1.0.1.1.1 INFLUENCE OF ORGANIC AND CONVENTIONAL FARMING PRACTICES ON WEEDS IN MURANG'A AND THARAKA-NITHI COUNTIES, KENYA

BY

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A RESEARCH THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE DEGREE OF MASTER OF ENVIRONMENTAL SCIENCE (ENVIRONMENTAL SCIENCE) IN THE SCHOOL OF AGRICULTURE AND ENVIRONMENTAL SCIENCES OF KENYATTA UNIVERSITY

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DECLARATION

Declaration by Candidate:

This work is my original work and has not been presented for a degree in any other university or any other award.

Signed: ………………………. Date: ....

Obadiah Mwangi Maina

Declaration by Supervisors:

We confirm that the work reported in this thesis was carried out by the student under our supervision.

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DEDICATION

This work is dedicated to my wife Jerusha Wangui Mwangi and my son Osteen Maina Mwangi.

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ABBREVIATIONS AND ACRONYMS

ANOVA	Analysis of variance
Conv. High	Conventional High
Conv. Low	Conventional Low
ICIPE	International Center of Insect Physiology and Ecology
IWM	Integrated weed management
K	Potassium
KALRO	Kenya Agricultural and Livestock Research Organization
KIOF	Kenya Institute of Organic Farming
LR	Long Rains
LSD	Least Significant Difference
LTE	Long Term Experiment
N	Nitrogen
Org. High	Organic High
Org. Low	Organic Low
P	Phosphorus
RCBD	Randomized Complete Block Design
SR	Short Rains
SSA	Sub-Sahara Africa

ABSTRACT

Developing nations along the equator are facing problems with amplified food requirements due to rapid population growth. Population in African is estimated to be 2.5 billion by 2050. Despite 60% of its population engaging in agriculture, production of sufficient food is still a problem as a result of deprived soil nutrient, low seed quality, infestation by pests and diseases and poor weed management practices. The goals of the research were to; i) evaluate the influence of varying N and P fertilizer application rates on weed density and diversity in conventional and organic farming systems, ii) identify species of weeds that dominate in conventional and organic farming systems and, iii) assess how weed density, dominance, and diversity are influenced by crop rotation in conventional and organic farming systems. To address these objectives, soil samples were taken between July 2017 and December 2019 in long term trial established since 2007. Trials were set in a randomized complete block design comparing conventional and organic farming at high and low inputs in Thika and Chuka sites in Kenya. For high inputs, 225kg N $ha^{-1}$and 125kg P ha^{-1}were used, and for low inputs 45kg N ha^{-1} and 26kg P ha^{-1} were used in six-cropping season. The influence of farming systems on weeds was determined in a greenhouse experiment using soil samples taken. Weed seedling emergency method was used for weed data collection. The samples were sieved using a 3mm sieve and treated with gibberellic acid to break weed seeds dormancy then placed in germination trays and placed randomly inside the greenhouse. Watering was done at moderate soil moisture to ensure weed seeds germinate. Germinated weed seedlings were counted and their species identified. The data obtained were analyzed using analysis of variance on GenStat 14th edition and means separated using least significant difference *($P \leq 0.05$)*. The outcomes indicated that farm inputs, cropping sequence and weed management practice were the key factors significantly *($P \leq 0.05$)* influencing weed density, dominance and diversity. Chuka and Thika recorded 13 and 12 weed species, respectively. Fertilizer application rates of 225kgNha^{-1} and 125kgPha^{-1} resulted to a significant *($P<0.05$)* high density of *Bidens pilosa, Amaranthus hybridus, Stellaria media* and *Galinsoga parviflora.* In the two trial sites, organic high resulted to a significant *($P<0.05$)* high weed density. Dominant weed species were *Bidens pilosa* (17.8%), *Galinsoga parviflora* (17.7%), *Schkuhria pinnata* (13.9%) and *Setaria verticillate* (13.1%) in Chuka and *Stellaria media* (23.5%), *Bidens pilosa* (23%), *Eleusine indica* (20%), and *Amaranthus hybridus* (11.9%) in Thika. Their densities were reduced under the 3-years crop rotation. Maize-cabbage rotation decreased weed density except for *Eleusine indica* and *Sonchus oleraceus* while maize-beans rotation increased density of *Eleusine indica*. Shannon diversity (*H'*) index was high in organic farming. Shannon evenness ratio in Thika and Chuka for organic high to conventional high and organic low to conventional low were (2:1 and 2:1.4), and (2:1.8 and 2:1.6), respectively. From the study result, fertility input leads to increase in weed density while integration of intercrop in a crop rotation, helped in controlling weed density.

CHAPTER ONE: INTRODUCTION

1.1 Background of the Study

Population increase in tropical developing nations has resulted in a rise in food demand, which is currently unsustainable (Rosegrant *et al*., 2002; Maja *et al*., 2021). African population is projected to double from 1.4 billion by 2050 (United Nation, 2019) of which 60% of its inhabitants depending on agriculture for their livelihood (Sibhatu, 2016). Despite, 60% of African population engaging in agriculture, producing sufficient food is still a challenge (Struik, 2017). Recently, agricultural intensification has been actively promoted in sub-Saharan Africa (SSA) as a promising strategy to increase production of food in resource constrained farming systems (Haggar *et al*., 2020). However, sub-optimal yields have been common occurrences in majority of farming systems despite the high resource investments made (Albrecht *et al*., 2016). This is highly associated with low soil productiveness, use of unimproved seed varieties, uneven distribution of rainfall, pest and diseases as well as poor weed management practices (Kisaka *et al*., 2015; Sibhatu, 2016; Mucheru-Muna *et al*., 2021; Wacal *et al.,* 2021).

Farming communities considered it worthwhile to address the low land fertility issues in tropical nations, particularly toward the end of the previous century (Bado *et al.*, 2018). To address issues of soil fertility and weed management, farming communities embraced continuous conventional practices where weed control was enhanced by use of herbicides application and usage of inorganic fertilizers to increase soil fertility (Vanlauwe *et al*., 2011; Sasson, 2018). Conventional farming practices come in with its own challenges with over dependent on these inorganic inputs, change in weed diversity and other environmental concerns (Bekunda *et al*., 2002). This resulted in some farmers restricting the application of inorganic fertilizers and herbicides and in its place embracing farming practices that are organic (Chivenge *et al*., 2009; Mugwe *et al*., 2009; Mutegi *et al*., 2012). They mainly opted to practice the use of organic fertilizers and organized rotational cropping to enhance soil fertility and weed management (Pieterse *et al*., 2019).

Organic farming, which results to better biological, chemical, physical soil property changes, has been embraced within the tropical regions (Chen *et al*., 1999; Mazzoncini *et al*., 2010; Bationo *et al*., 2012; Bolo *et al.*, 2021). Despite so, it came with weed management challenges (Tadele, 2017). In many cases, weeds still result in yield loses of up to 25% despite the control measures practiced (Zhang *et al*., 2003; Khan *et al*., 2005; Rich *et al*.,2008). Globally, weeds have been described to cause up to 40% harvest loss (Sharma *et al*., 2021). This has been attributed to weeds being ever present in the crop fields and more adaptive than many crop varieties, especially within the tropical regions (Kaur *et al*.,2018).

Intervention to enhance soil productiveness in organic and conventional cropping systems didn't only lead to increased yield but also increase in weed density, diversity and dominance (Doohan *et al*., 2010). Study by Zhu *et al.* (1998) indicated that presence of phosphorus (P) fertilizers influences weed diversity in the field while nitrogen (N) deficiency results in change of dominant weed species without decreasing weed species quantity. This was also supported by Yin *et al.* (2006) who found that *Portulaca oleracea* and *Chenopodium album* were only present in fields with high P application during the time of the research. Use of manure in organic farming has also led to importation of weed seeds into the farm thus leading to increase in weed density (Casagrande *et al*., 2016; Durán-Lara *et al.*, 2020; Liu *et al*., 2020).

Weed management practices such as over-reliance on herbicides in conventional farming systems, have led to increased weeds species that are resistant (McErlich *et al*., 2014). Over dependence on glyphosate has led to the appearance of 34 glyphosate-resistance species of weeds worldwide (Schütte *et al*., 2017). Over time, these species of weed become dominant and hard to control (Owen & Micheal, 2008; Pieterse *et al*., 2019). As a result of this, farmers have also integrated rotation practices to manage these weeds (Saulic *et al*., 2022). Research done on effectiveness of crop rotation has shown that weed density at the end of the research is always lower than that in the beginning of the rotation practice (Zhao *et al*., 2021; Maclaren *et al*., 2021; Dominschek *et al*., 2021).

Management of perennial and annual weeds is an important activity in conventional and organic farming systems (Thomsen *et al.*, 2015). Crop rotation and other weed management practices affect weed species density, diversity and dominance. For better weed management practices, it's of great importance to understand how weeds are influenced by these management practices. Therefore, proper understanding of different farming practices and their effect on weed composition is of great help in weed management.

1.2 Problem Statement

With continuous increase in global human population, production of sufficient food crops to sustain this population has become a challenge that needs to be addressed (Godfray, 2010). This has led to agricultural intensification (Van Grinsven *et al*., 2015). Despite these efforts, weeds are ever present during cropping season and compete with crops for the limited resources present making them a key threat in crop production that needs to be addressed (Pinke *et al*., 2011). Their density and diversity is highly influenced by the type of farming practices in place (Kremen *et al*., 2012; Seyyedi *et al*., 2016; Hernández-Villa *et al*., 2020).

1.3 Justification of the Study

The presence of weeds is directly influenced by the management practices which differ within the farming systems (Korre s*et al*., 2018). Applications of fertilizers and herbicides have direct impacts on weed density, diversity and dominance (Doohan *et al*., 2010; Gherekhloo *et al*., 2016; Korres *et al*., 2018). The management practices vary in conventional and organic farming systems from one region to the other (Bajwa, 2014; Tang *et al*., 2014; Edgar *et al.*, 2017). However, there is little evidence on how weeds are influenced by management practices embraced by organic and conventional growers within Highlands of Central Kenya. Therefore, a need for research to understand how organic and conventional farming systems under different management practices affect weed density, dominance and diversity in Murang'a and Tharaka-Nithi Counties is important.

1.4 Research Questions

The research endeavored to response to the following questions:

1. To what extent do different application rates of N and P fertilizer impact weed density and diversity in organic and conventional farming systems?
2. Which are the dominant weed species in organic and conventional farming systems?
3. How does crop rotation affect weed density, species dominance, and diversity in organic and conventional farming systems?

1.5 Research Objectives

Broad objective: The overarching objective of this study is to understand the influence of fertilizer application rates, crop rotation, and farming systems (organic and conventional) on weed density, diversity, and species dominance for better weed management practices.

The findings seek to address the following objectives:

1. To ascertain the impact of different N and P fertilizer application rates on weed density and diversity in organic and conventional farming systems.
2. To identify the dominant weeds in organic and conventional farming systems.
3. To determine the effects of crop rotation on weed density, species dominance, and diversity in organic and conventional farming systems.

1.6 Research Hypotheses

The research was directed by the following hypotheses:

1. Different application rates of N and P fertilizer significantly influence weed density and diversity in organic and conventional farming systems.
2. The dominant weeds significantly vary in conventional farming system and organic farming system.
3. Crop rotation significantly influences weed density, species dominance, and diversity in organic and conventional farming systems.

1.7 Significance of the Study

Study results will be used to determine the influence of organic and conventional farming systems in relation to weed density, dominance, and diversity. This will help to enlighten farmers on the best farming systems in regard to weed management. It will also help to understand weed composition in the two farming systems and the best practices that lead to reduced weed density in their farms. Results from the study will contribute to existing knowledge that can be used by researchers and other stakeholders to recommend proper weed management practices.

1.8 Conceptual Framework

The choice of farm inputs and management practices are the major factors influencing weed density, dominance and diversity in organic and conventional farming systems (Saulic *et al*., 2022) (Figure 1.1). Conventional farming practices embrace intensive use of synthetic herbicide and fertilizer while organic farming systems entail use of organic fertilizers and cultural ways to control weeds (Xia *et al*., 2019). Increased dependence on herbicides to manage weeds has resulted in herbicides resistance weeds species and disappearance of herbicide sensitive weed species (Heap, 2014). Organic farming has been promoted over conventional farming due to its less impact on the environment (Garg & Balodi. 2014). However, use of farmyard manure and biological weed control measures in organic farming

may lead to high weed density and diversity (Khan *et al*., 2016). Consequently, this study tries to establish which farming system with integrated crop rotation would result in better weed management.

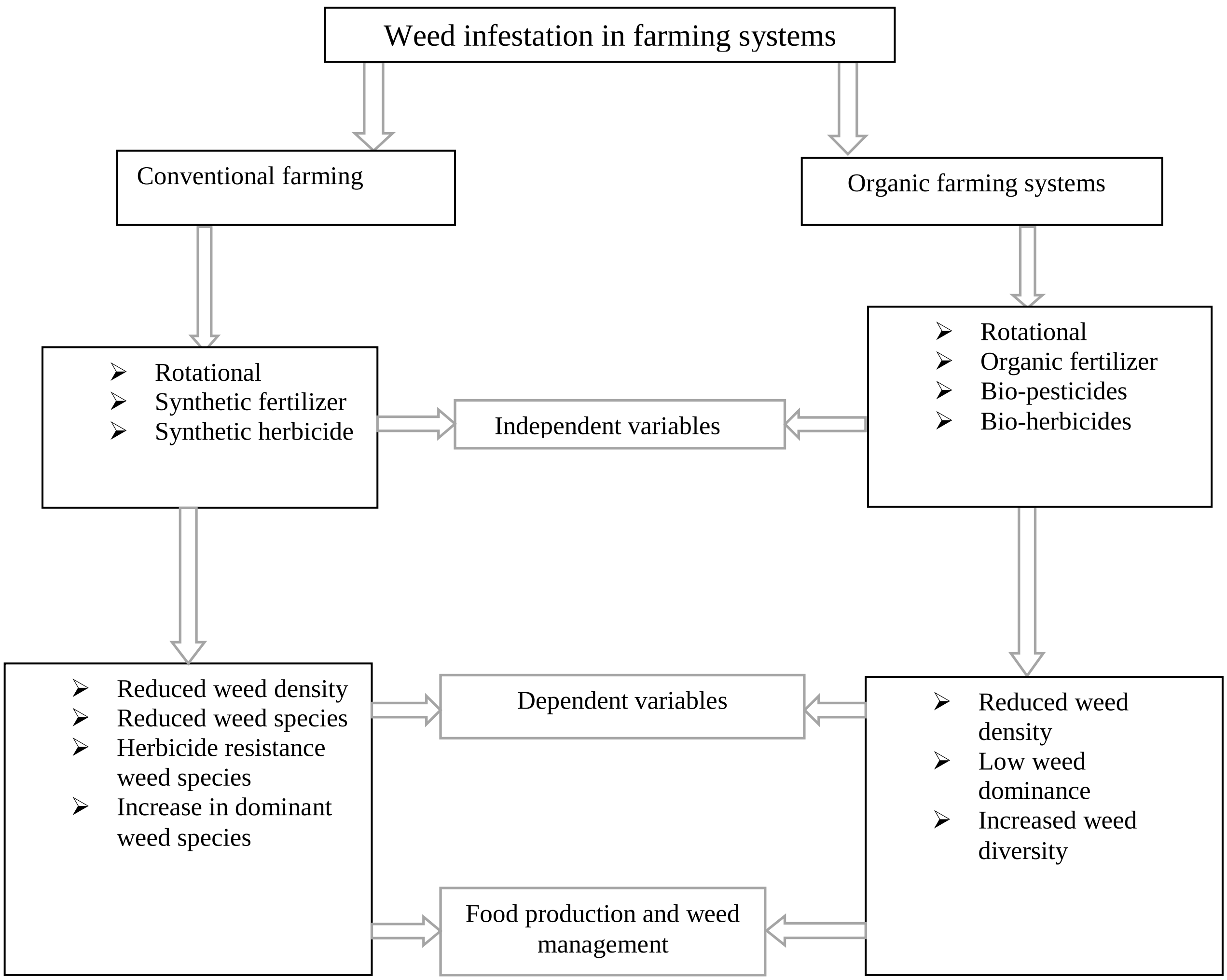

Figure 1.1 Conceptual framework showing the interaction between dependent and independent variables and intervening variables.

(Source: Obadiah, 2022)

1.9 Definition of Terms

Conventional farming: A farming practice involving reliance on synthetic fertilizer, herbicide, pesticide, intensive tillage, mono cropping system and use of machinery (Sumberg *et al*., 2022).

Organic farming: It's a farming system which is based on a chemical free management practice based on avoiding use of synthetic inputs and relying on natural substances (Seufert *et al*., 2017).

Weed: They are plants growing where they are not needed, with high growth rate and persistent, offering competition to the desired crop, causing harm and interfere with agricultural processes, leading to increased labor and costs while reducing yields (Randall, 2012).

Ecosystem: The interaction of a group or community of organisms within their physical environment (Tsujimoto *et al*., 2018).

Biological weed control: It's the utilization of the weeds natural enemies to control its density to a tolerable level (Schwarzländer *et al*., 2018).

Crop rotation: It's an exercise of cultivating diverse crops in succession within different seasons on the same land (Bullock *et al*., 1992).

Weed seed bank: It is the resting place of weed seeds existing on the soil surface and dispersed in the soil profile which act as an origin of future weed population (Kumar *et al*., 2019).

Weed density: Denotes the measure of all weed species present in a specific area (Maszura *et al*., 2018).

Weed dominance: Is the measure of abundance of a specific weed species within a community (Booth *et al*., 2003).

CHAPTER TWO: LITERATURE REVIEW

2.1 Overview

The main interest of agriculture extensification and intensification is to offer enough healthy food for the growing population (Dias*et al*., 2016). However, weeds are a major challenge in the achievement of maximum crop yields (Pinke *et al*., 2016). Losses caused by weeds have exceeded other categories of agricultural pests and diseases (Abouziena *et al*., 2016). They lower crop yield, quality, and act as alternative hosts for crop pests (Cober & Morrison, 2011). Weed seeds are the main source of newly emerging weed species in the cropland and they are reserved in the soil horizon where most of activities take place also known as the soil weed seedbank (Auškalnienė *et al*., 2018). Composition of weed seeds in this horizon is influenced by cropping systems and farming practices carried out on the fields (Kent*et al*., 2001; Hyvönen *et al*., 2002; Koocheki *et al*., 2009; Haring *et al*., 2018; Shahzad *et al*., 2021).

The competitive ability of any given weed community in the crop field is based on the density, diversity and evenness (Auffret, 2011; Oreja *et al*., 2022). Management practices applied at any given farming systems have a direct influence on weed community of which it may result to increase in weed density or elimination of some weed species thus giving chance to weed species that end ups being dominant in this farming systems (Osipitan *et al*., 2019). Management practices embraced by conventional farmers has been associated with increase of some weed species that are dominant and resistant to herbicide application as an effect of persistent use of herbicide by conventional growers (Melander *et al*., 2013). Difference in plant nutrients inputs in the two-farming system also have direct impacts on weed density (Edesi *et al*., 2012). Fertilizer applications influence weed density as well as their diversity (Cheimona *et al*., 2016).

For the weeds species to get to production stage, they must pass a series of life cycles which can be interrupted by farm management practices and interaction with the crops (Fried *et al*., 2019; MacLaren *et al*., 2019). Weed management control measures should focus on various stages in the life of weeds and minimize the likelihood of any particular weed species proliferating to a point where they pose a significant risk to agricultural output (MacLaren *et al*., 2020). Understanding the life cycle and the germination characteristic of any given weed helps in timely interjections before the weed gets noxious and hard to control (Mahaut *et al*., 2020).

Integrated weed management (IWM) is the most efficient way in long-term weed control (Mia *et al*., 2020). IWM maximizes the assortment of the condition and distress encountered by weed both within the season and between the years (Scursoni *et al*., 2019). Application of multiple weed control mechanisms on the same field within the same season is more likely to reduce weed density in a shorter period (Roslim *et al*., 2021). This is because the possibility of any given weed species being resistant to various control approaches is harder than that of a single control method (Gaines *et al*., 2021). This can be achieved through, among others, rotational cropping and intercropping as each type of crop has its own unique control practices such spacing, preparation of seedbed, fertilizer input methods and weed control methods (Khan *et al*., 2019).

Knowledge of the constituents and varieties of weed is of great importance before application of any management tool (Alonso-Ayuso *et al*., 2018; Elba *et al*., 2018). Weed composition and diversity determines the competitive ability of any given crop in the field (Carlesi *et al*., 2021). Knowledge of short-term dynamics of these weeds seeds and their subsequent populations will aid in advance weed management preparedness for a farmer (Schwartz-Lazaro *et al*., 2019).

For a sustainable weed management, knowledge is needed on the relations between weeds and the management practices, influence of the environment, in both short and long terms in order to achieve a sustainable productivity within a diverse farming system (Bàrberi, 2002; Ward *et al*., 2014). Understanding how conventional and organic farming practices influence weed density, dominance and diversity can greatly help in the overall weed management strategies (Kumar *et al.*, 2019).

2.2 Crop-Weeds Competition

Increased weed density has a direct correlation on crop yield decrease; this is a result of weeds competing with crops (Smith *et al*., 2010). The amount yield loss in crop and quality loss is affected by various factors including weed density relative to crop, duration of weed presence, population of the crop and variety (Swanton *et al*., 2015). Increasing crop population helps to reduce yield loss caused by weeds as they are able to limit the space occupied by the weeds (Tamene *et al*., 2016; Dass *et al*., 2017). This can be realized by increasing plant population and using planting methods that maximize every available space, such as reduced inter-row spacing (Bajwa *et al*., 2017). For example, Wilson *et al.* (1995) observed that, increase in wheat population resulted in reduced weed density. Moreover, increase in weed density has been reported to cause a significate decrease on plant height especially in rice and wheat (Korav *et al.*, 2018).

A diverse weed community may have less effect on crop yield compared to that with just a few species of weed (MacLaren *et al*., 2020). Adeux *et al*. (2019) in a long-term experiment of cropping system indicated that a weed community which is more diverse resulted in reduced yield loss. A diverse weed community is less aggressive within a certain crop (Blaix *et al*., 2018; MacLaren *et al*., 2020). For instance, Storkey & Neve (2018) reported a decline in wheat produce loss from 60 to 30% when weed species increased from seven to twenty species. Adeux *et al.* (2019b) indicated that weed communities with many species resulted to reduced loss of cereal produce and that of the 6 weed species studied, 2 showed no significant yield loss and that reduced weed diversity was highly linked to increased yield loss more that weed density increase.

Moreso, a community of weed which is more diverse provide benefits in endorsing larger biodiversity at other trophic echelons (Marshall *et al*., 2016; Bàrberi *et al.*, 2010), which by chance may help in regulating weed density (Bohan *et al*., 2011; Petit *et al.*, 2018) along with the numbers of pest (Gurr *et al.*, 2003; Landis *et al*., 2005). Weeds offer a variety of bionetwork services which are beneficial to crops and ecology (Blaix *et al*., 2018), which are only available in diverse weed community (Isbell *et al*., 2017). This has been exhibited by pollinators: weed diversity can intensify bee health, diversity, and their input to crop yields (Bretagnolle & Gaba, 2015). Thus, higher weed diversity as it is the case of organic farms is of great benefit in crop production.

2.3 Soil Fertility Effect on Weed Abundance and Diversity

Soil fertility reflect the ability of soils to provide essential nutrients for crop production drawing both from its own reserves and external applications (Gianquinto *et al*., 2013). Application of fertilizer changes soil fertility, which impacts crop growth and weed density and species composition on the farm (O'Donovan *et al*., 1997). The type of fertilizer differs between organic and conventional farming systems (Araújo *et al*., 2008) which also influences weed species distribution (Kordbacheh *et al*., 2023). Inorganic fertilizer releases nutrient faster than inorganic fertilizer which affect nutrient uptake by crop and weeds as well as weed composition (Cordeau *et al*., 2021). The rate and the type of fertilizer influences different weed species differently as different species have different demand for various nutrients (Baker *et al*., 2018). Some weed species thrive well under high soil fertility e.g., *Amaranthus hybridus*, *Bidens pilosa*, *Galinsoga parviflora* and *Commelina benghalensis* which are used by farmers in Chuka as major indicators of soil fertility (Mairura et al., 2007). This shows that high fertilizer application rates enable the weed species to grow faster and produce more seeds (Desbiez et al., 2004). Other weed species such as *Portulaca oleracea*, *Tagetes minuta* and *Schkuhria pinnata* are associated with low soil fertility (Mairura et al., 2007; Handa et al., 2012).

The influence of fertilizer utilization on weed competing with crops is influenced by point of application method, time of application, amount used, and the kind of nutrient supplied (Vencill *et al*., 2012). Placement method of the fertilizer i.e., banding, or broadcast application methods is also a major factor when it comes to weed management (Bajwa *et al*., 2015). Strategic nutrient placement, such as banding, results to reduced density of weeds by 50% compared to broadcast placement method (O'Donovan *et al*., 2007). For weed control, many studies support band application for organic or inorganic fertilizers compared to broadcast methods (Petersen, 2003; Santos *et al*., 2004). Also, application of fertilizer when weed control is ineffective, stimulates high weed density resulting to low yield to a point where the yield is much lower than where low level of fertilizer was applied (Blackshaw *et al*., 2008). Thus, before fertilizer application, the field should be kept free from weed and the right method of application should be encouraged (Sweeney *et al*., 2008).

Increased fertilizer application rates in agricultural farms led to an increase in weed dominance especially for species that are able to respond and become competitive under high fertility conditions (Kaur *et al*., 2018). Nitrogenous fertilizer supplies crucial macro-nutrient, nitrogen (N) used to enhance crop produce, despite so, weed composition and aggressive ability is highly influenced by changes of N levels in the soil (Guerra & Steenwerth, 2012). For instance, the additional of high nitrogen fertilizers can promote germination of some weed seed species such as *Chenopodium album* L., *Amaranthus powellii* and *Amaranthus retroflexus* L. (Hossain & Begum, 2015). Weeds compete with crops for the available N limiting its availability to crops (Swanton *et al*., 2015). Moreover, Sweeney *et al*. (2008) stated that additional nitrogen resulted in increased weed biomass, whereas Berner *et al.* (2008) indicated that slow nitrogen release by farmyard manure tends to profit weeds more than crops that demand nitrogen at an early stage. Thus, nutrient management, especially N, is important for a successful weed management plan.

Application of fertilizers with high phosphorus (P) and potassium (K) also do influence weed species composition significantly, research by Chand *et al*. (2014), showed that *Cyperus rotundus* becomes dominant in agricultural filed where there is high application of P and K fertilizers. Little *et al*. (2022) indicated that *Datura stramonium* and *Desmodium tortuosum* density increase significantly with increase in application of P and K while *Stellaria media* was the most responsive to P and *Poa annua* showed great response to K application (Blackshaw *et al*., 2009). Experiment by Jiang *et al*. (2018) showed that the weed density of *Mazus japonicas* and *Alepocurus aequalis Sobol* had a significant increase with increase in P fertilizer application rates while, *Conyza Canadensis* substantially diminished. In a long-term experiment of 47 years, Bank *et al*. (1976) found that use of P fertilizer favored the growth *Amaranthus* weeds and that weeds that are broadleaf failed to flourish well in plots getting balanced fertilizer treatments. Another experiment by Grant *et al*. (2007) with comparable application rates of K to a separate group of 19 weed species showed that 7 species increased in their biomass under high K, particularly, *Lamium amplexicaule* (L.) and *Bassia scoparia* (L.).

Change of nutrient in the soil due to fertilizer application determines the type of weed species available (Kaur *et al*., 2018). Therefore, application of fertilizer can lead to intra- and inter-species competition of weeds in the farmland while possibly growing the competitive ability of crop plants to the weeds (Jiang *et al*., 2018). Suding *et al.* (2004) indicated that low N availability in the soil enhances the intraspecies competition of weeds, whereas P has significant impact on the interspecies contention. Weed density and diversity is enhanced in fields where there is high application of P and K, while deficiency of the same in the soil hinders the growth of some weed species (Kristensen *et al*., 2008).

Compost manure from animal and plant residues is the major source of soil nutrient used by organic farmers (Brust, 2019). Preparations of compost manure require skills and understanding to prevent it serving as a vector for weed seeds (Epelde *et al*., 2018). Many growers' luck this this skill thus, end up using immature compost and fresh animal manure which leading to additional weeds seeds into their farm (Casagrande *et al*., 2016; Durán-Lara *et al*., 2020; Liu *et al*., 2020). For instance, cattle manure in its raw form may harbor viable weed seeds, which can potentially spread a weed infestation beyond its initial location on the farm and in cases where the manure is sourced externally, it can also introduce a new weed problem that was previously non-existent (Ronge *et al*., 2020). For organic farmers to use compost manure they require skills in how they have to prepare and handle it. This helps to eliminate weed seeds and other diseases and pathogenic vectors as a result of decomposition process where microbial produces heat during respiration and exposure to a range of biochemical (Saulic *et al*., 2020).

2.4 Organic Farming Practices and Weeds Management

Organic farming aims at crop production when enhancing environmental conservation and biodiversity preservation (Hole *et al*., 2005; Fuller *et al*., 2005). The Research Institute of Organic Agriculture (FIBL, 2007) indicated that there are 179 countries practicing organic farming in the world (Willer *et al*., 2017). Organic farming is highly practiced in Asia 36%, followed by Africa 29% and Europe 17% (Chebet, 2021). Most of the organic farmers are small holders. Their main challenge is in weed management particularly in SSA which lies in the tropical region and weeds are present throughout the year (Soti *et al*., 2020). This makes it hard to fully control weeds without necessarily using herbicides (Liebman *et al*., 2009).

Organic growers use crop rotation, cover cropping and intercropping as some of the weed management practices. However, their implementation requires use of knowledge on weed life cycle to target the most sensitive stage and disrupt it (Gallandt, 2014). A well-planned crop rotation with use of diversified crop species can help in controlling certain weeds, particularly weeds that are associated with certain types of crops (Davis *et al*., 2012).

2.4.1 Crop Rotation as a Weed Management Tool

Organic farmers often use crop rotation to enhance soil fertility and economic diversity as well as a weed management method (Liebman *et al.,* 1997). Crop rotation entails use of varying crop species at different times on the same field (Weisberger *et al*., 2019; Tiwari *et al*., 2021). Different types of crop species with varying planting times and management help to interrupt the growth patterns of weed species and prevent dominance of some specific weed species (Storkey *et al*., 2021; Saulic *et al*., 2022). Research done on effectiveness of crop rotation has shown that weed density at the end of the research is always lower than that in the beginning of the rotation practice (Dominschek *et al*., 2021; MacLaren *et al*., 2021; Zhao *et al*., 2021). Weisberger *et al.* (2019) reported that diverse crop rotations can lead to weed density decrease of up to 49% compared to continuous cropping. Having a crop which is highly vegetative such as potatoes before a crop that has low capacity to contest with weeds, the vegetative crop helps to reduces weed density (Hunjan *et al*., 2020). Blackshaw (1994) found that *Bromus tectorum* (L.) density stayed moderately steady when winter wheat (*Triticum aestivum L.*) was interchanged with oilseed rapes (*Brassica napus L.*), but in a continuous wheat cropping its density increase rapidly. Berbeć *et al*. (2020) found that weed density of *Amaranthus hybridus* L. and *Chenopodium album* L. prior corn was typically lower ensuing the hay years of the 4-year rotation.

Despite so, understanding interactions between various types of crops used during rotation and their ability to prevent weed establishment or seed production is of great importance for effective weeds control (Schwartz-Lazaro *et al.,* 2019). Thus, for better weed control through crop rotation it's important to familiarize with factors such as crop type, inter-row spacing, type of fertilizer used as well as cropping season that influences weed density, dominance and diversity (De mol *et al.,* 2015). For successful weed suppression, a well-designed crop rotation and mostly the sequence in which they have to follow is of great importance (Anderson, 2005; Gallandt, 2014). Having crops with different life cycles during the rotational practices can help in disrupting weed associated with certain agricultural conditions (Leon & Wright, 2018; Storkey *et al*., 2021). Use of diversified crop species helps in controlling certain weeds from dominating crop field particularly weeds that are associated with certain crops species (Davis *et al*., 2012). Moreover, evaluation of crop rotation should be done regularly to determine if problematic weeds are surviving crop rotation schemes and come up with new adjustments for effective management.

2.4.2 Use of Intercropping in Weed Management

Intercropping entails having more than two crops growing together and at the same period where the growth of one crop doesn't interfere with other crop growth (Liebman *et al*., 2009; Maitra *et al*., 2021). Intercropping help to increase diversity in the cropping system and enhance resources use such as sunlight, available nutrients and soil water as well as reducing the chances of uncovered space in the farm that give room to emerging weeds (Bahadur *et al*., 2015; Ranaivoson *et al*., 2017; Elsalahy *et al*., 2019). This has been utilized as a weed management tool in organic farming systems (Sharma *et al*., 2021). For better weed control in intercropping, the following factors have to be considered, plants composition, varieties, and density (Koocheki *et al*., 2017; Koocheki *et al.*, 2019). For instance, Abraham & Singh (1984) indicated that a grain sorghum (*Sorghum bicolor (L.*) intercropped with forage cowpea (*Vigna unguiculata (L.)* had lower weed densities and less weed dry matter likened with sole-cropped sorghum. Also, intercropping maize and bean has been noted to reduce soil weed seedbank of some weed species such as *Amaranthus ssp*, *Cyperus ssp* and *Cammelina ssp* while favoring weed species such as bindweed (*Convolvulus arvensis*) and *Datura stramonium* when compared with monocropping (Muthamia *et al*., 2002; D'Amico-Damião *et al*., 2021).

2.4.3 Use of Mulching in Weed Management

Mulching helps to control weed by inhibiting emergency of weed seeds or by stunting the growing seedlings that have already sprouted (Patil *et al*., 2013; Mechergui *et al*., 2021). Mulching inhibits weed by blocking their access to light and forming a physical barrier that obstructs their emergence. Moreso, some organic mulches do have allelopathic effect (Farooq *et al*., 2020). There are different types of mulching materials majorly from organic matter and inorganic matter; choice of the mulching material depends on its availability and cost of the resources (Kader *et al*., 2017; Yang *et al*., 2017). Utilization of black or white polyethylene sheets as mulch after one hand weeding was found to control 98% of weeds (Abouziena *et al*., 2016). The usage of residues from crops as a mulch helps to create micro-environments that offer shelter to animals and insects that feed on the weed seeds (Hossain *et al*., 2015). Rye mulch excellently managed the weeds owing to its allelopathic effect while some of the organic mulching materials produced phytotoxic compounds which prevent weed seeds from germinating (Narwal, 2010).

2.4.4 Use of Cover Crop in Weed Management

Organic farmers used cover crops for several benefits which includes soil protection against erosion, improving soil structure, enhancement of soil fertility and as a weed management tool (Wayman *et al*., 2017; Osipitan *et al*., 2018). Cover crops are vigorous growing plants that establish and cover the soil surface before the weeds emerge (Ingels *et al*., 1994; Tiwari *et al*., 2021). Their effectiveness mostly relies on the species of the cover crop used, its supervision and the targeted weed composition (Sharma *et al*., 2018). A cover crop helps to control weed through, prevention of weed seed emergency by hindering them from direct sunlight, out competing weeds in nutrient uptake, soil moisture and partly through allelopathic effects (Soti & Racelis. 2020; Mennan *et al*., 2020). Research by Schipanski *et al*. (2014) noticed that a cover crop of red clover planted prior to maize and soyabean, reduced weed by an average 24% comparative to the no crop cover. Boydston & Hang (1995) elucidates that remains of *Brassica napus* integrated into field prior to planting potatoes suppressed weed density by 85% and lowered weed biomass by 96%.

Some cover crops such as barley, grain sorghum, wheat, oats and Sudan grass can be used to manage broad leaf weed species as a result of their allelopathic effect (Narwal, 2010; Hesammi *et al*., 2014). For this reason, organic farmers who have this knowledge opts to do a continuous cropping of rye for several seasons if weeds have presented a persistent problem in the past. However, highest allelopathic effects has been recorded on cover crops such as *Fagopyrum esculentum*, *Avena strigosa* and *Raphanus sativus* of up to 28% with the best target weed species being *Stellaria media* which is highly affected by the allelopathic chemical produced by cover crops (Dhima *et al*., 2006; Kunz *et al*., 2016; Sturm *et al*., 2018).

2.4.5 Hand and Mechanical Weeding

This involves use of hand tools in weed management as well as pulling weeds using hands physically (Bond & Grundy, 2001). Hand weeding remains the most effective and basic means of weed management within small holder organic farmers who lack suitable equipment and machines due to their high initial investment cost (Bond *et al*., 2001; Guto *et al*., 2012; Gallandt, 2014). Despite being effective, it is also labor intensive and time consuming (Bàrberi *et al*., 2002; Ronald *et al*., 2011). Also, identifying crops from weed is a bit challenging and particularly to some weed species that resembles crop, to add on to this, crop damage is at this stage is an often occurrences even to a skilled casuals (Hussain *et al*., 2015). For large scale farming systems, farmers need weeding equipment's that can work on a large space within a short period with optimal weed control (Rask & Kristoffersen. 2007). This has led to innovations in weeding mechanization using harrowing, torsion finger weeder and compressed air weeding in some European countries (Van Der Weide *et al*., 2008).

2.4.6 Tillage as a Weed Management Method

Tillage is the most popular weed management practice done by organic farmers (Baker *et al*., 2015). The use of different tillage equipment influences soil weed seedbank size and composition (Barberi, *et al*., 2001). Different equipment leaves weed seed at different depths and at different distribution within the soil profile (Hosseini *et al*., 2014). This may affect weed emergencies in different seasons and their population within the field (Travlos *et al*., 2020). Chauhan (2018) noted that weed seeds buried at 1cm depth emergency was 82% but the weed emergency decreased to 59% at a depth of 3cm. Young & Cousens (1999) found seed germination of common sowthistle (*Sonchus oleraceus* L.) was highest at a depth of 0 to1cm and at a depth of 5 and 10 cm no seed germinated. Weed seed germination may be enhanced through tillage whereby seed buried deep are brough near the soil surface, increase soil aeration and temperature as well as removal of plant cover that was hindering germination (Chauhan *et al*., 2006; Kells & Meggitt,2018).

2.5 Conventional Farming and Weed Management

Conventional farming refers to a farming system characterized by high technological innovations with the utilization of inorganic fertilizers, pesticides, herbicides, and intensive tillage (Frison, 2016). Increased human population growth has triggered agricultural intensification during the last few decades leading to high applications of agrochemicals to meet growing food demands (Majeed, 2018).

2.5.1 Use of Herbicide to Control Weed

In conventional farming, weed management is a key component if maximum yield and profit are to be realized (McErlich *et al*., 2014). With the innovation of herbicide in the early 1940s (Spark *et al*., 2021), conventional farmers realized that with the use of herbicide weeds can be controled within a short duration of time and with a higher effectiveness compared to cultivation (Khan *et al*., 2015). This resulted to conventional farmers highly depending upon herbicides when it come to weed managemnets (Magani, 2011). Inter-row weed control, which was always difficult and expensive to control using mechanical methods become easier with the application of selective herbicide (Van Der Weide *et al*., 2008).

Conventional growers have been using herbicide such as 2,4-dichlorophenoxyacetic acid (2,4-D) to control broadleaf weed in corn, wheat, rice, and other grass crops farms while, nonselective weed control herbicide such as Glyphosate allowed them to control weeds without pre plant tillage (Ito *et al*., 2007; Nakka *et al*., 2019).With the use of herbicide, farmers has been in a position to control weed within short duration, reduced cost and time used for cultivation and erosion of soil associated with soil disturbances during weeding (Green, 2012; Bonny, 2016).

High dependance on herbicides by conventional growers has reduced farmers knowledge on other weed management practices that are accepted in producing organic crops (McErlich *et al*., 2014; Barzman *et al*., 2015). In most cases, conventional grower will always look for more advanced herbicide to use whenever a new weed challenge emerges rather than evaluating other cultural practices that can help manage the weeds (Armengot *et al*.,2013). Weed management cannot rely only on one method for successive weed control, rather a integration of different weed control tactics is required to avoid weed getting adapted and being able to survive regardless of the management practice (Green, 2012; McErlich *et al.,* 2014). Although herbicides came in with many benefits, there are also challenges associated with their use which include, loss of genetic diversity, issues related to health, emergency of weed species that are resistance to their application, remain of their traces in the soil and water bodies contamination (Walsh & Powles. 2014; Schütte *et al.,* 2017; Abbas *et al.,* 2018).

2.6 Gaps in Literature Review

Research on performance and factors attributed to organic versus conventional farming systems has been done in many parts of the world. In these two farming systems, weed management is a key factor when it comes to production of crops. Conventional and organic farming systems differ in terms of fertilizer application, cropping pattern and weed management that results in different weed density, dominance and diversity. Weed management in organic farming system has been a great challenge particularly with no use of herbicide. This has led to high weed density being associated with organic growers despite the control efforts. Despite weed management being effective with the use of herbicide in conventional farms, challenges of herbicide resistant weeds, environmental pollution, loss of biodiversity and consumer health has been of great concern. Thus, integrated weed management practices must be achieved for sustainable weed management practices. With this, research on best bet weed management practices within the two farming systems under different fertilizer application levels in Central Kenya is important. And the need for better understanding on the farming systems that lead to sustainable weed management practice in Murang’a and Tharaka-Nithi Counties ecological areas is still needed.

CHAPTER THREE: RESEARCH METHODOLOGY

3.1 Study Area Description

The research was undertaken in two sites located in the sub-humid areas of Central Highlands in Tharaka-Nithi (Chuka) and Murang'a (Thika) Counties. The selection of the two counties was based on past and current intensive research work relating to challenges on weed management in the two sites and their unique rainfall patterns, soil characteristics and being within the same agro-ecological zone that represent the Central Highlands of Kenya. The sites are characterized by bimodal rain seasons with long rains (LR) coming from April to June. October to December marked the short rainy season (SR). There was also a need to investigate weed challenges encountered by small-scale and large-scale farmers within the study area for better weed management recommendations.

3.1.1 Tharaka-Nithi

The study site in Chuka, Tharaka-Nithi County was located at Kiereni Primary School in Mugwe Ward. Kiereni Primary School lies between latitude 0.3229° S, and longitudes 37.6546° E 00^{o} 07' (Figure 3.1). The site is located in the semi-humid zone Upper Midland (UM2) and 1450 meters of above sea level east of Mt. Kenya slopes.

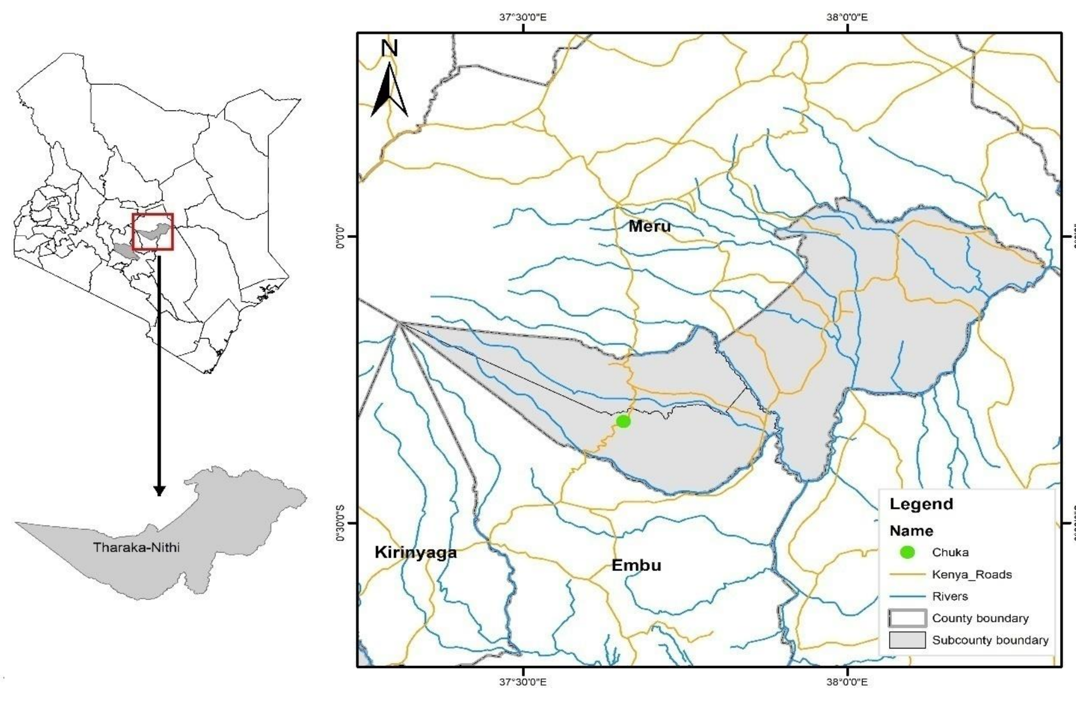

Figure 3.1. Map of Tharaka-Nithi County indicating Chuka Kiereni Primary school where the research was done. Source (Musalia *et al*., 2016).

Highlands's temperature ranges between 14°C - 30°C while lowland varies between 22°C - 36°C (Nderi *et al*., 2014). The County has a dual-mode precipitation with March-June marking the 1st cropping season and October- December the 2nd cropping season (Recha *et al*., 2012). With this kind of climatic conditions, the farmers are able to grow cash crops in the highlands such as tea and coffee and other food crops e.g sorghum, millet, green gram, cowpeas, maize, beans and pigeon peas. Temperatures within the year are about 20°C and the precipitation varies between 1500-2400mm. Soils within the area are humic nitisols originating from volcanic activities (Wagate *et al.*, 2010).

3.1.2 Murang'a County

The study was conducted at KALRO-Kandara research station near Thika in Murang'a County Gatanga ward, and 40km from Nairobi capital center. The site is located in between latitude 00° 59′ S and longitudes 37° 04′ E (Figure 3.2). The site is positioned in the semi-humid zone upper midland zone 3 (UM3) and 1548 meters above seas level.

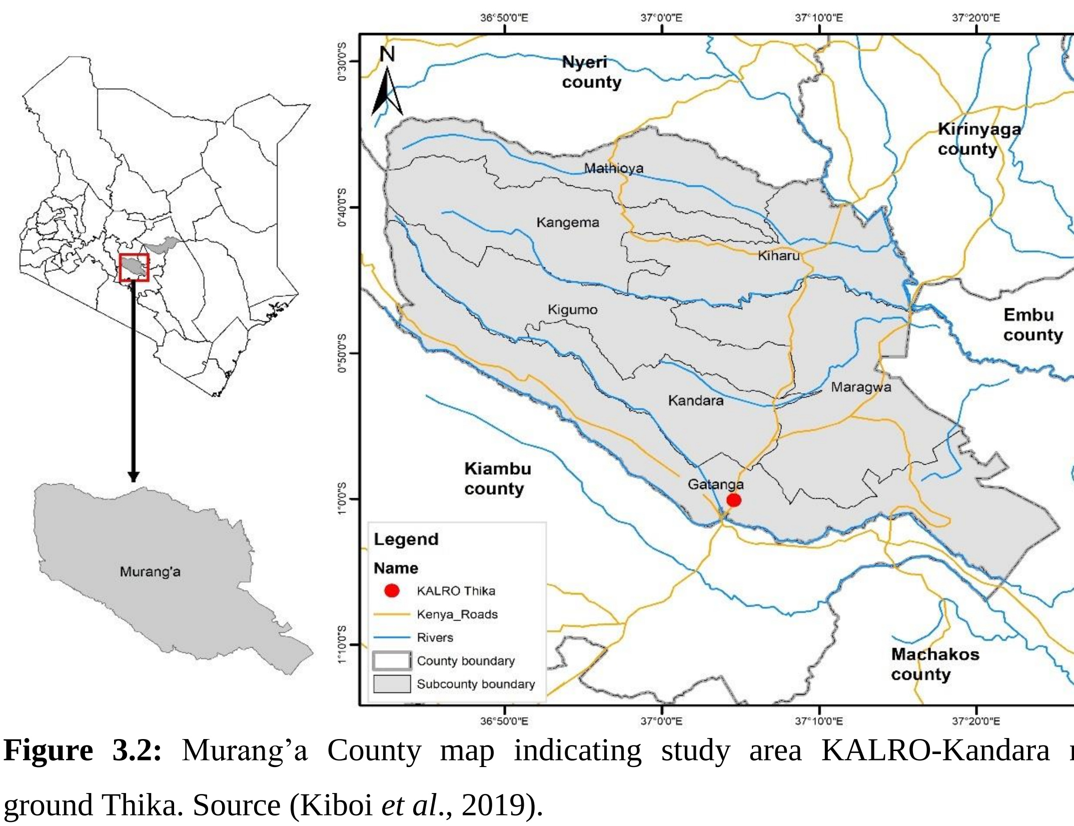

Figure 3.2: Murang'a County map indicating study area KALRO-Kandara research ground Thika. Source (Kiboi *et al*., 2019).

The area has humic nitisols type of soils, which are brown in color with good drainage and depth (Kisoro, 2015). The average yearly precipitation range between 900-1100mm. With long rains appearing from March - May and October - November short rains, marking their cropping seasons (Kirumba *et al*., 2014). Farmers in this County grow cash crops such coffee, macadamia, tea, avocado, mangoes among others. Food crops include maize, bananas, cassava, beans, millets, cassava among others.

3.2 Study Site and Experimental Design

3.2.1 Site Description and History of Chuka and Thika

The research was carried out from January 2017 - December 2019 in an ongoing existing experiment that was set up in early 2007. The aim was to evaluate the effectiveness of organic farming practices against conventional farming practices among others in terms of yield, nutrient uptake, biodiversity, pests, disease and weeds. The two systems were contrasted under two nutrients levels i.e., high and low inputs. The organic and conventional high input systems (organic high and conventional high) characterized marketable growers as the organic and conventional low input systems (organic low and conventional low) characterized small holders and with crop production for household use and local market (Table 3.2).

Table. 3.2: Long-term trials in Chuka and Thika fertility inputs

Treatments	Farm inputs application per season
Organic high	Organic fertilizer and rock-phosphate at 225kg N and 125 kg P/ ha/ year, irrigation and bio-pesticides
Organic low	Organic fertilizer at 45kg N and 26 kg P/ha/year no plant protection.
Conventional high	Artificial fertilizers at 225kg N and 125 kg P/ ha/year, irrigation, pesticides.
Conventional low	Artificial fertilizers at 45kg N and 26 kg P/ha/year, pesticides at limited rates

Bio-pesticides used; Thuricide (*Bacillus thuringiensis* v. Kurstaki neem (*Azadirachta indica*) oil extract), Dipel (*Bacillus thuringiensis* v. Kurstaki + Achook), (*Azadirachta indica*), Fungi icipe isolate 30 (*Metarhizium anisopliae*) + Delfin (*Bacillus thuringiensis*).

3.3 Experimental Design

Soil samples used for weeds examination were taken at the end of each cropping season. The trials plots from which soils were taken, were laid out in a randomized complete block design. This was duplicated four times in Chuka and in Thika five times. Trial plots measuring 8m × 8m with an inner net plot of 6m × 6m were used for data collection and management practices for the four farming practices (Figure 3.3). Each trial had two planting seasons every year and the crops planted during these seasons are as shown in Table 3.3. Crop rotation was done based on farmer's practices within the area and the crop rotational principles as recommended by Kenya Institute of Organic Farming (KIOF) (Székely, 2005).

Table 3.3: Description of crop rotation within 6-season in 3-years in Chuka and Thika

	2017		**2018**		**2019**	
TREATMENTS	LRS	SRS	LRS	SRS	LRS	SRS
Conventional high	Maize	Cabbage	Maize	Beans	Maize	Potatoes
Organic high	Maize	Cabbage	Maize	Beans	Maize	Potatoes
Conventional low	Maize	Cabbage	Maize	Beans	Maize	Potatoes
Organic low	Maize	Cabbage	Maize	Beans	Maize	Potatoes

Maize: *Zea mays L.*, Cabbage: *Brassica oleracea*., Potatoes: *Solanum tuberosum*., Beans: *Phaseolus vulgaris L*., SRS: Short rains season, LRS: Long rains season.

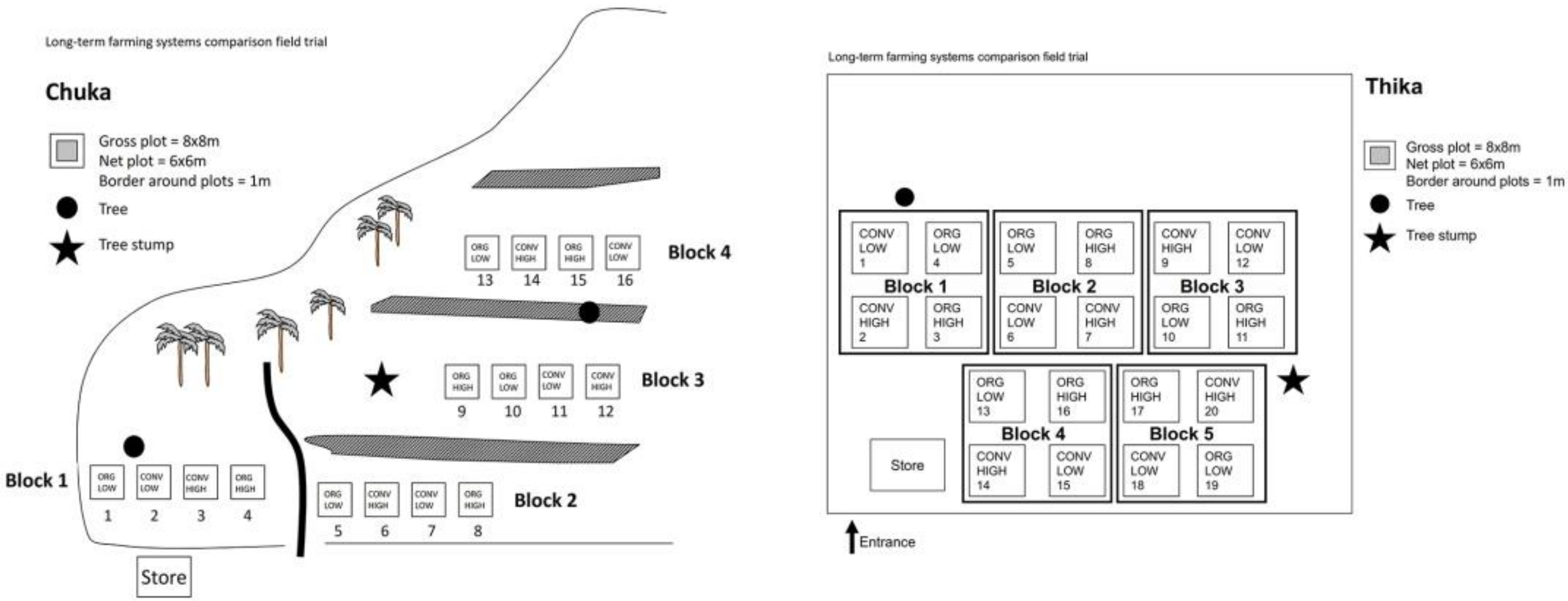

Figure 3.3: Showing the layout of Chuka and Thika long term experimental site. Source (Karanja, et al., 2020)

3.3.1 Management Practices Under the Four On-Station Long-Term Treatments

3.3.1.1 Land Preparation, Input Application, Pest and Disease Management

Land was prepared early enough before the onset of rains. This was carried out by use of hand hoe in all the four farming systems where a fine tilth was achieved. The following inputs were used in the four treatments; for conventional farming, synthetic fertilizers, herbicide and pesticide for conventional high and synthetic fertilizer and pesticides at limited rates were used for conventional low. For organic farming, organic fertilizer, rock-phosphate, and bio-pesticides were used for organic high and organic fertilizer with no plant protection were used for organic low. Supplementary irrigation (using drip irrigation at a depth of 0.3 m) was given to crops under the organic high and conventional high farming systems during periods of drought and when soil moisture was below 40% of field capacity. Soil moisture was measured using Time Domain Reflectometer (TDR, TRIME-PICO IPH, IMKO GmbH). Maize in the high input systems within the two sites received 102 mm ha^{-1} of supplementary irrigation water and cabbage 209 mm ha^{-1}. No irrigation was done on beans and potatoes at either site because there was adequate rainfall amount that was well distribution during the time, they were on seasons.

In conventional high and conventional low, Di-ammonium phosphate (DAP) was used as basal application when planting and Calcium ammonium nitrate (CAN) during top-dressing. In organic high and organic low, farmyard manure (FYM) was used at the scale of 10t ha^{-1} and 5t ha^{-1}, respectively together with rock phosphate during planting. *Tithonia diversifolia* (Tithonia) was placed as mulch two weeks after planting to supply N and also inform of liquid extract during top dressing. At every plot (8 m × 8 m) 12.5kgs of fresh Tithonia leaves were used to prepare the liquid form. The leaves were cut into small pieces then soaked into water at a ratio of 1:5 (leaf to water) inside a drum. The drum was covered and kept for 14 days to allow nutrients to dissolve. After 14 days the liquid was diluted at the ration of 1:2 (liquid Tithonia to water) and then applied as foliar to crops. This experiment intended to provide equal amount of added N and P in the high input systems (conventional high and organic high) and low input systems (conventional low and organic low (Adamtey *et al*., 2016) (Table 3.4).

Table 3.4: Fertility, pest and disease management in Thika and Chuka located in the Central Highland of Kenya

Farming system	Fertility management	N (Kg ha^{-1})	P (Kg ha^{-1})	Pest & disease management
Conventional high	Synthetic fertilizers	225	125	Synthetic pesticides
Organic high	Organic fertilizer	225	125	Bio-Pesticides
Conventional low	Synthetic fertilizers	45	26	Synthetic pesticides
Organic low	Organic fertilizer	45	26	No crop protection

Organic fertilizers [Farmyard Manure (FYM), Tithonian mulch and rock phosphate]; synthetic fertilizer; [Calcium ammonium nitrate (CAN) and Di-ammonium phosphate (DAP)]; Bio-Pesticides [Thuricide (*Bacillus thuringiensis*) and neem (*Azadirachta indica*) oil extract]; synthetic pesticides [Bulldock (Beta-cyfluthrin), Confidor, Achook and Dragnet (Permethrin)].

Pest and disease management in organic high and organic low was achieved through application of bio-pesticides i.e., Thuricide (*Bacillus thuringiensis*) and neem (*Azadirachta indica*) oil extract. In conventional high and conventional low, synthetic pesticides i.e., Bulldock (Beta-cyfluthrin), Confidor, Achook and Dragnet (Permethrin) were used to control pest while synthetic fungicide (Ridomil gold) was applied to control diseases as shown in the Table 3.4.

3.3.1.2 Planting and Weed Management Practices

Planting was done on the onset of rainfall in the two sites where two seeds per hole were planted for maize and beans with inter- and intra-row spacing of 75 cm × 25 cm and inter- and intra-row spacing of 45 cm× 15 cm, respectively. For cabbage and potatoes, one plant per hole was planted with a spacing of inter- and intra-row spacing of 60 cm × 45 cm and 70 cm × 95 cm, respectively.

After planting, pre-emergency weed control was done in the conventional plots using Governor 580SE (acetochlor 340 g/l + mesostrione 40 g/l + atrazine 200 g/l) herbicide at the rate of 12.5 ml per litre of water. After crops emergence, weeding was done using hand hoe twice in the organic plots and once in the conventional plots through the recommended husbandry (Muriuki & Quereshi, 2001). Weed assessment was aimed to be done at the end of cropping season after conducting all the management practices in the four treatments.

Drip irrigation at 30cm depth was applied to crops in organic high and conventional high farming systems when the water content in the soil was below 40% that of the field capacity. Maize in conventional high and organic high within the two sites received 102 mm ha^{-1} and cabbage 209 mm ha^{-1} of irrigation. Beans and potatoes didn't receive any irrigation at either site because there was adequate rainfall amount that was well distribution during the time they were on seasons.

3.4 Sampling

Soils samples for weed seeds analysis were taken from each plot at the end of cropping seasons from July 2017 during the LRS and ended in December 2019 during the SRS. Soils sampling was done at a depth of 0-20 cm. This was done by using Y-method (Colbarch *et al*., 2000) where four points were selected randomly from the 6m× 6m net plot. Soil samples taken from the four points were then mixed into a harmonized sample to ensure even distribution of weed seeds before obtaining one sample per replicate. The samples were then packed in a manila paper marked with the dates, plot number and the type farming system and replicate in which the sample was obtained from. The samples were transported to KALRO Kabete center laboratory where they were air-dried to achieve a constant weight and then stored at room temperature.

3.5 Sample Preparations and the Experimental Design Inside the Greenhouse

To determine the composition and the size of the soil weeds seedbank, the method used was weeds seedling emergency. This comprised counting weed seedlings germinating from the soil samples. The soil samples were prepared in alignment with this method. Before initiating germination, stones and pebbles that could hinder weed seeds germination were removed through passing the soils in a 3 mm sieve from the samples of the soil collected in the field. To ensure a high germination percentage of the weed seeds, the samples were treated with gibberellic acid at a dilution of 1000 mg/l (De Mello *et al*., 2009) to break weed seeds dormancy. After the preparations, the samples were taken into the greenhouse.

In the greenhouse, soil samples from conventional high and conventional low were used as the control for organic high and organic low farming systems, respectively. Soil samples from each of the four farming systems were spread out in the germination trays at a depth of 3 cm. The germination trays used were measuring 375 mm × 300 mm × 30 mm each. The choice of the trays was determined by the research done by Mandumbu *et al*. (2005) which indicated that weed seeds germination is highest at a depth of 2-3 cm and should not exceed 5 cm in germination trays. A depth of 3 cm gives weed seeds better chances to access light which is an important aspect during germination. The trays used were perforated to allow excess water to drain.

Experimental trays were randomly placed inside a greenhouse at KALRO Kabete Food Crop Research Institute. The controlled environment inside the greenhouse prevented weeds seed rain that could have been brought by wind to contaminate the set experiment. A total of 216 trays, (120 from Thika trial plots and 96 from Chuka trial plots), each representing one replicate were kept inside the greenhouse. Temperatures inside the greenhouse were not controlled and each tray was watered using a spray bottle with 300 ml of water on each day to sustain a moderate soil moisture favorable for weed seeds to germination, all the trays were exposed to equal amount light that was evenly distributed inside the greenhouse.

Counting and identification started a week after germination has taken place for some weed species that are easily identifiable at the early stages. Those that couldn’t be easily identified at the early stage were allowed to grow to a point where identification could be done by the use of their reproductive and vegetative parts i.e., leaf shape and structure, leaf formation on the stem, flower formation and their color and root types. Weed identification app (PlantNet) from google play store and guidebooks on weed and specimen vouchers deposited at KALRO Kabete laboratory were used during weed species identification. Once the weed seedling was identified, it was recorded and then uprooted from the germination trays. This process was repeated after every 5 days. The experiment was terminated when seedling emergency ceased. The sum total of all the weed seedlings that emerged from the soil samples were taken as the estimate of weed density. The total count of each species helped to ascertain weed diversity and dominance within the four farming systems.

3.6. Data Analysis

The density of the weed was calculated as the sum of all species of weed present in one meter square while the weed species density was determined by summing up all the number of plants of a specific weed species in one meter square. Equation 1 was used to evaluate density of weeds;

$$\text{Weed density}(M^{-2}) = \frac{\text{No. seedling germinated X [Bulkdensity}(kgm^{-3})] \text{ X Sampling depth}}{\text{Dry weight of the soil sample (Kg)}}$$

$D = (N * 8.56 * 20)/200$ Equation 1

In this: D: represents density of weed in m^{-2} from the depth soil sample was taken,

N: sum of weeds in each sample,

8.56: experimental site means of the bulk density (g cm^{-3}) of the soils,

20: the depth at which samples were taken (cm),

200: subsample mass (g).

Estimates of species diversity and evenness was done using Shannon's diversity index (*H'*) and Shannon's evenness as (E_H,) (Sawicka *et al*., 2020). Equations 2 and 3 were used to calculate Shannon's diversity index and Shannon's evenness index, respectively.

$H' = -\Sigma p_i * ln(p_i)$ Equation 2

Σ: indicates the summation of the weed species

ln: Natural logarithm

p_i: indicated the percentage of species *i* in the whole community.

$E_H = H / ln(S)$ Equation 3

H = Shannon's diversity index

ln(*S*)= Natural logarithm of species present.

Data on weed density, impact of N and P inputs rates and crop rotation on weeds in the farming system was subjected to analysis of variance using GenStat software 14th edition

(Payne, 2009). Mean of weed species was compare using analysis of variance (ANOVA) and separation of means using Least Significant Difference (LSD) at $P \leq 0.05$.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Influence of Different Rates of N And P on Weed Species Density in Chuka and Thika Trials

Different fertilizer application rates significantly *(P<0.05)* influenced the weed species density, where application of 225 N kg/ha and 125 P kg/ha resulted to high weed density compared to 45 N kg/ha and 26 P kg/ha. During the 2017 long rains, high application rates resulted to a significant *(P<0.05)* higher weed density in *Amaranthus hybridus*, *Bidens pilosa* and *Stellaria media* by 25.6%, 38.2% and 49.2%, respectively compared to low application rates in Thika (Table 4.1). Their density decreased significantly *(P<0.05)* from 2017 short rain season to 2019 long rain season. The densities of *Chenopodium album*, *Commelina benghalensis*, *Eleusine indica*, *Fallopia convolvulus*, *Oxalis corniculata*, *Sonchus oleraceus* and *Stellaria media* decrease (*not statistically significant*) with decrease in N and P fertilizer rates of application across the six cropping seasons in Thika (Table 4.1).

Table 4.1: Weed species density (Plants M^{-2}) as impacted by varying rates of N and P fertilizer application in Thika located in the Central Highland of Kenya

Season	N & P application rates	A.H	B.P	C.A	C.B	E.I	F.C	G.P	O.C	P.O	S.O	T.M	S.M
LR 2017	225 N & 125 P	19.5c	27.5cd	0.0a	0.0a	20.5ab	6.0b	10.5a	5.0a	0.0a	0.0a	19.5b	30.5b
	45 N & 26 P	14.5bc	17.0abcd	0.0a	0.0a	8.0ab	0.0a	4.5a	0.0a	0.0a	0.0a	0.0a	15.5ab
SR 2017	225 N & 125 P	5.5ab	31.5d	3.5a	6.0b	23.5b	0.0a	0.0a	7.0a	0.0a	5.5a	3.5a	16.5ab
	45 N & 26 P	8.0ab	5.5ab	2.0a	0.0a	13.5ab	0.0a	0.0a	1.0a	5.5a	1.5a	2.0a	11.0a
LR 2018	225 N & 125 P	5.0a	16.0abcd	0.0a	0.0a	22.5b	0.0a	0.0a	3.5a	0.0a	5.0a	00.0a	23.0ab
	45 N & 26 P	2.5a	13.5abc	0.0a	0.0a	12.5ab	2.0ab	0.0a	0.0a	2.5a	2.0a	0.0a	7.5a
SR 2018	225 N & 125 P	8.5ab	5.0ab	0.0a	0.0a	7.0ab	0.0a	0.0a	3.0a	0.0a	0.0a	2.0a	17.5b
	45 N & 26 P	3.0a	12.5abc	0.0a	0.0a	8.5ab	0.0a	4.5a	4.0a	3.5a	1.0a	1.5a	8.5a
LR 2019	225 N & 125 P	1.0a	7.0ab	3.0a	0.0a	10.0ab	0.0a	0.0a	3.0a	0.0a	3.5a	0.0a	11.0a
	45 N & 26 P	7.0ab	3.0a	1.5a	2.0ab	3.5a	0.0a	0.0a	1.5a	1.5a	1.0a	0.0a	8.5a
SR 2019	225 N & 125 P	4.5a	20.5bcd	1.0a	0.0a	4.5a	0.0a	0.0a	3.5a	0.0a	3.5a	6.0a	9.0a
	45 N & 26 P	6.0ab	4.5ab	0.0a	1.0ab	8.5ab	0.0a	0.0a	1.5a	1.5a	1.0a	0.0a	8.5a
	LSD	**9.5**	**16.9**	**4.7**	**5.7**	**17.3**	**5.6**	**10.9**	**10**	**5.7**	**7.3**	**7.3**	**7.3**
	P-value	**0.04**	**0.04**	**0.715**	**0.558**	**0.253**	**0.534**	**0.594**	**0.925**	**0.534**	**0.75**	**0.17**	**0.003**

225 kg N ha^{-1} and 125 kg P ha^{-1} represent; Conv. High and Org. High and 45 kg N ha^{-1}and 26 kg P ha^{-1} represent; Conv. Low and Org. low. A.H-*Amaranthus hybridus*; B.P-*Bidens pilosa*; C.A-*Chenopodium album*; C.B-*Commelina benghalensis*; E.I-*Eleusine indica*; F.C-*Fallopia convolvulus*; G.P-*Galinsoga parviflora*; O.C-*Oxalis corniculata*; P.O-*Portulaca oleracea*; S.O-*Sonchus oleraceus*; T.M-*Tagetes minuta*; S.M-*Stellaria media*. *Column with means with the same letter shows no significantly difference at P<0.05.*

While in Chuka, *Amaranthus hybridus*, *Bidens pilosa* and *Galinsoga parviflora* were significantly *(P<0.05)* higher by 28.5%, 63.4% and 4.8%, respectively at the start of the experimental seasons. Their density decreased significantly *(P<0.05)* over the 2018 and 2019 cropping seasons except for *Bidens pilosa* which showed no significant difference by the end of the cropping seasons (Table 4.2). The densities of *Chenopodium album*, *Commelina benghalensis*, *Fallopia convolvulus*, *Oxalis corniculata*, *Setaria verticillata*, *Sonchus oleraceus* and *Stellaria media* decreased (*not statistically significant*) with the decrease in fertilizer application rates in Chuka within the six cropping seasons (Table 4.2). Contrary, in 2017 long rain and short rain season, the density of *Schkurihria pinnata* and *Portulaca oleracea* was higher by 38% and 42.9% during the long rains and 29.5% and 33.3% during the short rains, respectively with decrease in the application rates of N and P. The density of *Schkurihria pinnata* remained high under the low application rates in 2017 SR, 2018 LR, 2018 SR and 2019 SR. Low application rates of N and P hindered the presences of *Chenopodium album* in 2017 SR, 2018 SR, 2019 SR and 2019 LR and in *Tagete minuta* in 2017 SR, 2018 LR and 2018 SR (Table 4.2).

Table 4.2: Weed species density (Plants M^{-2}) as influenced by different rates of N and P fertilizer application in Chuka located in the Central Highland of Kenya

Seasons	N & P application rates	A.H	B.P	C.A	C.B	F.C	G.P	O.C	P.O	S.P	S.V	S.O	T.M	S.M
LR 2017	225 N & 125 P	17.5e	20.5bcd	0.0a	0.0a	0.0a	21.0e	17.0a	6.0abc	15.5bc	24.0d	11.5a	0.0a	4.5a
	45 N & 26 P	12.5cde	7.5ab	0.0a	0.0a	3.0a	20.0de	13.5a	15.0c	22.5c	10.0abc	0.0a	0.0a	0.0a
SR 2017	225 N & 125 P	0.0a	16.5abcd	1.5a	0.0a	3.5ab	16.5bcde	6.0a	1.5ab	13.5abc	16.5cd	1.5a	1.0a	0.0a
	45 N & 26 P	1.0ab	13.0abc	0.0a	4.0ab	0.0a	12.0bcd	0.0a	3.0ab	16.0bc	10.0abc	2.5a	0.0a	2.5a
LR 2018	225 N & 125 P	3.0abc	16.5abcd	0.0a	0.0a	1.5a	19.5de	5.5a	1.5ab	8.5ab	12.5abcd	2.5a	4.5a	2.5a
	45 N & 26 P	11.0bcde	10.5abc	0.0a	0.0a	7.0ab	11.0abc	13.0a	3.0ab	11.5abc	7.0abc	0.0a	0.0a	7.5a
SR 2018	225 N & 125 P	4.5abc	16.5abcd	10.5a	0.0a	10.5b	14.5bcde	10.5a	11.0bc	6.0ab	11.5abc	7.0a	2.0a	0.0a
	45 N & 26 P	0.0a	6.5a	0.0a	0.0a	0.0a	13.0bcde	4.0a	3.5ab	7.0ab	4.0a	1.0a	0.0a	9.5a
LR 2019	225 N & 125 P	1.0ab	29.5d	4.0a	0.0a	0.0a	17.5cde	2.0a	0.0a	13.0abc	4.5ab	1.0a	1.0a	1.5a
	45 N & 26 P	4.0abc	7.5ab	0.0a	1.5a	0.0a	3.5a	6.5a	0.0a	8.0ab	5.0abc	0.0a	0.0a	0.0a
SR 2019	225 N & 125 P	6.0abcd	23.0cd	11.5a	16.0b	0.0a	14.0bcde	3.0a	2.0ab	4.0a	16.0bcd	6.5a	0.0a	5.5a
	45 N & 26 P	16.0de	4.50a	0.0a	0.0a	0.0a	9.0ab	6.0a	1.0ab	8.5ab	6.0abc	2.0a	0.0a	0.0a

LSD	**10.9**	**13.6**	**14.6**	**14.3**	**7.4**	**8.5**	**17.2**	**10.5**	**11.2**	**11.8**	**13.7**	**4.6**	**10.9**
P-value	**0.029**	**0.039**	**0.62**	**0.499**	**0.118**	**0.023**	**0.597**	**0.116**	**0.117**	**0.071**	**0.77**	**0.061**	**0.594**

225 kg N ha^{-1} and 125 kg P ha^{-1} denotes; Conv. High and Org. High and 45 kg N $ha^{-1}$and 26 kg P ha^{-1} represent; Conv. Low and Org. low. A.H-*Amaranthus hybridus*; B.P-*Bidens pilosa*; C.A-*Chenopodium album*; C.B-*Commelina benghalensis*; F.C-*Fallopia convolvulus*; G.P-*Galinsoga parviflora*; O.C-*Oxalis corniculata*; P.O-*Portulaca oleracea*; S.P-*Schkuhria pinnata*; S.V-*Setaria verticillata*; S.O-*Sonchus oleraceus*; T.M-*Tagetes minuta*; S.M-*Stellaria media*. *Column with means with the same letter shows no significantly difference at $P<0.05$.*

Different application rates of fertilizer significantly *(P<0.05)* influenced the density of *Bidens pilosa, Amaranthus hybridus* and *Stellaria media* in Thika and *Amaranthus hybridus*, *Bidens pilosa* and *Galinsoga parviflora* in Chuka. Fertilizer application and especially N and P alter soil fertility, which affects not only the crop growth but also the diversity of the associated weed species (Guerra & Steenwerth. 2012). The effect of fertilizer on weed density and diversity is also influenced by the rates of application and the nutrient composition of the fertilizer (Blackshaw *et al*., 2009).

Fertilizer application rates of 225 N and 125 P kg/ha resulted to a significant *(P<0.05)* higher weed density of *Amaranthus hybridus* (25.6%), *Bidens pilosa* (38.2%) and *Stellaria media* (49.2%) in Thika and *Amaranthus hybridus* (28.5%), *Bidens pilosa* (63.4%) and *Galinsoga parviflora* (4.8%) in Chuka compared to application of 45 N and 26 P kg/ha. This shows that high fertilizer application rates enable these weed species to grow faster and produce more seeds (Desbiez *et al*., 2004). These weed species are associated with areas with high fertile soils and thus used as indicators of well fertile soils (Desbiez *et al*., 2004). Mairura *et al*. (2007) stated that *Amaranthus hybridus*, *Bidens pilosa*, *Galinsoga parviflora* and *Commelina benghalensis* are used by farmers as the major indicators of high soil fertility.

The densities of *Portulaca oleracea* and *Schkuhria pinnata* increased in 2017 by 38% and 42.9% during the long rains and 29.5% and 33.3% during the short rains, respectively (*not statistically significant*) with decrease in fertilizer application rates. Although the majority of weed species increased with increase in application rates of fertilizer, high fertilizer application rates hindered their growth and seed production (Banks *et al*., 1976; DeBels *et al*., 2012). Soil fertility is crucial in determining the diversity and density of weed species (Baker *et al*., 2018). These is a firmed by Yin *et al*. (2006) who noted that increased N fertilizer inputs rates resulted to a decrease in density of *Portulaca oleracea* which also was supported by Mohammed *et al*. (2019) who noticed that high dosage of nitrogenous fertilizer reduced its growth and hindered its germination. Research by Mairura *et al*. (2007) found that *Schkuhria pinnata* do well in low fertility soil and its presence in the farm is used as an indicator of low soil fertility. Disagreeing results were obtained by El-Sherbeny *et al*. (2015) who indicated that *Portulaca oleracea* produces more branches with increase in the application rates of NPK fertilizers.

Differences in input rates of N and P fertilizer influenced the availability of *Chenopodium album*, *Tagetes minuta* and *Fallopia convolvulus*. This weed species were only present in treatments with fertilizer rates of 225 N kg/ha and 125 P kg/ha and absent in treatments were rates were 45 N kg/ha and 26 P kg/ha. Research by Yin *et al*. (2006) demonstrated that weed diversity is subjected to the availability of specific fertility elements in the soil where N and P plays a major role. N deficiency in the soil does affect the germination of some weed species while deficiency of P in the soil hinders the growth of some weed species (Kristensen *et al*., 2008). This can be linked to the absence of *Chenopodium album* and *Tagetes minuta* in treatments with low N and P.

4.2 Influenced of Different Rates of Fertilizer Applications in 2017-2019 on Weed Density in the Four Farming Systems in Chuka and Thika Trials

Difference rates of fertilizer application resulted to a significant *($P<0.05$)* influence on the weed density within the six-cropping season in the four farming systems. There was high weed density at the beginning of the seasons with conventional high and organic high having the highest weed density compared to conventional low and organic low in Thika and Chuka. At the end of the first cropping season 2017 LS, weed density in conventional high, conventional low, organic high and organic low was, 194, 69, 92, and 54, respectively in Chuka and 146, 119,132 and 73, respectively in Thika (Figure 4.3)

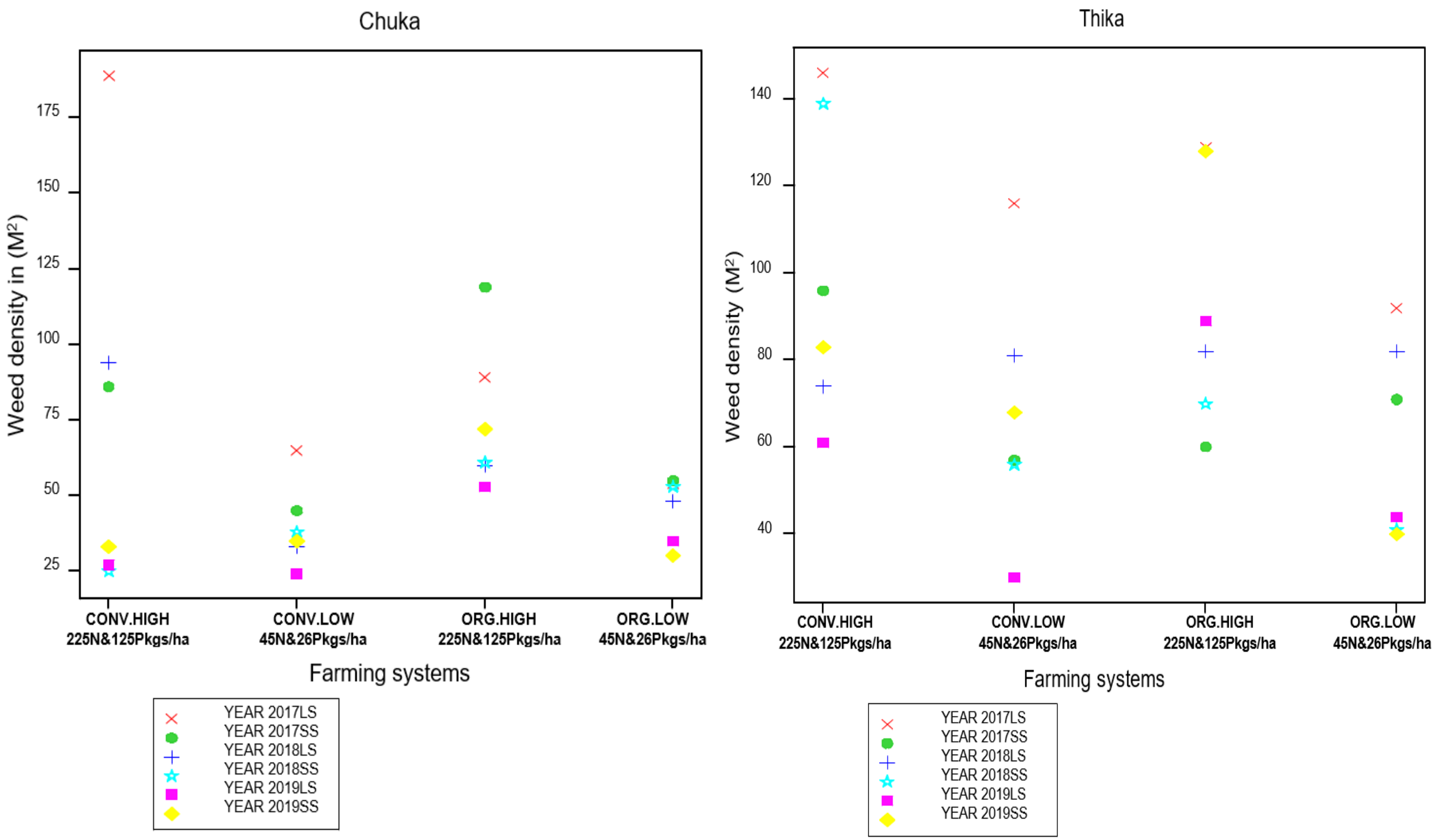

Figure 4.3: Weed densities in the four-farming system as influenced by the management practices and fertility rates in year 2017-2019 long rain seasons and short rain season at Chuka and Thika located in the Central Highland of Kenya

The density of weed decreased significantly *(P<0.05)* from 2017 long rains to 2017 short rains in organic high, organic low, conventional high and conventional low in Thika and Chuka. In Thika, weed density decrease in conventional high, conventional low, organic high and organic low by 51%, 31%, 38% and 12%, respectively while in Chuka, conventional high, conventional low, organic high and organic low decreased by 50%, 45%, 32% and 10%, respectively (Figure 4.3). Despite a continuous decrease of weed density within conventional high, conventional low and organic low from 2017 LS-2019 SS, weed density in organic high increase by 5.5% and 42.1% in Chuka and Thika, respectively by the end of cropping season in 2019 (Figure 4.3).

During the 2017 long rain season, weed density was high under conventional high and organic high farming system. This can be associated with high application of synthetic and organic fertilizer in conventional high and organic manure and rock phosphate in organic high which resulted to weed proliferation (Buhler *et al.,* 1999; Ryan *et al.,* 2009; Allan *et al.,* 2015). In additional to that, irrigation supplement during the dry seasons in the two farming systems contributed to an increase in their weed density. Research by Gholamhoseini *et al*. (2013) noted that the use of irrigation provides a favorable condition for the survival and germination of seeds of weeds (Pinke *et al.,* 2012; Hosseini *et al.,* 2014).

Weed density decrease during the 2017 short rain season in conventional high and conventional low by 51% and 31%, respectively in Thika and in Chuka by 50% and 45%, respectively. This decrease can be associated with the effect of intensive weed management by use of herbicide which is regarded as the most effective weed control methods (Graziani *et al.,* 2012; Tesfay *et al*., 2014). Despite a continuous decrease of weed density within conventional high, conventional low and organic low by the end of the 2019 short rain season, weed density increased in organic high by 5.5% and 42.1% in Chuka and Thika, respectively. This increase could be associated with high use of organic manure as well as nonuse of herbicide in this farming system. Research by Arif *et al*. (2015) indicated that addition of farmyard manure resulted to soil weed seed increase compared to inorganic fertilizers, this concurs with Cheimona *et al*. (2015) who also documented that use of composite manure led to importation of more weed seeds into the farm that resulted to weed density increase by 19% when compared to inorganic fertilizers.

4.3 Influence of Site and Fertilizer Application on Weed Species Density and Diversity During Long Rains and Short Rains in Chuka and Thika Trials

The number of weed species recorded within the two experimental sites was 14 with Thika and Chuka recording13 and 12 weed species, respectively. The combined effect of different rate of fertilizer applications and adaptability of a particular weed species to the geographical conditions where the two experiments were location affected the availability of some weed species. In this case, *Schkuhria pinnata* and *Setaria verticillata* were absent in all the trial treatments in Thika, while in Chuka, *Eleusine indica* was not recorded.

Despite the treatments within the two regions receiving the same management practices and fertilizer application rates, the density of *Galinsoga parviflora* was significantly *($P<0.001$)* higher in Chuka by 90% compared to Thika while the density of *Stellaria media* was 95% higher in Thika compared to Chuka (Table 4.3). There was also a significant *($P<0.001$)* in the density of *Galinsoga parviflora* (86%) and *Oxalis Corniculata* (80%) during the long and the short rain seasons in Chuka compared to Thika and in *Stellaria media* (96%) in Thika during long and short rain seasons compared to Chuka (Table 4.3).

Table: 4.3: Weed species and density (plants m^{-2}) variation in the year 2017-2019 long and short rains season in Thika and Chuka located in the Central Highland of Kenya

Weed Species	A.H	B.P	C.A	C.B	E.I	F.C	G.P	O.C	P.O	S.P	S.V	S.O	S.M	T.M
Thika	7.1a	13.6a	0.9a	0.8a	11.9b	0.7a	1.6a	3.0a	1.2a	0.0a	0.0a	2.0a	13.9b	2.9a
Chuka	6.4a	14.3a	2.3a	1.8a	0.0a	2.1a	14.3b	7.3a	4.0a	11.2b	10.6b	3.0a	0.7a	2.8a
LSD	**3.8**	**5.7**	**2.7**	**2.9**	**3.6**	**2.0**	**3.1**	**3.7**	**2.6**	**2.6**	**2.9**	**2.7**	**3.7**	**3.1**
P-value	**0.7**	**0.802**	**0.32**	**0.47**	**0.001**	**0.15**	**0.001**	**0.024**	**0.04**	**0.001**	**0.001**	**0.47**	**0.001**	**0.958**
Long Rain Season														
Thika	8.2a	14.0a	0.8a	0.3a	12.8a	1.3a	2.5a	2.4a	0.7a	0.0a	0.0a	1.9a	16.0a	3.5a
Chuka	8.2a	15.3a	0.7a	0.3a	0.0b	1.9a	15.4b	9.6b	4.4a	13.2b	10.5b	2.5b	0.9b	2.7b
LSD	**6.1**	**8.2**	**1.8**	**0.9**	**5.6**	**3.3**	**5.7**	**5.3**	**4.3**	**4.2**	**4.8**	**4.3**	**6.8**	**5.0**
P-value	**0.98**	**0.7**	**0.92**	**0.84**	**0.001**	**0.72**	**0.001**	**0.01**	**0.08**	**0.001**	**0.001**	**0.04**	**0.001**	**0.74**
Short Rain Season														
Thika	5.9a	13.2a	1.1a	1.2a	10.9a	0.1a	0.8a	3.3a	1.8a	0.0a	0.0a	2.1a	11.8a	2.2a
Chuka	4.6a	13.3a	3.9a	3.3a	0.0b	2.3a	13.2b	4.9a	3.5a	9.2b	10.7b	3.4a	0.5b	2.9b
LSD	**5.0**	**8.6**	**5.3**	**5.9**	**5.1**	**2.5**	**2.7**	**4.9**	**3.3**	**3.1**	**3.9**	**3.6**	**3.4**	**4.3**
P-value	**0.59**	**0. 91**	**0.28**	**0.45**	**0.001**	**0.07**	**0.001**	**0.51**	**0.28**	**0.001**	**0.001**	**0.45**	**0.001**	**0.75**

A.H-*Amaranthus hybridus*; B.P-*Bidens pilosa*; C.A-*Chenopodium album*; C.B-*Commelina benghalensis*; E.I-*Eleusine indica*; F.C-*Fallopia convolvulus*; G.P-*Galinsoga parviflora*; O.C-*Oxalis corniculata*; P.O-*Portulaca oleracea*; S.P-*Schkuhria pinnata*; S.V-

Setaria verticillata; S.O-*Sonchus oleraceus*; S.M-*Stellaria media*; T.M-*Tagetes minuta*. *Column with means having same letter shows no significant difference at P≤0.05.*

Variation on weed density and composition of species within the two fields can be associated with suitability and adaptation of particular weed species to the climate of the area (Fried *et al*., 2008; Rana *et al*., 2016). Fertilizer management practices within Chuka with the climatic condition of a place greatly favored increase of *Galinsoga parviflora* and *Oxalis Corniculata* while as *Stellaria media* was favored by the climatic conditions of Thika. Site location of a place does have great influence in the determination of composition of weed species and their density (Peters *et al*., 2014; De Mol *et al*., 2015; Mary, 2021).

4.4 Influence of Farming System on Weed Dominance in Chuka and Thika During 2017-2019 Cropping Seasons

Weed species were considered to be dominant if their density was more than 10 % of the total weed density at the end of six-cropping seasons. Out of the 14 weed species identified in Chuka and Thika, *Bidens pilosa* (20%) was the most dominant weed species in the four farming systems in Thika and Chuka. The weed species that dominated in Chuka were, *Bidens pilosa* (17.8%), *Galinsoga parviflora* (17.7%), *Schkuhria pinnata* (13.9%) and *Setaria verticillate* (13.1%) and the least dominant weed species were, *Stellaria media* (0.9%), *Commelina benghalensis* (2.2%), *Fallopia convolvulus* (2.6%) and *Chenopodium album* (2.8%) (Figure 4.4). Their density varied within the farming systems where organic high and organic low farming system resulted to high weed density (*though not statistically significant*) of the dominant weed species compared to conventional high and conventional low.

Over 2017-2019, organic low and conventional high farming systems resulted to a significant *(P<0.001)* decrease in the densities of *Galinsoga parviflora* and *Schkuhria pinnata* across all the seasons (Figure 4.4). *Bidens pilosa* was resilience to change in management practices as it increased (*not statistically significant*) under conventional high and organic low farming systems when all the other dominant weed species were decreasing (Figure 4.4).

The type of crop in season also had an influence on dominant weed species density. Maize under organic high and conventional high led to increase (*not statistically significant*) in the density of *Galinsoga parviflora* and *Bidens pilosa* (Figure 4.4). During the short rain season, in 2017 when cabbage was in season, the weed densities of *Eleusine indica* and *Bidens Pilosa* increased (*though all not statistically significant*) in organic low (Figure 4.4). During the 2018 short rains season, presence of beans led to increase (*though all not statistically significant*) in the weed density of *Galinsoga parviflora* under organic low. The presence of potatoes in 2019 short rain season resulted to an increase (*though all not statistically significant*) of *Schkuhria pinnata* and *Setaria verticillata* under conventional low (Figure 4.4).

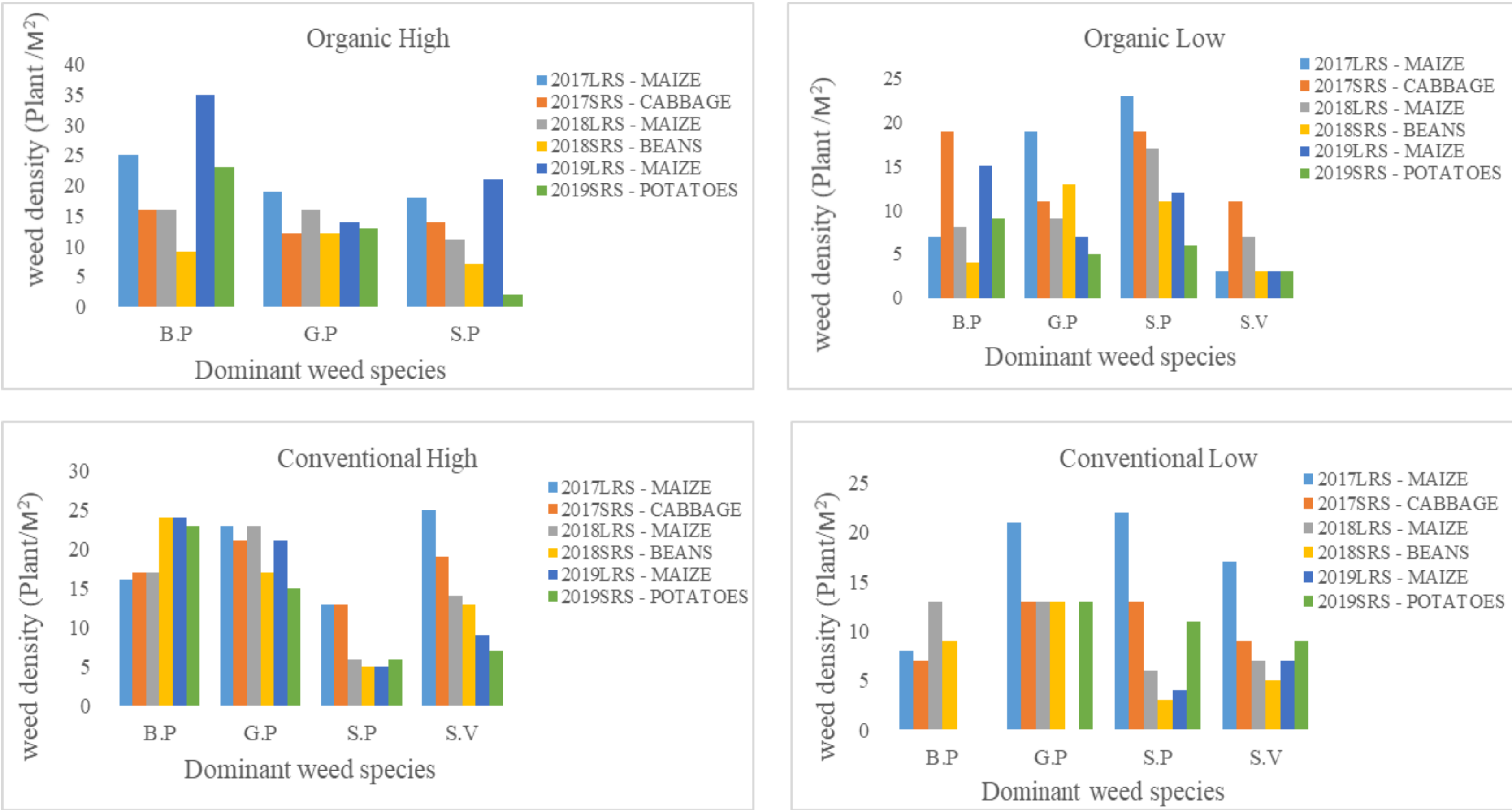

Figure 4.4: Dominant weed species within the four farming systems in 2017-2019 cropping seasons in Chuka trial site located in the Central Highland of Kenya

B.P-*Bidens pilosa*; G.P-*Galinsoga parviflora*; S.P-*Schkuhria pinnata*; S.V-*Setaria verticillata*; LRS – long rain season; SRS – short rain season

In Thika the dominant weed species were *Stellaria media* (23.5%), *Bidens pilosa* (23%), *Eleusine indica* (20%), and *Amaranthus hybridus* (11.9%) while *Fallopia convolvulus* (1.1%) *Commelina benghalensis* (1.3%) *Chenopodium album* (1.5%) *Portulaca oleracea* (2.0%) *Galinsoga parviflora* (2.7%) were the least dominant weed species (Figure 4.5). Over the year 2017-2019, organic low and conventional high farming systems resulted to a significant *(P<0.001)* decrease in the densities of *Stellaria media* under conventional high (Figure 4.5). In Thika, conventional low resulted to high density of *Amaranthus hybridus* compared to organic high and organic low (Figure 4.5). *Eleusine indica* was only dominant under conventional high and conventional low farming systems. Its density decreased under conventional high farming system but increased under conventional low farming system (Figure 4.5).

The type of crop in season also had an influence on dominant weeds species density. Maize under organic high and conventional high led to increase (*not statistically significant*) in the density of *Galinsoga parviflora* and *Bidens pilosa* (Figure 4.5). During the short rain season, in the year 2017 when cabbage was in season, the weed density of *Bidens pilosa* and S*etaria verticillata* increased (*though all not statistically significant*) in organic high farming system (Figure 4.5). In Thika *Bidens pilosa* and *Stellaria media* increased under organic low and conventional low, respectively. The presence of potatoes in 2019 short rain season resulted to an increase (*though all not statistically significant*) in the densities of *Bidens pilosa* and *Amaranthus hybridus* in organic high and organic low and *Eleusine indica*, *Amaranthus hybridus* and *Stellaria media* in conventional low (Figure 4.5).

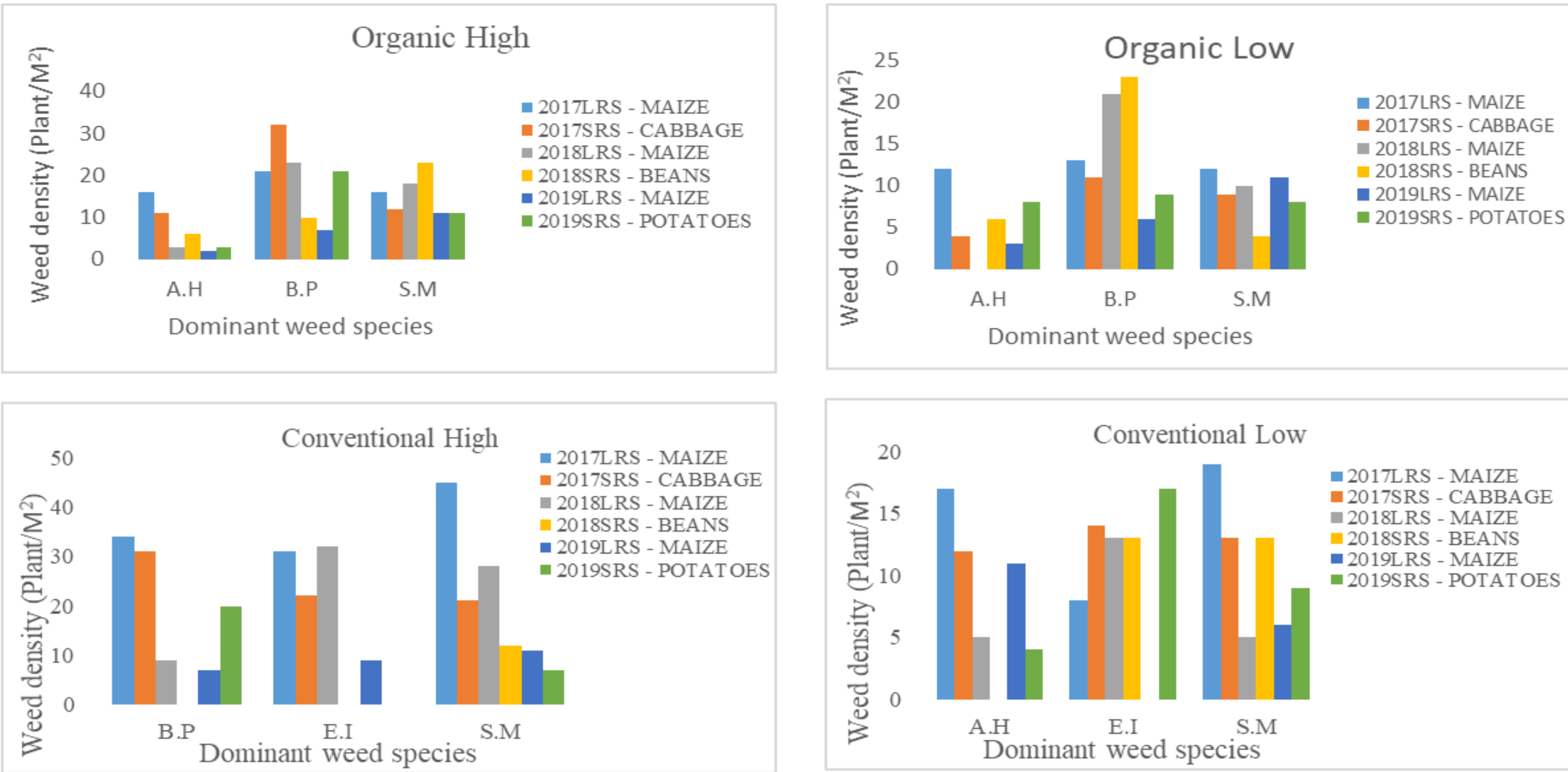

Figure 4.5: Dominant weed species within the four farming systems in 2017-2019 cropping season in Thika located in the Central Highland of Kenya

A.H-*Amaranthus hybridus*; B.P-*Bidens pilosa*; E.I-*Eleusine indica*; S.M-*Stellaria media*. LRS – long rain season; SRS – short rain season

Weed species that dominated these farming systems were; *Bidens pilosa*, *Galinsoga parviflora*, *Schkuhria pinnata*, *Setaria verticillata*, *Amaranthus hybridus*, *Eleusine indica* and *Stellaria media*. Their dominance can be attributed to their adaptive mechanism to the management practices in these farming systems. Their adaptive characterise helps them to survive in all cropping seasons from 2017 to 2019 (Mortimer, 1997; Neve *et al*., 2009; Bajwa, 2014; Heap, 2014). These weed species take advantage on applied fertilizer to produce more seeds which germinate whenever there is soil disturbance and adequate soil moisture (Demjanová *et al*., 2009). These weed species are also able to develop resistance to herbicide application over time (Wortman *et al*., 2010; Sharma & Singh, 2014; Kaur *et al*., 2018; MacLaren *et al*., 2020).

Bidens pilosa dominated all the four farming systems in Chuka and in organic high, organic low and conventional high in Thika. High dominance of *Bidens pilosa* (20%) can be linked to its rapid growth, high nutrient use efficiency, ability to produce seeds over short period and efficient seed dispersal (Chen *et al.*, 2017). Mhlanga *et al*. (2016) found that *Bidens pilosa* produces more seed under nitrogen rich soils and this can be associated with its high density under conventional high and organic high farming systems. High weed density of *Bidens pilosa* was recorded under maize crop compared to cabbage, beans, and potatoes. Similar results have also been observed by Lemos *et al*. (2013) who also noted high density of *Bidens pilosa* in maize field compared to other types of crops. Moreover, Ndam *et al*. (2014) opinioned that despite shading by maize, *Bidens pilosa* continued to increase from research done in maize fields in Cameroon. Khatib *et al*. (1995) as well reported *Bidens pilosa* as one of the most dominant weed species in maize plantations.

Galinsoga parviflora (17.7%) and *Stellaria media* (23.5%) dominated in all the four farming systems in Chuka and Thika, respectively. This support research done by Butkevičienė *et al*. (2021) at Vytautas Magnus University Experimental Station in Lithuania which indicated that *Stellaria media* covered 25% of the total annual weeds and (16.6%) was *Galinsoga parviflora* in a three-course crop rotation. Bedada *et al*. (2021) also recorded *Galinsoga parviflora* as the most dominate weed species with 31% over Dodota, Sire, Arsinegele and Arene districts, 86.29% over Shashemene and Wondo districts and 75.56% over Shala and Bishan-guracha districts in Central

Ethiopia bean fields. This shows that *Galinsoga parviflora* has a quick response to the change in management practices and ability to adapt to different farming systems. Research on adaptive characteristic of *Galinsoga parviflora* by Shen *et al.* (2019) indicated that the species is well adaptive to a wide range of environmental condition, lacks seed dormancy, has high seed germination rates, grows rapidly and it able to produce flower at an early stage. Its significant high density under conventional high and conventional low farming systems where weed control was achieved through herbicide application shows its ability to develop resistance over herbicide application (De Cauwer *et al.*, 2021). Herbicide resistance of *Galinsoga parviflora* was also studied by Paula *et al*. (2022) who noted its ability to resist herbicide even at a higher dosage.

Stellaria media dominated in all the four trial plots in Thika. *Stellaria media*, has been recorded as one of the most dominate weed species (Kims *et al*., 1992; Saska *et al*., 2008; Verma & Kapoor, 2010; Licznar-Malanczuk & Sygutowska,2016). The weed has ability to quickly colonize disturbed field though considered as a weak competitor (Bitarafan & Andreasen, 2019). This can be associated with its density being relatively the same in organic high and organic low farming systems from the year 2017 long rain season to 2019 short rain season. Despite being one of the most dominant weed species in Thika, there was a significant decrease *($P<0.001$)* of 84% in its density under conventional high farming system by the end of year 2019. Use of herbicide under conventional farming system can be associated with its decrease (Schöb *et al*., 2015). Same outcomes were also gotten by Al-Khatib & Kadir (1995) who recorded 86% decrease in its density when controlled using herbicide.

Amaranthus hybridus dominated only in Thika trials under organic high, organic low and conventional low. Dominance of *Amaranthus hybridus* in most of the agricultural fields is related to its adaptive characteristic which includes high growth rate, high number of seeds production with high germination percentage and tolerance to stress (García *et al*., 2019; Van Volkenburg *et al*., 2020; Mhlanga *et al*., 2015). In organic high and organic low farming systems, the density of *Amaranthus hybridus* increased when beans were on season. This can be associated with the ability of *Amaranthus hybridus* to rapidly grow and outcompete the crop (Bedada *et al*., 2021). *Amaranthus hybridus* showed a slight decrease under conventional low farming system. Despite so, its dominance under farming system where herbicide is used, shows its ability to develop resistance over the used herbicide (Larran *et al.*, 2018; García *et al.*, 2020; Scursoni *et al.*, 2022).

Schkuhria pinnata (13.9%) was among the species that dominated in all trial plots in Chuka. Dominance of *Schkuhria pinnata* in agricultural land has also been reported by (Haripo, 2015; Mncube & Banda, 2017; Baker *et al*., 2018). The weed showed a continuous decrease under organic high and organic low farming system throughout the seasons except in 2019 long rains when maize was in season while in conventional high and conventional low there was a decrease in the year 2017 and 2018 rain season, however, the decrease stopped during 2018 short season and in 2019 rain seasons where weed density increased. Mncube & Banda (2017) recorded *Schkuhria pinnata* as one of competitive weed species in maize field in Swaziland. Marava (2016) observed that use of herbicide to control *Schkuhria pinnata* weed has been effective, but the weed develop resistance over time making it difficult to control (Mashayamombe *et al*., 2013).

Setaria verticillate dominated under organic low, conventional high and conventional low in Chuka trial plots. Combined effect of the management practices and use of herbicide under conventional high resulted to a decrease in its density by 72% at the end of 2019 short rains season. Moyer *et al*. (1989) has recorded similar result of 90-95% reduction in the density of *Setaria verticillate* through use of herbicide in crop fields of Hanang plains in Tanzania. *Setaria verticillate* has been recorded as a weak competitor in crop field and easily controlled using herbicide (Renton *et al*., 2014; Guglielmini *et al*., 2017).

Eleusine indica was only present in conventional high and conventional low farming system in Thika. At the end of 2019 short rain season, its density had increase under conventional low by 71%. Shekoofa *et al*. (2020) reported that the density of *Eleusine indica* continued increasing regardless of the type of herbicide application in an experiment conducted under a glasshouse at the University of Tennessee. A significant increase of *Eleusine indica* in this farming system where herbicide application was done to control weed, shows its high resistance to herbicide (McErlich & Boydston, 2014). *Eleusine indica* has been reported as a troublesome annual weed in many parts of the world (Jalaludin *et al*., 2010; Chen *et al*., 2017) that has ability to resist multiple types of herbicides (Seng *et al*., 2010; McCullough *et al*., 2013; Deng *et al*., 2020; Vazquez-Garcia *et al*., 2021; Li *et al*., 2022).

4.5 Influence of Crop Rotation on Weed Density, Species Dominance, and Diversity in Organic and Conventional Farming Systems in Thika and Chuka

Crop rotation as a weed management tool influences the density of weeds their dominance and their diversity with farming system which may also vary with farming systems.

4.5.1 *Weed Density as Influenced by Change of Crops Within the Four Farming Systems in Chuka and Thika*

Weed density within the four farming systems was significantly *($P<0.001$)* influenced by the type of crop in season. Maize-cabbage rotation in the year 2017 resulted to a significant *($P<0.001$)* decrease in weed density under organic high and conventional and organic low in Thika by 47.7%, 56.6% and 50.2%, respectively. In Chuka, weed density decreased significantly *($P<0.001$)* by 54.4% and 30.0% in conventional high and conventional low, respectively (Table. 4.4).

In 2018, weed density decreased significantly *($P<0.001$)* in maize-beans rotation under conventional low, organic high and organic low by 33%, 15.5% and 9.4%, respectively in Thika. While in Chuka, weed density decreased by 55.0% and 44.3% in conventional high and conventional low. However, weed density increased by 24.9% and 4.7%, under organic high and organic low, respectively (Table 4.4).

Table 4.4. Weed density as influenced by crop rotation within the four farming systems during 2017-2019 cropping seasons in Chuka and Thika located in the Central Highland of Kenya

	THIKA			
	Weed density (No. of weeds m^{-2})			
Crop	**Conventional high**	**Conventional low**	**Organic high**	**Organic low**
Maize	90.0d	116.0f	128.3e	144.7f
Cabbage	96.0e	60.7c	55.7a	72.0d
Maize	72.7b	83.3e	84.0c	85.0e
Beans	137.0f	55.7b	71.0b	43.0b
Maize	61.7a	31.0a	88.7d	45.0c
Potatoes	82.3c	69.7d	129.3f	41.3a
LSD	**0.30**	**0.13**	**0.42**	**0.43**
P- Value	**0.001**	**0.001**	**0.001**	**0.001**
	CHUKA			
Maize	185.7f	64.7e	88.0e	52.3d
Cabbage	84.7d	45.3d	120.3f	54.0e
Maize	94.7e	34.3c	60.7b	49.0c
Beans	26.3b	32.7b	62.7c	53.3d
Maize	25.3a	22.0a	53.7a	33.0a
Potatoes	34.3b	34.0c	71.7d	31.3a
LSD	**0.73**	**0.30**	**0.43**	**0.72**
P- Value	**0.001**	**0.001**	**0.001**	**0.001**

Mean of value with the same letters in column are not significantly different at $P \leq 0.05$. *LRS- Long Rain Season, SRS- Short Rain Season.*

Weed density was significantly *(P<0.001)* affected by maize-potatoes rotation in 2019. This resulted in weed density increase at conventional high, conventional low and organic high by 33.4%, 124.8%, and 45.8% in Thika and 35.6%, 54.5% and 33.5% in Chuka, respectively. However, the rotation also caused a reduction in the weed density in organic low in Thika and Chuka of 8.2% and 5.2%, respectively (Table 4.4). Weed density was highly reduced under conventional high, conventional low, and organic low farming system compared to organic high farming system in Thika and Chuka as a result of crop rotation within the three years. Variation of densities in weed species with change of crop type can be link to the association that weed develop towards certain type of crop and farming system (Smith *et al*., 2014; Korav *et al*., 2018).

The significant different in weed density within the four farming systems can be associated with the change of crops in every season. Maize-cabbage rotation resulted to a significant decrease *(P<0.001)* in the weed density across the four farming system. The decrease can be linked to the different management practices associated with the change of crop. Crop morphology and spacing are also major factors that influence weed density (Liebman *et al*., 1993; Bajwa *et al*., 2017). The effectiveness of crop alternation to lower weeds is highly inclined to the type of crops in season (Melander *et al*., 2013; Nichols *et al*., 2015).

Maize-beans crop rotation resulted to a decrease in weed density in conventional low, organic high and organic low by 33%, 15.5% and 9.4%, respectively in Thika and 55.0% and 44.3% in conventional high and conventional low, respectively in Chuka. However, in Chuka, weed density increased by 24.9% and 4.7%, under organic high and organic low, respectively. Maize-beans rotation has been used to manage weeds by many smallholders' farmers (Ouda *et al*., 2018; Andert, 2021). Research done by Mhlanga *et al*. (2015) in the University of Zimbabwe farm showed that maize followed by beans crop rotation reduced weed density by 61.5%. These results were also affirmed through another experiment in the same University conducted by Pieterse *et al*. (2019) on the efficiency of maize beans rotation which indicated a significant reduction of weed density by 59%.

Maize-potatoes crop rotation resulted in a significant raise of weed density in conventional high, conventional low and organic high. A significant increase in weed density can be accredited to its the poor competition ability (Caldiz *et al*., 2016), where weeds are able to establish faster than the crop (Abdallah *et al*., 2021).

4.5.2 *Influenced of Crop Rotation on Species Within the Four Farming Systems in Thika and Chuka trials*

Crop rotation significantly *(P<0.001)* influenced all the weed species across the four farming systems in Chuka and Thika. However, increase or decrease in the density of specific weed species was also determined by the crop in season and the type of farming system. In organic high, the 3-year crop rotation resulted to a significant *(P<0.001)* decrease in densities of *Amaranthus hybridus, Chenopodium album, Oxalis corniculate* and *Stellaria media* while in organic low there was a significant *(P<0.001)* decline in the densities of *Amaranthus hybridus, Bidens pilosa*, *Eleusine indica, Portulaca oleracea* and *Stellaria media* (Table 4.5).

Under conventional high, crop rotation resulted to a significant *(P<0.001)* decrease in the densities of *Galinsoga parviflora, Oxalis corniculate*, *Setaria verticillate, Sonchus oleraceus*, and *Schkuhria pinnata* (Table 4.5). However, crop rotation under this farming system resulted to a significant *(P<0.001)* increase in the density of *Bidens pilosa*. Moreover, its density remined high under organic high and conventional high farming systems across all the seasons in Thika (Table 4.5). Under the conventional low, crop rotation resulted to continuous decrease in the density of *Amaranthus hybridus*, *Bidens pilosa*, *Schkuhria pinnata* and *Setaria verticillate* (Table 4.5). The density of *Oxalis corniculate* increased in conventional low despite the crop rotation practice (Table 4.5).

The density of some weed species was highly altered by the type of the crop in season and their sequence. Under maize-cabbage rotation, the densities of *Eleusine indica* and *Sonchus oleraceus* increased significantly *(P<0.001)* in all the four-farming system (Table 4.5). Also, there was a significant *(P<0.001)* increase in the density of *Portulaca oleracea* and *Tagetes minuta* as a result of maize-beans rotation in all the four farming system. Maize-potatoes rotation resulted to an increase of weed species density in all the four farming systems in Thika (Table 4.5).

Table. 4.5. Influence of crop rotation on weed species density (No. of weed m^{-2}) within the four farming systems in Thika located in the Central Highland of Kenya

Organic high										
CROP	A.H	B.P	C.A	C.B	E.I	O.C	P.O	S.O	S.M	T.M
Maize	16.0e	21.0c	0.0a	0.0a	10.7b	10.7c	0.0a	0.0a	16.0c	15.7f
Cabbage	11.7d	31.3e	7.0d	0.0a	25.0e	14.0d	0.0a	11.0d	12.0b	6.7d
Maize	3.0ab	23.0d	0.0a	0.0a	13.0c	0.0a	0.0a	3.0b	18.0d	0.0a
Beans	6.0c	10.0b	0.0a	0.0a	14.0d	6.0b	4.3b	0.0a	23.0e	1.7b
Maize	2.0a	7.0a	6.0c	4.0c	11.0b	6.0b	0.0a	7.0c	10.7a	2.7c
Potatoes	3.7b	21.0c	2.3b	2.0b	9.0a	7.0b	0.0a	7.0c	11.0a	11.7e
LSD	1.085	0.86	0.92	0.94	0.86	1.03	0.43	0.94	0.43	0.43
P- Value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Organic low										
	A.H	B.P	C.A	C.B	E.I	G.P	O.C	P.O	S.O	S.M
Maize	12.3f	12.7d	0.0a	0.0a	8.3d	9.0b	0.0a	0.0a	0.0a	12.0e
Cabbage	4.0c	11.0c	0.0a	0.0a	13.0f	0.0a	0.0a	11.0d	3.0c	9.0c
Maize	0.0a	21.0e	0.0a	0.0a	12.0e	0.0a	0.0a	5.0c	0.0a	10.7d
Beans	6.0d	23.0f	0.0a	0.0a	4.0b	9.0b	2.0b	3.0b	2.0b	4.0a
Maize	3.0b	6.0a	3.0b	4.0c	7.0c	0.0a	0.0a	3.0b	2.0b	11.0d
Potatoes	8.0e	9.0b	4.0c	2.0b	0.0a	0.0a	0.0a	3.0b	2.0b	8.0b
LSD	0.92	0.43	0.94	0.94	0.79	0.94	0.74	0.74	0.94	0.86
P- Value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Conventional high										
	A.H	B.P	C.B	E.I	F.C	G.P	O.C	S.O	S.M	T.M
Maize	22.7e	33.7 f	0.0a	30.7d	11.7c	20.7b	0.0a	0.0a	45.0 e	22.7c
Cabbage	0.0a	31.0 e	12.0b	22.0c	0.0a	0.0a	0.0a	0.0a	21.0 c	0.0a
Maize	7.0c	9.0 c	0.0a	32.0e	4.0b	0.0a	7.0b	7.0b	25.7 d	0.0a
Beans	11.0d	0.0 a	0.0a	0.0a	0.0a	0.0a	0.0a	0.0a	12.0 b	1.7b
Maize	0.0a	7.0 b	0.0a	9.0b	0.0a	0.0a	0.0a	0.0a	10.3 b	0.0a
Potatoes	6.0b	20.0 d	0.0a	0.0a	0.0a	0.0a	0.0a	0.0a	7.0 a	0.0a
LSD	0.92	0.79	0.74	0.92	0.79	0.43	0.74	0.74	2.95	0.54
P- Value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Conventional low									
	A.H	B.P	C.B	E.I	O.C	P.O	S.O	S.M	T.M
Maize	17.0 f	21.0d	0.0a	8.0b	0.0a	0.0a	0.0a	18.7f	0.0a
Cabbage	12.0 e	0.0a	0.0a	14.0d	2.0b	0.0a	0.0a	13.0d	3.7b
Maize	5.0 c	6.0c	0.0a	13.0c	0.0a	0.0a	4.0b	5.0a	0.0a
Beans	0.0 a	2.0b	0.0a	13.0c	6.0d	4.3b	0.0a	14.0e	0.0a
Maize	11.0 d	0.0a	4.0c	0.0a	3.0c	0.0a	0.0a	6.0b	0.0a
Potatoes	4.0 b	0.0a	2.0b	17.0e	3.0c	0.0a	0.0a	9.0c	0.0a
LSD	0.74	0.99	0.94	0.74	0.94	0.43	0.74	0.858	0.43
P- Value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

A.H-*Amaranthus hybridus*; B.P-*Bidens pilosa*; C.A-*Chenopodium album*; C.B-*Commelina benghalensis*; E.I-*Eleusine indica*; F.C-*Fallopia convolvulus*; G.P-*Galinsoga parviflora*;

O.C-*Oxalis corniculata*; P.O-*Portulaca oleracea*; S.O-*Sonchus oleraceus*; S.M-*Stellaria media*; T.M-*Tagetes minuta*. *Mean of values with similar letter in the same column denotes no significantly different at P≤0.05.*

In Chuka, the 3-year crop rotation resulted to significant *(P<0.001)* decrease in the densities of *Oxalis corniculate*, *Portulaca oleracea* and *Schkuhria pinnata* in organic high and a significant *(P<0.001)* decline in the density *Amaranthus hybridus, Galinsoga parviflora* and *Setaria verticillate* in organic low (Table 4.6). In conventional high, crop rotation resulted to a significant *(P<0.001)* decline in the density of *Oxalis corniculate*, *Sonchus oleraceus, Schkuhria pinnata* and *Setaria verticillate* (Table 4.6). However, crop rotation under this farming system resulted to a significant *(P<0.001)* increase in the density of *Bidens pilosa* and its density remined high under organic high and conventional high farming (Table 4.6).

Maize-cabbage rotation increased significantly *(P<0.001)* the weed densities of *Eleusine indica* and *Sonchus oleraceus* in all the four-farming system. Additionally, there was also a significant *(P<0.001)* increase in the density of *Portulaca oleracea* and *Tagetes minuta* during maize-beans rotation in all the farming system. Maize-potatoes rotation resulted to an increase of weed species density in all the four farming systems in Chuka and Thika, respectively (Table 4.6).

Table. 4.6: Influence of crop rotation on weed species density (No. of weed m^{-2}) within the four farming systems in Chuka located in the Central Highland of Kenya

Organic high										
Crop	A.H	B.P	F.C	G.P	O.C	P.O	S.M	T.M	S.P	S.V
Maize	12.0e	24.3d	0.0a	19.0 e	11.0 e	12.0 d	0.0 a	9.0 c	18.0 e	23.0 d
Cabbage	0.0a	16.0b	2.0b	12.0 a	0.0 a	0.0 a	2.0 b	0.0 a	14.0 d	14.0 c
Maize	6.0c	16.0b	0.0a	16.0 d	7.0 d	3.0 b	9.0 d	3.0 b	11.3 c	11.0 b
Beans	9.0d	9.0a	8.0c	12.0a	0.0 a	11.0 c	4.0 c	0.0 a	7.0 b	10.0 b
Maize	2.0b	35.0e	0.0a	14.0 c	4.0 b	0.0 a	0.0 a	3.0 b	21.0 f	0.0 a
Potatoes	12.0e	23.0c	0.0a	12.7 b	6.0 c	0.0 a	0.0 a	11.0 d	2.0 a	24.3 e
LSD	0.74	0.86	0.94	0.43	0.94	1.00	1.00	0.94	0.43	1.33
P- Value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Organic low									
	A.H	B.P	G.P	O.C	P.O	S.P	S.V	S.O	T.M
Maize	12.0d	7.0 b	19.0d	11.0e	7.0d	0.0a	3.0a	0.0a	0.0a
Cabbage	0.0a	19.0 f	12.0a	0.0a	0.0 a	2.0b	11.0c	2.0b	5.0b
Maize	10.0d	8.3 c	16.0c	7.0d	6.0d	0.0a	3.0b	0.0a	0.0c
Beans	0.0a	4.0 a	12.7a	0.0a	0.0 a	2.0b	3.0a	2.0b	7.0a
Maize	5.0b	15.0 e	14.0b	4.0b	2.3 b	0.0a	3.3a	0.0a	0.0a
Potatoes	9.0c	9.0 d	12.7a	6.0c	4.0 c	4.0c	3.0a	4.0c	0.0a
LSD	0.93	0.43	0.92	0.94	1.14	1.00	0.43	1.00	0.94
P- Value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Conventional high							
	B.P	C.A	G.P	O.C	S.O	S.P	S.V
Maize	15.7a	0.0a	23.0 d	23.0e	23.0e	13.3c	25.0f
Cabbage	17.0b	3.0b	21.0 c	12.0c	3.0b	13.0c	19.3e
Maize	17.0b	0.0a	22.0 cd	4.0b	5.0c	6.0b	14.0d
Beans	24.0d	21.0c	17.0 b	21.0d	14.0d	5.0a	13.0c
Maize	24.0d	0.0a	21.0 c	0.0a	0.0a	5.0a	9.0b
Potatoes	23.0c	0.0a	15.0 a	0.0a	0.0a	6.0b	7.0a
LSD	0.429	0.939	1.286	0.939	0.939	0.4288	0.4288
P- Values	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Conventional low									
	A.H	B.P	F.C	G.P	O.C	P.O	T.M	S.P	S.V
Maize	13.0c	8.0bc	6.0b	21.0c	6.0b	23.0c	0.0a	22.0e	17.0d
Cabbage	2.0b	7.0b	0.0a	13.0b	0.0a	6.0b	0.0a	13.0d	8.3bc
Maize	12.0c	13.0d	14.0c	13.0b	8.0c	0.0a	8.0b	6.0b	7.0b
Beans	0.0a	9.3c	0.0a	13.0b	0.0a	6.0b	19.0c	3.0a	5.0a
Maize	3.0b	0.0a	0.0a	0.0a	13.0d	0.0a	0.0a	4.7b	7.0b
Potatoes	23.0d	0.0a	0.0a	13.0b	12.0d	0.0a	0.0a	11.0c	9.0c
LSD	0.742	0.92	0.94	0.74	0.939	0.996	0.939	0.858	0.858
P- Value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

A.H-*Amaranthus hybridus*; B.P-*Bidens pilosa*; C.A-*Chenopodium album*; F.C-*Fallopia convolvulus*; G.P-*Galinsoga parviflora*; O.C-*Oxalis corniculata*; P.O-*Portulaca oleracea*; S.P-*Schkuhria pinnata*; S.V-*Setaria verticillata*; S.O-*Sonchus oleraceus*; S.M-*Stellaria media*; T.M-*Tagetes minuta*. *Values of mean followed by the same letter within the same column shows no significant different at $P \leq 0.05$.*

Crop rotation resulted to the decrease of the density of *Amaranthus hybridus, Chenopodium album, Oxalis corniculate, Stellaria media, Portulaca oleracea, Schkuhria pinnata, Galinsoga parviflora, Setaria verticillate* and *Sonchus oleraceus.* This decrease can be associated with different management practices and soil disturbances resulting from change of crop i.e., maize, cabbage, beans, and potatoes during rotational cropping (Garrison *et al*., 2014; Mhlanga *et al*., 2015). Changing crops is one of the easiest and most efficient means of controlling weeds (Liebman & Davis, 2000; Garrison *et al*., 2014). The weed community faces distinct biotic and abiotic limitations from each crop it interacts with leads to decrease or increase in weeds emergency, establishment, and seed production (Turk & Tawaha, 2003; Bahadur *et al*.,2015; Nichols *et al*., 2015). This hinders establishment of some weed species that can easily get used to the management practices (Neve *et al*.,2009; Cirujeda *et al*.,2011; Fried *et al*., 2012). Hosseini e*t al*. (2014) found that rotation of crops leads to a high decline in the density of weeds in comparison to monocropping.

The significant decrease in the weed densities resulting from crop rotation has also been recorded by Demjanová *et al*. (2009) who noticed a significant decrease on the dominate weed species which included *Amaranthus hybridus*, *Chenopodium album* and *Fallopia convolvulus* in field trials in Experimental Station of the Slovak Agricultural University in Nitra in south-western Slovakia. *Galinsoga parviflora, Amaranthus hybridus*, *Chenopodium album*, *Bidens pilosa*, *Eleusine indica*, *Tagetes minuta, Portulaca oleracea*, *Commelina benghalensis* and *Fallopia convolvulus* have been recorded as some of the dominant weed species related with maize crop production (Rana *et al*., 1998; Lehoczky & Reisinger, 2003; Glowacka. 2011; Keller *et al*., 2014; Ahmadet *et al*., 2016; Rana *et al*., 2018) of which their density is maintained low through crop rotation (Murphy *et al*., 2006; Demjanová *et al*., 2009).

Despite crop rotation leading to decrease in the density of some weed species, *Sonchus oleraceus* and *Eleusine indica* increased significantly *($P<0.001$)* in all the four-farming system in Thika and Chuka under maize-cabbage rotation. Their increase under different management practices shows their resilience despite change of the management practices.

Increase in the density of *Sonchus oleraceus* can be associated with its ability to resist herbicide and to germinate all year round (Werth *et al*., 2011). Chauhan *et al.* (2006) noted that the weed species is less competitive in a dense population, thus the decrease in other weed species density gives it a chance to increase. High resistance of *Eleusine indica* to many herbicides and its fast adaptation to management practices has been associated with its dominance in many cropping fields (Lee *et al*., 2000; Lopes Ovejero *et al*.,2013; Plaza *et al*., 2021). Maize-potatoes rotation resulted to a substantial increase in most of the weed species density in all the four farming systems in Chuka and Thika. The significant increase in weed density under this crop rotation could be attributed to the row spacing which is a bit wide slow growth and development of potatoes at the early stage which give space for weeds establishment (Zarzecka *et al*., 2020).

4.5.3 ***Influence of Crop Rotation on Shannon's Diversity (H') of Weed Species in Thika and Chuka Trials***

The diversity of weed species differed significantly *(P<0.001)* in organic low, organic high, conventional low and conventional high because of crop rotation and different in management practices in Chuka and Thika. In Chuka and Thika regions weed species diversity within 2017-2019 ranged between (*H'*= 1.97-0.92) and (*H'*= 1.33-2.06), respectively (Table 4.7). Conventional high and conventional low farming systems in Thika and Chuka resulted to a decrease in Shannon diversity index in all the six cropping seasons between year 2017 –2019 (Table 4.7). In Thika, Shannon diversity (*H'*) index in conventional high decreased from *H'*= 1.88 in 2017 to *H'*= 0.94 in 2019. This shows that, the number of weed species under conventional high had reduced by half at the end of 2019 in Thika. In Chuka, Shannon diversity of weeds species (*H*') under conventional high reduced from *H'*= 1.92 in 2017 to *H'*= 1.43 in 2019 which translate to 26% decrease.

Table 4.7: Diversity of Weed Species as Influenced by Crop Rotation Under Different Treatment in Thika and Chuka located in the Central Highland of Kenya

	Thika					
	2017		**2018**		**2019**	
	LS	**SS**	**LS**	**SS**	**LS**	**SS**
Treatment	**Maize**	**Cabbage**	**Maize**	**Beans**	**Maize**	**Potatoes**
Conventional high	1.88d	1.34a	1.67c	0.92a	1.08a	0.94a
Conventional low	1.33a	1.43b	1.50b	1.42b	1.26b	1.32b
Organic high	1.76c	1.94d	1.36a	1.57c	1.97d	1.89d
Organic low	1.59b	1.82c	1.27a	1.71d	1.78c	1.48c
LSD	**0.019**	**0.019**	**0.095**	**0.018**	**0.013**	**0.018**
P- Value	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
			Chuka			
Conventional high	1.92b	1.71b	1.79a	2.13b	1.33a	1.43a
Conventional low	1.96c	1.92c	2.04b	1.63a	1.43b	1.55b
Organic high	2.02d	1.58a	2.06b	2.04b	1.64d	2.04d
Organic low	1.78a	1.73b	2.00b	1.60a	1.58c	1.87c
LSD	**0.019**	**0.019**	**0.061**	**0.090**	**0.019**	**0.017**
P- Value	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**

LS- Long season, SS- Short season, *Values of means in the same column followed by the same letter show no significant different at P≤0.05*

The value of Shannon diversity(*H'*) index was high in organic farming systems contrasted to conventional farming system by the end of 2019 in Thika and Chuka. Organic high maintained high Shannon diversity by the end of 2019. In Thika and Chuka, Shannon diversity (*H'*) index in organic high increased from *H'*= 1.76 in 2017 to *H'*= 1.89 in 2019 and *H'*= 2.02 in 2017 to 2.04 in 2019, respectively (Table 4.7). This was an increased in weed species richness of 7% and 5% in Thika and Chuka, respectively under organic high farming system. Shannon diversity (*H'*) index ratio for organic high to conventional high and organic low to conventional low were 2:1 and 2:1.4, respectively in Thika while in Chuka it was 2:1.8 and 2:1.6, respectively.

Results on Shannon diversity shows that conventional farming system results to decrease in species weed. Crop rotation and the management practices under conventional high resulted to a decrease in Shannon diversity index (*H'*) from *H'*= 1.88 to 0.94 and *H'*= 1.92 to 1.43 between 2017 and 2019 in Thika and Chuka, respectively. This coincides with findings by Armengot *et al*. (2013) which stated high Shannon diversity index (*H'*=2.5) in organic weed communities and low Shannon index of (*H'*=1.5) in conventional farming system. Armengot *et al.* (2012) also recorded that the values of Shannon diversity index in organic farming system can be two time greater than that of conventional farming system. This agrees with the study finding where the Shannon diversity (H') index of organic high was twice high (ratio of 2:1) that of conventional high in Thika. Lower Shannon diversity index under conventional farming systems can be attributed to continuous herbicide application which leads to complete elimination of weed species that are high prone to herbicide (Buhler *et al.*, 1999; Berbeć *et al*., 2018). This study proves that organic farming practices results to higher weed diversity compared to conventional farming system (Ngouajio *et al*., 2002; Gibson *et al.*, 2007; Liebman & Davis, 2009).

4.5.4 *Influence of Crop Rotation on Shannon's Evenness (EH,) of Weed Species in Thika and Chuka From 2017 to 2019*

The two-region showed high Shannon's evenness (E_H,) across the four farming systems which ranged between 0.82-0.99 and 0.78-0.99 depending on farming system and the season in Chuka and Thika, respectively (Table 4.8). There was a significant different *($P<0.001$)* in Shannon's evenness (E_H,) within the four farming systems and across the 3-years experimental period. Evenness index decreased under conventional high by 0.99-0.89 (10%) and 0.97-0.86 (11.34%) in Thika and Chuka, respectively while organic low resulted to an increase from 0.91 – 0.96 (5.5%) by the end of 3-year crop rotation (Table 4.8). In Thika and Chuka, evenness index was high during maize season in the year 2017 and 2018 while in Thika evenness index was low during maize season in the year 2018 and 2019.

Table 4.8: Shannon's evenness (E_H,) of weed species as influenced by crop rotation in Thika and Chuka located in the Central Highland of Kenya

	Thika					
	2017		**2018**		**2019**	
	LS	**SS**	**LS**	**SS**	**LS**	**SS**
Treatment	**Maize**	**Cabbage**	**Maize**	**Beans**	**Maize**	**Potatoes**
Conventional high	0.99c	0.78a	0.86a	0.97c	0.83b	0.89a
Conventional low	0.94b	0.92c	0.98d	0.91b	0.89c	0.96c
Organic high	0.97c	0.88b	0.94b	0.98c	0.79a	0.93b
Organic low	0.91a	0.89b	0.96c	0.89a	0.88c	0.96c
LSD	**0.017**	**0.018**	**0.017**	**0.0172**	**0.02**	**0.019**
P- Value	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**
	Chuka					
Conventional high	0.97a	0.97c	0.86a	0.84a	0.98c	0.86b
Conventional low	0.96a	0.89a	0.93b	0.88b	0.91a	0.82a
Organic high	0.98a	0.93b	0.85a	0.88b	0.95b	0.91c
Organic low	0.99a	0.94b	0.92b	0.82a	0.91a	0.92c
LSD	**0.020**	**0.019**	**0.019**	**0.019**	**0.019**	**0.019**
P- Value	**0.311**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**

LS- Long season, SS- Short season. *Mean of values in column tagged on by same letter shows no significant different at P≤0.05.*

Higher range of evenness index of 0.82-0.99 and 0.78-0.99 in Chuka and Thika, respectively showed that the farming systems had only few dominant weed species. The 3-year crop rotation created unfavourable condition for dominant weeds species to fully establish within the four farming systems. Benaragama *et al.* (2019) indicated that crop rotation helps in controlling weeds species dominance which leads to relative evenness in weed species. Despite so, the evenness index increased under organic high and decreased under conventional high farming structure by the end of 3-year crop rotation in Thika and Chuka. Organic farming systems results in high evenness of weed species in contrast with conventional farming systems (Wortman *et al.*, 2010; Mhlanga *et al.*, 2015). Intensive use of herbicide that aims at specific weed species based on the kind of crop in season is linked to the low evenness index of weed species in conventional farming system (Muoni *et al.*, 2014). Oreja *et al*. (2022) indicated that eradication of species by the use of herbicide with low reproductive rates reduces diversity and evenness.

CHAPTER FIVE: SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary of findings

Application of 225 N kg/ha and 125 P kg/ha resulted to a significant *(P<0.05)* high weed density in contrast with 45 N kg/ha and 26 P kg/ha. *Amaranthus hybridus*, *Bidens pilosa*, *Stellaria media* and *Galinsoga parviflora* their density increased with increase in fertilizer application rates while *Schkurihria pinnata* and *Portulaca oleracea* increased with decrease in fertilizer application rates. High N and P fertilizer application rates led to a significant *(P<0.05)* higher weed density in organic high compared to conventional high, conventional low and organic low in Chuka and Thika by the end of the cropping season in the year 2019.

Dominant weed species were *Bidens pilosa*, *Galinsoga parviflora*, *Schkuhria pinnata*, *Stellaria media*, *Eleusine indica* and *Amaranthus hybridus.* The densities of this dominate weed species were reduced significantly *(P<0.05)* through crop rotation proved except for *Bidens pilosa* of which its density remained high in all the farming system.

Crop rotation influenced weed density significantly*(P<0.001)* within the four farming systems. Maize-cabbage rotation resulted to a rise in the weed density of *Eleusine indica* and *Sonchus oleraceus* in all the four farming systems while a rotation of maize-beans decreased the density of *Portulaca oleracea* and *Tagetes minuta.* Maize-potatoes rotation resulted to an increase in the densities of *Galinsoga parviflora* and *Setaria verticillate* in organic low. In conventional high, crop rotation resulted to a significant *(P<0.001)* decline in the density of *Oxalis corniculate*, *Sonchus oleraceus*, *Schkuhria pinnata* and *Setaria verticillate*. The density of *Bidens pilosa* was not inclined to the change of crop. Despite crop rotation in the four farming systems, weed diversity was reduced in conventional high and conventional low farming systems and increased in organic high and organic low farming systems.

5.2 Conclusions

The current study will contribute on enlightening farmers within Tharaka-Nithi and Murang’a Counties on the best farming system and management practices when dealing with some of the problematic weed species within the regions. From the study its evidence that high fertilizer application rates, favours increase in the density of *Amaranthus hybridus*, *Bidens pilosa*, *Stellaria media* and *Galinsoga parviflora*.

Moreover, from the study, it is clear that the dominant weed species within the two experimental areas are *Bidens pilosa*, *Galinsoga parviflora*, *Schkuhria pinnata*, *Stellaria media*, *Eleusine indica* and *Amaranthus hybridus* of which their density can be maintained low through crop rotation.

Furthermore, results from the study have proved that use of crop rotation helps in management of weeds in all the farming systems. Rotation of maize with cover crop ultimately reduced weed density in both organic and conservation farming systems and also helps in control of dominant weed species. However, knowledge of the target weed species is crucial as it may result in an increase in some weed species. For example, maize-beans rotation led to an increase in weed density of *Bidens Pilosa*.

5.3 Recommendation

1. Fertilizer application should be placed in a manner that only the target crop will benefit to avoid benefiting weeds which results to increasing weed density.

2. Farmers should embrace crop rotation when dealing with dominant weeds as their density reduces with change of crop.

3. Maize-cabbage rotation should be discouraged when dealing with *Eleusine indica* and *Sonchus oleraceus* as it results to increase in their density and maize-beans encourage when dealing with *Portulaca oleracea* and *Tagetes minuta* but discouraged when dealing with weed species that are highly favored by increase of N in the soils e.g., *Bidens pilosa.*

5.4 Areas for Further Studies

From the study's results, advance research is proposed in the areas below.

1. Evaluation on soil weeds seedbank in conventional high, conventional low, organic high and organic low under the same conditions whereby conventional high and organic high aren't irrigated during the dry season.
2. Effect of soil weed seed bank in the four farming systems on crop yield.

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APPENDICES

Appendix 1. Scientific Names and Common Names of the Weed Species Observed From the Experimental Sites

Scientific name	Common names	Family	Life cycle
Amaranthus hybridus	Smooth pigweed	Amaranthaceae	Annual
Bidens pilosa	Black-jack	Asteraceae	Annual
Chenopodium album	lamb's quarters	Amaranthaceae	Annual
Commelina benghalensis	wandering jew	Commelinaceae	Perennial
Eleusine indica	Goosegrass	Poaceae	Annual
Fallopia convolvulus	Black Bindweed	Polygonaceae	Annual
Galinsoga parviflora	gallant soldier	Asteracea	Annual
Oxalis corniculata	creeping woodsorrel	Oxalidaceae	Annual/Perennial
Portulaca oleracea	Purslane	Portulacaceae	Annual
Schkuhria pinnata	Dwarf Marigold	Schkuhria	Annual
Setaria verticillata	Bristly foxtail	Poaceae	Annual
Sonchus oleraceus	Sow thistle	Asteraceae	Annual
Stellaria media	Chickweed	Caryophyllaceae	Perennial
Tagetes minuta	Mexican marigold	Asteraceae	Annual

Appendix 2. Soil Samples Preparation

In the laboratory, soil samples were all set in alignment with the guidelines of weed seedling emergency methods as illustrated by Forcella *et al*. (2002). Before initiating germination on the soil samples collected from the field, stones and pebbles that could hinder weed seeds germination were removed through passing the soils in a 3mm sieve. To ensure high germination percentage of the weed seeds, the samples were treated with gibberellic acid at a concentration of 1000 mg/l (De Mello *et al.*, 2009) to break weed seeds dormancy. Soil samples from each of the four farming systems were spread out in the germination trays measuring 375 mm x 300 mm x 30 mm each. Where a total of 216 trays (120 from Thika trial plots and 96 from Chuka trial plots), each representing one replicate were used (Plate 2.1). After this, the soil sample was randomly placed inside a greenhouse at KALRO Kabete Food Crop Research Institute. Each tray received 300ml of water on daily basis (using a spray bottle) to maintain moderate soil moisture favorable for weed seeds to germination, all the trays were exposed to equal amount light that was evenly distributed inside the greenhouse.

Plate 2.1. Indicating soil sample preparation work inside the KALRO Kabete laboratory.