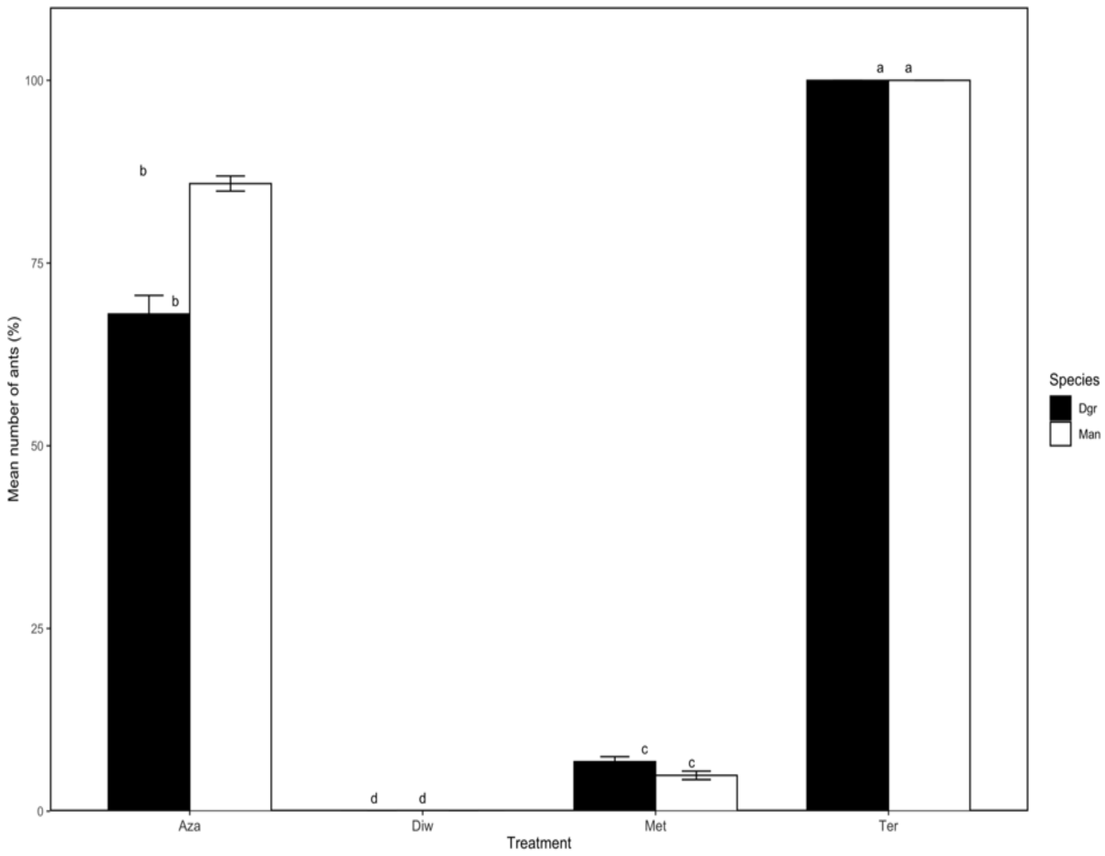

Figure 6.2: Percentage mortality (mean± standard error) of *Dorylus gribodoi* and *Megaponera analis*. Dgr-*Dorylus gribodoi,* Man- *Megaponera analis.* Aza- Azadirachta indica*,* Man- *Megaponera analis,* Met- *Metarhizium anisopilae*, Dgr-*Dorylus gribodoi,* Man- *Megaponera analis,* Diw-Distilled water, Ter-Termidol. Data was collected at 30 minutes (Termidor EC), 1 hour (*Azadirachta indica*) and 48 hours for *M. anisoplae.*

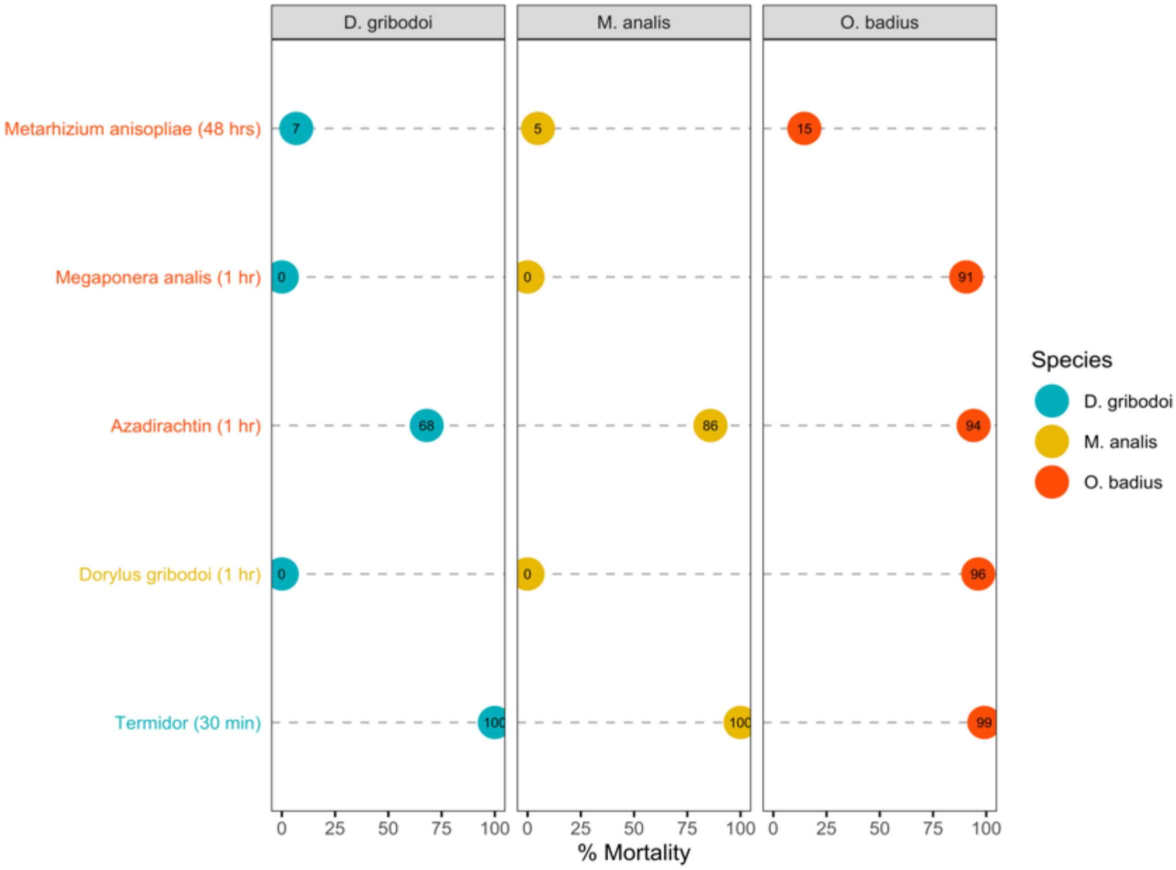

Figure 6.3: Mortality rates of *Dorylus gribodoi, Megaponera analis* and *Odontotermes badius* under different treatments.

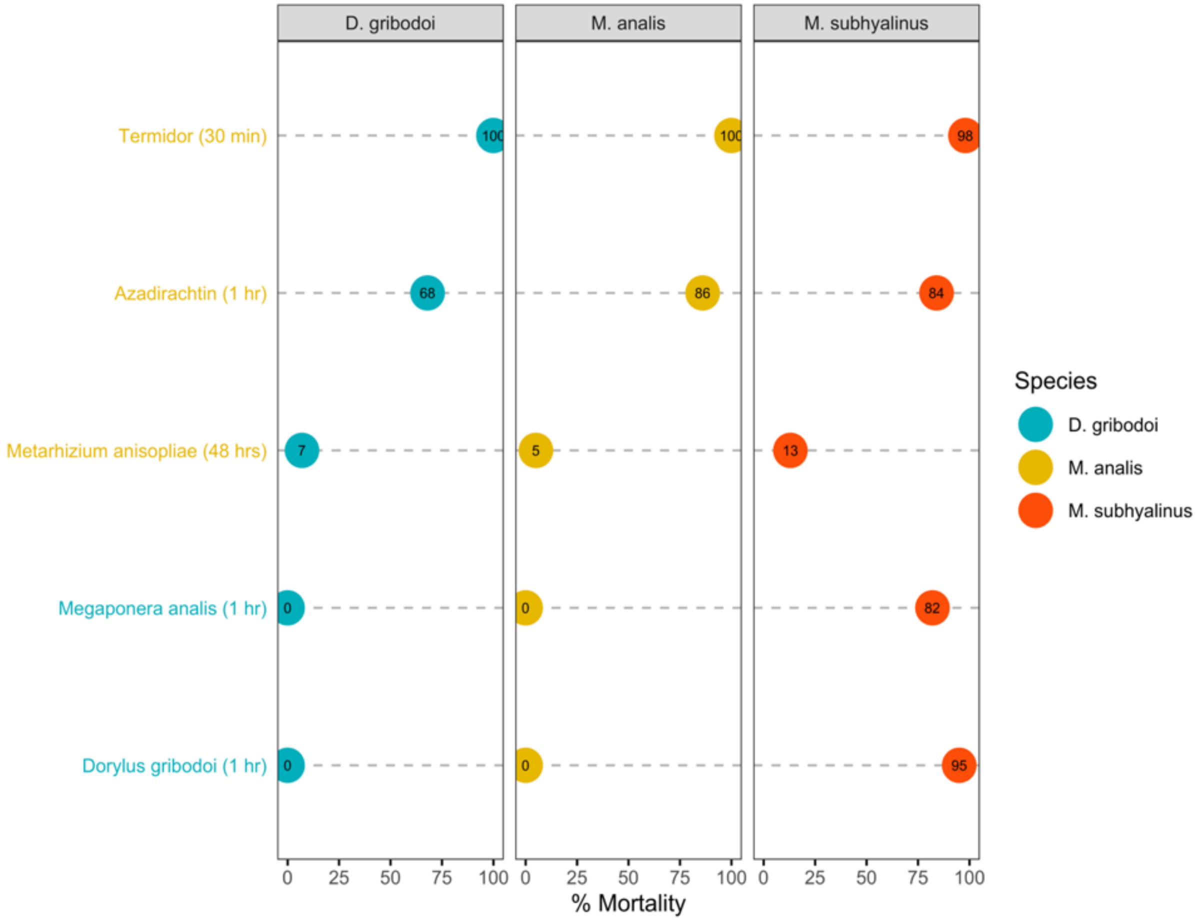

Figure 6.4: Mortality rates of *Dorylus gribodoi, Megaponera analis* and *Macrotermes subhyalinus* under different treatments.

There was a significant time*treatment interaction (P<0.0001) in the mean mortality of *M. subhyalinus*, *O. badius, D. gribodoi* and *M. analis* due to *A. indica* treatment. The mean mortality of termite and ant species was significantly higher after 1-hour exposure (Table 6.3). There was a significant effect of treatment (Termidor) on *M. subhyalinus*, *O. badius, D. gribodoi* and *M. analis.* The only significant time*treatment interaction (P<0.0001) was in *O. badius*. After 15 minutes of exposure to Termidor (Fipronil 9.1%), mean mortality of *O. badius* and *M. subhyalinus* was 99.95±0.61 and 95.52±0.95, respectively. These means were not significantly different after 30 minutes of exposure. There was 100% mortality of the two ant species after 15 minutes (Table 6.4).

Table 6.3: Percentage mortality (mean± standard error) of *M. subhyalinus*, *O. badius, D. gribodoi* and *M. analis* caused by *Azadirachta indica* at 30 and 1hour of exposure

Species	*Azadirachta indica* 30 min		1 hr		P value		
	Mean	SE	Mean	SE	Treatment	Time	Time* Treatment
Odontotermes badius	52.23a	1.09	94.05b	1.80	<0.0001	<0.0001	<0.0001
Macrotermes subhyalinus	43.45a	1.12	84.33b	1.25	<0.0001	<0.0001	<0.0001
Dorylus gribodoi	26.08a	1.18	68.03b	2.54	<0.0001	<0.0001	<0.0001
Megaponera analis	32.58a	1.18	85.88b	1.03	<0.0001	<0.0001	<0.0001

Means with different letters across the row are significantly different.

Table 6.4: Percentage mortality (mean± standard error) of *M. subhyalinus*, *O. badius, D. gribodoi* and *M. analis* caused by Termidor EC (Fipronil 9.1%) at 15 and 30 minutes of exposure

Species	Termidor				P value		
	15 min		30 min				
	Mean	SE	Mean	SE	Treatment	Time	Time*Treatment
Odontotermes badius	99.95a	0.61	99.08a	0.58	<0.0001	0.02*	0.02*
Macrotermes subhyalinus	95.52a	0.95	97.58a	0.83	<0.0001	0.13	0.13
Dorylus gribodoi	100a	0	100a	0	<0.0001	0.33	0.33
Megaponera analis	100a	0	100a	0	<0.0001	0.33	0.33

Means with different letters across the row are significantly different.

6.4 DISCUSSION

Metarhizium anisoplae caused a mean mortality of 14.58% and 13.15% on *O. badius* and *M. subhyalinus,* respectively after 48 hours of exposure. These mortalities were significantly lower than the other bio-control agents. *M. anisoplae* is an entomopathogenic fungus that infects termites and causes death (Maniania *et al*., 2002; Abonyo *et al*., 2016; Khaenje *et al*., 2013). *Metarhizium anisoplae* is a sporulating fungus whose infection starts when the fungal spores fall on the termite's surface, germinates and grows inside the body. The infection process is fast; therefore, the fungus is highly infectious and death of the termites is recorded within 48 hours (Syazwan *et al*., 2021). Similar to observations made in this study, Addisu et al. (2013) observed that a *M. anisoplae* suspension of 1.0 X10^8 spores per ml caused a mortality of 20% in *Macrotermes* spp. Termites have the ability to collectively defend themselves against *M. anisopliae* infection in different ways, such as grooming the infected ones, cannibalism or burying them (Davis, *et al*., 2018). When the infected termites die, the infection in the colony is reduced. This may explain the low mortality that was observed after exposure in the early days (Addisu *et al*., 2013).

Dorylus spp. are natural enemies of termites and are used as a form of pest control (Mark, 2007). In the current study, *M. anisopliae* caused the lowest mortality on both *Megaponera analis* and *Dorylus gribodoi*. The two ant species caused greater than 90% mortality in *O. badius* and *M. subhyalinus.* However, the ant species were also severely affected by other treatments such as Termidol which caused 100% mortality in 30 minutes. Abonyo et al. (2016) studied the effects of ants in close interaction with *Odontotermes* spp. and found that there were no effects of direct exposure to *M. anisopliae* on the mortality of ants predating on termites. Ant species living in the soil and belonging the Order Hymenoptera and family Formicidae are predatory on other invertebrates or arthropods participating in the cycle of litter and wood degradation such as termites (Eggleton, 2011). Luke et al. (2014) demonstrated that most of the ant species feed on termites by raiding. Termites are attractive prey for predatory ants because they provide food which contain high levels of protein and are relatively sessile and stable through time (Buczkowski and Bennett, 2007). Based on the results from the current study, when considering the combined use of predatory ants and other biocontrol agents, it's important to consider the effects that the agents would have on the ants.

In this study, the commonly used chemical termidor Fipronil 9.1% caused the highest mortality to termite and ant species. Fipronil 9.1% is non-selective and controls a wide range of insects (Overmyer *et al*., 2005; Iqbal and Evans, 2017). Sarmad et al. (2020) showed that Fipronil had high efficacy and caused high mortality to *Odontotermes obesus* using white sugarcane and maize straw as bait. In the current study, *Azadirachta indica* was found to cause mortality of 94.05% within a period of one hour. Addisu *et al.* (2014) in a study on effectiveness of bio-pesticides (botanicals) against *Macrotermes* spp., under laboratory conditions found that, *Azadirachta indica* at a concentration of 35% recorded a 100% mortality on *Macrotermes* spp., which was similar to mortality caused by diazinon

60% EC. This study has also demonstrated the influence of the interaction of time and treatment which corroborates findings from other studies (Sun *et al.*, 2014; Syazwan *et al.*, 2021).

Addisu et al. (2013) reported that botanicals such as *Azadirachta indica* (neem), *Allium sativum* (garlic) and physic nut (*Jatropha* spp.) can be used in insect pest management and successfully demonstrated their efficacy in termite control in Ethiopia. Furthermore, Dhaliwal and Ramesh (2013) reported that *Azadirachta indica*-based insecticide had low mammalian toxicity and can be applied as foliar spray or soil drench. The use of plant extracts is an important part of integrated pest management (Okweche *et al.*, 2021). This study has demonstrated the efficacy of different biocontrol agents against *O. badius* and *M. subhyalinus.* However, since the experiment were carried out under laboratory conditions, it is important to evaluate how the treatments would control termites under field conditions. In addition, field trials should also consider combination of various treatments and their effects on non-target organisms.

CHAPTER SEVEN

GENERAL OVERVIEW (SYNTHESIS)

7.1 INTRODUCTION

This chapter synthesizes the research findings of the study. It also summarizes the major conclusions and recommendations and proposes the way forward in management of termite species in maize fields. The main objective of the study was to determine the distribution, diversity and control of termite species in Embu and Machakos counties. For the diversity study, focus was on natural vegetation, maize-beans intercrop and maize monocrop macrohabitats. The role of chemical and physical properties of soil in shaping the functional diversity of termites was also assessed. In addition, control of termites using different biological control methods was explored.

The specific objectives were;

i. To determine the effects of natural vegetation, maize-beans intercrop and maize monocrop on diversity of termite species in Embu and Machakos Counties.
ii. To assess the effect of soil properties on functional diversity of termites in Embu and Machakos Counties.
iii. To evaluate the effect of intercropping maize with soybean, common beans and sorghum on infestation levels of termites.
iv. To compare the effect of *Azadirachta indica*, *Metarhizium anisopliae*, *Megaponera analis* and *Dorylus gribodoi* on mortality of *Macrotermes subhyalinus* and *Odontotermes badius.*

7.2 SUMMARY OF THE MAJOR FINDINGS

7.2.1 Termites species diversity in natural vegetation, maize-beans intercrop and maize monocrop in Embu and Machakos counties.

The study was conducted in Kithimani, Matuu, and Ndalani locations of Machakos county and Kangaru, Kamiu and Ena of Embu county, Kenya. Sampling across all sites in the macrohabitats (natural vegetation, maize-beans intercrop and maize monocrop) was done during dry and wet seasons for two consecutive years (dry season one -July to September

2018, dry season two – Jan to March 2019, wet season one – Oct to Dec 2018 and wet season two – March to May 2019). The study showed that:

- There were seven termite species in Embu and Machakos counties but Machakos county had the highest number—seven due to the presence of *Trinervitermes gratiosus*. Presence of *T. gratiosus* in Machakos County may have been due to region-specific factors.
- Season significantly influenced the abundance of *M. subhyalinus*, *M. herus*, and *C. formosanus* with all the species occurring in greater numbers during the wet season in Embu county. *Macrotermes subhyalinus* and *M. herus* were positively associated with rainfall while T. *gratiosus* was negatively correlated with minimum temperature and rainfall.
- Soil properties affected termite abundance and diversity, for instance, *T. gratiosus* was negatively associated with Magnesium but positively correlated to pH and sand.
- *Macrotermes subhyalinus* and *M. herus* showed a positive association with Phosphorous and silt while *C. formosanus* was positively correlated to Calcium and Magnesium.
- In additive diversity partitioning, α component contributed 98.3% of species richness while for Simpson diversity, α component contributed 99.1% of the total diversity; an indication that most species were similar within fields in the two Counties.
- There was low beta diversity within each county which may be an indication of lack of significant differences in microhabitats which resulted in homogenization of the termite communities.

7.2.2 Effects of soil properties and seasons on functional diversity of termites

Termites were collected at monthly intervals from three locations each in Machakos (Kithimani, Matuu, and Ndalani locations) and Embu (Kangaru, Kamiu and Ena) County, Kenya. Three replicates each of maize sole crop, maize and beans mixed cropping and natural vegetation were sampled from each location. Sampling across all sites in the macrohabitats was done during dry and wet seasons for two consecutive years (dry season one -July to September 2018, dry season two – Jan to March 2019, wet season one – Oct to Dec 2018 and wet season two – March to May 2019). For soil physico-chemical analysis, samples were collected from each of the macrohabitats and a composite sample of 500g was used for analysis at the Kenya Agricultural and Livestock Research Organization, National Agricultural Research Laboratories.

From the study:

- Four termite functional groups were identified in both Embu and Machakos Counties. Group II (*Trinervitermes gratiosus*; grass feeder) was only recorded in Machakos while Group I (*Coptotermes formosanus*; wood feeder), IIf (*Macrotermes subhyalinus*, *M. herus*, *Odontotermes badius*, *O. longignathus*; fungus cultivators) and IV (*Cubitermes ugandensis*; soil feeder) were recorded in Machakos and Embu.
- Termite functional groups in different locations were clearly separated according to county.
- Group I, II and IV occurred in high numbers during the wet season in Machakos while group I and IIf were also present in high numbers during the same season in Embu.
- Group I, IIf and IV had a positive correlation with rainfall, while group II was negatively correlated to rainfall and minimum temperature.
- Group II and IV were positively correlated to sand and silt, respectively while group IIf was negatively associated with sand.
- In both Counties, group IIf termite species were significantly abundant in natural vegetation compared to other macrohabitats.
- Group II and IV were positively correlated to sand and silt, respectively while group IIf was negatively associated with sand.
- Nestedness accounted for the observed beta diversity in maize mono crop, maize-bean intercrop and natural vegetation in Embu.

- In Machakos county, termite assemblages in natural vegetation were driven by nestedness while turnover shaped communities in maize monocrop and maize-beans intercrop macrohabitats.
- Season and macrohabitat differentially affected termite functional groups based on the level of disturbance.

7.2.3 Effect of intercropping maize with soybean, common beans and sorghum on infestation levels of termites

The experiment was conducted in Yatta sub-county in Machakos county, Eastern Kenya (1.2358° S, 37.5961° E). The region is within the arid and semi-arid lands at an elevation of 700-800 a.s.l. There were three intercrops (treatments) consisting of maize-soybean (*Glycine max*; variety Nam 1), maize-sorghum (*Sorghum bicolor*; variety SDS 3220; 'macia') and maize-bean (*Phaseolus vulgaris*; variety K31) intercrops. In addition, maize (*Zea mays*) monocrop was established as a control. Choice of intercrops was based on the crops that are commonly grown in the area.

The main results were as follows;

- In both seasons, *Macrotermes herus, M. subhyalinus, C. formosanus, O. badius, O. longignathus* and *C. ugandesis* were recorded.
- *Odontermes longignathus* was the indicator species in the maize monocrop, maize-beans and maize-soybean intercrops across the two seasons.
- *Macrotermes herus* was significantly associated with maize-beans intercrop while *M. subhyalinus* was associated with maize-monocrop.
- Maize-sorghum intercrop had the lowest number of species compared to other intercrops. The low number of these species in maize-sorghum intercrop in both seasons may explain the small percentage of lodged plants.
- In maize-beans intercrop, populations of *M. herus* and *M. subhyalinus* were significantly correlated with increased number of lodged plants. A similar observation was made in the maize monocrop and *M. subhyalinus*.

- In maize-soybean intercrop, abundance of *O. badius* was positively correlated with percentage of lodged plants.
- The lowest number of fungus-cultivators was in the maize-sorghum intercrop while soil feeders occurred in low populations.

7.2.4 Effect of *Azadirachta indica, Metarhizium anisopliae, Megaponera analis* and *Dorylus gribodoi* on mortality of *Macrotermes subhyalinus* and *Odontotermes badius*

The study was carried out in the University of Embu Botany laboratory. The treatments were *Azadirachta indica*, *Metarhizium anisopliae*, *Dorylus gribodoi*, *Megaponera analis* and Termidor EC (Fipronil 9.1%). Each treatment was replicated four times in a completely randomized design. Distilled water was used as a control. The experiments were carried out at 25±2°C and 60% relative humidity.

This study revealed that;

- Mean mortality of *O. badius* and *M. subhyalinus* varied significantly ($P<0.0001$) between different treatments.
- *Macrotermes subhyalinus* showed significantly higher mean mortality due *D. gribodoi* and Termidor (Fipronil 9.1%) compared to *M. analis* and *Azadirachta indica*.
- Mean mortality of *D. gribodoi* and *M. analis* due to the different treatments was significantly different.
- There was a significant time*treatment interaction ($P<0.0001$) in the mean mortality of *M. subhyalinus*, *O. badius, D. gribodoi* and *M. analis* due to *A. indica* treatment. The mean mortality of termite and ant species was significantly higher after 1-hour exposure.
- After 15 minutes of exposure to Termidor (Fipronil 9.1%), mean mortality of *O. badius* and *M. subhyalinus* was 99.95±0.61 and 95.52±0.95, respectively.

7.3 RECOMMENDATION, IMPLICATIONS AND WAY FORWARD

This study has revealed that change in land use due to agricultural intensification can result in shifts in diversity and abundance of termite species which contribute to beneficial ecosystem functions and cause damage to plants. Management of termite species in Kenyan cropping systems should be implemented with the realization that ecosystem functions performed by termites and the damage that they cause are mutually exclusive. Therefore, there is need to design programmes that can achieve an ecological balance between the two extremes. In Kenya, maize farming systems and clearing of natural vegetation to increase agricultural production, should consider maintaining an appropriate number of termite species in the field by using cropping practices and farm management practices that do not have detrimental effects on the soil engineers. In addition, termite control strategies should be such that non-target effects on beneficial insects are minimized. Continuous studies on assessment of the long-term impact of land use change on termite species are recommended.

The study has also revealed that there are shifts in functional groups that cause crop losses which has implications for productivity in maize based agro-ecosystems in Kenya. Based on these revelations, there is need for further studies on assessment on ecological implications of disturbance on diversity and abundance of termite functional groups. However, with the increasing change of land use due to agricultural intensification in Kenya, immediate measures are required to protect soil engineers through farming practices that conserve biodiversity.

This study showed that intercropping maize and sorghum reduces termite infestation; nevertheless, there is need to further evaluate the impact of termite infestations on yield under the different cropping patterns. Furthermore, other factors that may influence the level of termite damage such as tillage, seasons, application of fertilizers, rainfall and soil properties should also be evaluated. Immediate measures such as those proposed in this study are required to control termite infestation in maize and at the same time protect the soil engineers.

This study has compared the efficacy of different bio-control agents against *O. badius* and *M. subhyalinus.* However, since the experiment was carried out under laboratory conditions, it is important to evaluate how the treatments would control termites under field conditions. In addition, further studies on effect of time on efficacy of the biological control agents and their lethal and sub-lethal effects should also be done in the laboratory. Synergism of bio-control agents should also be tested in the field and effects of these combinations on termite species and non-target organisms should also be determined.

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