EFFECTS OF CONSERVATION AGRICULTURE ON WEED ABUNDANCE AND HERBICIDE RESIDUES IN A HUMIC NITISOL IN KABETE SUB-COUNTY, KENYA

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DECLARATION

I hereby declare that this thesis is my true work and has not been submitted for the award of any degree to any other university.

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DEDICATION

This thesis is dedicated to the entire Akello Family especially my late Grandparents Mr. Ibrahim Akello, Mrs. Prudenciana Akumu Otiato, my mum Resula Akello, and my uncle Felix Amu who nurtured my love for academics.

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LIST OF ABBREVIATIONS AND ACRONYMS

AHAS - Acetohydroxyacid Synthase

ALS - Acetolactate Synthase

ANOVA – Analysis of Variance

CA - Conservation Agriculture

CT - Conservation tillage

CAN – Calcium Ammonium Nitrate

DAP – Di-ammonium Phosphate

EI – Electron Impact

FAO - Food and Agriculture Organization

GC - MS – Gas Chromatography - Mass Spectrometry

GC - Gas Chromatography

HRAC - Herbicide Resistance Action Committee

HRGC - High resolution gas chromatography

HRMS - High resolution mass spectrometry

HSD - Honest Significant Difference

LOD - Limit of Detection

LOQ - Limit of Quantification

MS - Mass Spectrometer

MoALFC-Ministry of Agriculture, Livestock, Fisheries and Cooperatives

NIST - National Institute of Standards and Technology

PS – Photosynthesis

PH – Potential of Hydrogen

RCBD – Randomized Complete Block Design

SIM – Selected Ion Monitoring

USEPA – US Environment Protection Agency

WSSA - Weed Science Society of America

ABSTRACT

Conservation agriculture has often been fronted as a sustainable practice that minimizes soil degradation while improving crop yields and soil fertility through its principles of minimum tillage, mulching and crop rotation. However, the reduction of tillage operations has led to the challenge of weed control under CA. This has also led to the increased dependence on herbicides for weed control. However, these herbicides have a higher chance of persisting in the soil due to their chemical properties and soil properties. This study was conducted for two seasons (May- September 2021) and (October 2021- February 2022). Its main objective was to assess the effects of conservation agriculture on weed abundance and herbicide residues in soil as influenced by herbicide application under different tillage methods. It specifically assessed the effect of different tillage methods and herbicide application on the abundance and diversity of weeds, the distribution of Atrazine, S-metolachlor, and Nicosulfuron herbicides in soil under different tillage methods and determined the levels of Atrazine, S-metolachlor, and Nicosulfuron herbicides left in the soil under different tillage methods.

The three treatments were a combination of herbicides and the type of tillage methods. They were: (i) ripping + S-metolachlor 290 g l^{-1} + Atrazine 370 g l^{-1} + Nicosulfuron 240 g l^{-1}, (ii) jab planter + S-metolachlor 290 g l^{-1} + Atrazine 370 g l^{-1} + Nicosulfuron 240 g l^{-1} and (iii) hand hoeing with no herbicides applied (control).The treatments were replicated four times in a randomized complete block design (RCBD). The data was collected on weed abundance and diversity as affected by tillage methods and herbicide application as well as herbicide distribution and persistence as affected by ripping and jab planter tillage methods. The weed data was analysed using R statistical software while soil samples were analysed for Atrazine, S-metolachlor and Nicosulfuron using Gas Chromatography with Mass Spectrometry (GC-MS).

The results showed that in the first season tillage methods combined with herbicide application had a significant effect ($P < 0.0038$) on species richness with ripping recording the highest average species number of 2.05 m^{-2}, jab planter at 1.78 m^{-2} and hand hoe (control) at 1.53 m^{-2}. Shannon diversity also significantly varied ($P < 0.0072$) with ripping recording the highest average value of 0.59, followed by jab planter at 0.47 and finally the hand hoe (control) at 0.37. In the second season, tillage and herbicide application had no significant effect on species richness and Shannon diversity.

Atrazine, S-metolachlor and Nicosulfuron significantly leached down the soil profile based on the tillage methods applied. At 0-15cm in ripping and jab planter tillage methods, residues were 14.7 mg kg^{-1}, 15.6 mg kg^{-1} for atrazine, 18.5 mg kg^{-1}, 17.5 mg kg^{-1} for S-metolachlor and 5.6 mg kg^{-1} ,6.2 mg kg^{-1} for Nicosulfuron respectively. At 15-30cm in ripping and jab planter residues were 2.4 mg kg^{-1}, 1.3 mg kg^{-1} for Atrazine, 2.4 mg $kg^{-1,}$ 1.3 mg kg^{-1} for S-metolachlor, and 1.4 mg kg^{-1} and 1.4 mg kg^{-1} for Nicosulfuron respectively. While herbicides are increasingly being embraced by farmers practicing conservation agriculture, their persistence and leaching in soil presents an ecological and human health challenge. To reduce these risks associated with herbicide residues persistence in the soil, it is imperative for the government of Kenya to make available biopesticides and for farmers to embrace alternative ways of weed control such as use of biopesticides, use of agronomic practices like mulch and crop residues, push pull technique, crop rotation, and intercropping of crops with allelopathic properties such as sorghum that inhibit growth of weeds.

CHAPTER ONE: INTRODUCTION

1.1 BACKGROUND INFORMATION

Conservation agriculture (CA) is an agricultural practice that aims at minimizing soil degradation, improving crop yields and soil fertility through its principles of reduced tillage, mulching and crop rotation (FAO, 2017; Nyirenda and Balaka, 2021; Farooq et al., 2011). It can improve soil water infiltration (Mhlanga and Thierfelder, 2021), conserve moisture (Mutonga et al.,2019), prevent loss of arable land, enhance biological processes above- and belowground while regenerating degraded lands (FAO, 2017). Globally, conservation agriculture is largely capturing the attention of farmers. In the year 2015/16, it was practiced on about 180 million ha of cropland at the global scale, an increase from 106 million ha in the year 2008/09 (Kassam et al., 2018). In Africa, conservation agriculture is also on the rise amongst farmers, with the total area standing at 1.5 million ha in 2015/16, up from 0.48 million ha in 2008/09 (Kassam et al., 2018). In Kenya as of 2011, the total area under conservation agriculture was 33,100 ha (FAO, 2015). This increase in its uptake can be attributed to the various benefits it has over conventional tillage. Farooq et al. (2011), for instance, reported a slight increase in general crop yields over time under conservation agriculture system relative to conventional tillage. The increase in yield was attributed to the ability of conservation agriculture to minimize soil erosion, increase aggregate distribution and stability, increase infiltration and water content of the soil. Similarly, Otieno et al. (2019) notes that on average no-till combined with crop residue retention recorded a higher net benefit of Kshs. 29,569 per ha than conventional tillage without crop residue in Embu and Kirinyaga counties. The authors attributed the benefits to retention of soil moisture and the release of nutrients upon the decay of the crop residues, thus increasing crop yields and improving the economic status among resource-constrained farmers.

Weed management due to minimum tillage is a problem in conservation agriculture as opposed to conventional tillage. This is because reducing tillage tends to necessitate aggressive weed growth (Kaumbutho and Kienzle, 2007). As such, weed control in conservation agriculture mostly relies on the extensive application of herbicides (Zahan et al., 2015). The application of herbicides in weed control continues to rise. Between 1990 and 2019, herbicide use on a global scale rose from 40 to 53 percent of the total pesticides used (FAO, 2021). On a regional basis, Africa's herbicide use rose from 23 percent between 1990 and 1999 to 32 percent between 2010 and 2019 (FAO, 2021). In Kenya, herbicides have been used within conservation agriculture systems to control weeds as noted by Yeray (2012). As at 2020, Kenya imported herbicides worth Kshs. 3.6 billion, an increase from 1.8 billion in 2015 (Agrochemicals association of Kenya/Crop life Kenya, 2020). Increased use of these herbicides has however raised concerns such as contamination of soil, surface and groundwater, as well causing unknown long-term human health effects (Chauhan et al., 2012). These concerns have also been extended to the effect of herbicides on soil microorganisms that are key in crop production, since herbicide treatments have been found to have significant negative effects on soil microbes (Adhikary et al., 2014).

Despite their extensive use, farmers are unaware of the safe use of herbicides. Such indiscriminate use of the chemicals could be dangerous to the environment and human health (Zahan et al., 2015). Although they are designed in a way that they degenerate from the environment after their intended work, a few of them persist in the environment, especially under conservation tillage systems, posing a threat to the soil, crops, micro-organisms, and water resources (Janaki et.al, 2015).

1.2 STATEMENT OF THE PROBLEM

While conservation agriculture aids the continuance of a permanent soil cover, reduced soil tillage, and diversified plant varieties, it also leads to increased weed infestation Sekutowski

(2009) and increased dependence on herbicides for the management of weeds (FAO, 2017). The elimination of tillage activities prior to planting in conservation agriculture, leads to aggressive weed growth as it creates sustainable conditions for the growth of some weed species (Kaumbutho and Kienzle, 2007; Travlos et al. 2018) which has necessitated the need for nonselective pre- and post-emergence herbicides for weed control (Eslami, 2014). The use of these herbicides' aids in the significant reduction of weed densities, saves time and labour (Muoni et al., 2013). This alludes to their take up by farmers as shown by Yeray (2012) that, 22 out of 25 conservation agriculture smallholders in Bungoma, Kenya, normally sprayed herbicides prior to planting. This dependency on herbicides has brought about concerns such as pollution of soil, water resources and concealed indelible impacts on human health due to the persistent nature of herbicides (Chauhan et al., 2012). Whereas herbicides are increasingly used by farmers in Kenya, there is a lack of sufficient data on their persistence in soils under conservation agriculture. For this reason, this study aimed at assessing the movement and persistence of herbicides in soils under conservation agriculture systems in Kabete sub-county.

1.3 JUSTIFICATION

Weed abundance and diversity are higher in conservation agriculture than in conventional tillage (Montanya et al.2013; Govindasamy et al. 2020). As a result, herbicides are increasingly fronted as an effective way of controlling and managing weeds in conservation agriculture. There is the challenge of them persisting in the soil thus affecting basic soil functions and soil organisms. In turn causing the very damage conservation agriculture seeks to address. An understanding of their persistence in soils under conservation agriculture is therefore needed towards ensuring the sustainable conservation of soil resources. Although studies such as that carried out by Yeray (2012) depict that indeed herbicides are used in conservation agriculture in Kenya, fewer of these studies focus on how much of the herbicide residues are left in the soil after application and the effect of conservation tillage in their residual activity. Therefore, there is need for data illustrating the relationship between herbicide residues and tillage methods within conservation agriculture. Thus, this study will bring a better understanding of how tillage methods within conservation agriculture affect the abundance of weeds, persistence, and distribution of herbicides in soil.

1.4 OBJECTIVES

1.4.1 BROAD OBJECTIVE

To assess the effects of conservation agriculture on weed abundance and herbicide residues in soil as influenced by herbicide application under different tillage methods in Kabete sub-county.

1.4.2 SPECIFIC OBJECTIVES

- To assess the effect of different tillage methods and herbicide application on the abundance and diversity of weeds in Kabete sub-county.
- To assess the distribution of Atrazine, S-metolachlor, and Nicosulfuron herbicides in soil under different tillage methods in Kabete sub-county.
- To determine levels of Atrazine, S-metolachlor, and Nicosulfuron herbicides left in the soil under different tillage methods in Kabete sub - county.

1.5 RESEARCH HYPOTHESIS

This study hypothesized that:

- Tillage combined with herbicide application will decrease the abundance of weeds
- The distribution and persistence of the herbicide residues will vary based on the different tillage methods.
- Herbicide levels in the soil will vary based on the different tillage methods.

CHAPTER TWO: LITERATURE REVIEW

2.1 CONSERVATION AGRICULTURE

Conservation Agriculture (CA), is a tillage method that employs several agronomic technologies with the aim of improving the soil environment, reducing land deterioration, increasing water and nutrient use productivity. It encompasses three principles; least mechanical soil interference, constant soil cover and species variation (FAO, 2016; FAO 2017). The three CA principles are globally significant to every farming environment (FAO, 2011). The first two concepts are key in CA and need specialized equipment for the sowing operations on unplowed land with residues, management of cover crops or plant residues and control of weed (Mkomwa et al., 2015). CA ensures prompt farm activities and improvement of land cultivation for rainfed and irrigated production (Friedrich et al., 2011). It also increases biodiversity, reduces soil erosion, intercepts surface runoff, increases soil organic matter and improves natural biological processes above and underneath the surface of the ground as compared to conventional practices (FAO, 2011; Palm et al., 2014). Its practices of intercropping, mulching and pit planting were also found to contribute to soil fertility restoration in agricultural land (Nyirenda and Balaka, 2021). During the dry season, it provides a buffer to crop production as it ensures high soil moisture retention which results in higher yields than conventional intensive tillage systems (Palm et al., 2014; Friedrich et al., 2011; Mutonga et al. 2019). It is therefore viewed as a suitable, sustainable and environmentally friendly system for crop cultivation (Hobbs et al., 2007). As such there has been a growing trend towards conservation agriculture (CA) to enhance sustainability without compromising land productivity (Chauhan et al., 2012). CA was carried out worldwide on approximately 180 M ha of farmland, in 2015 and 2016. This is the equivalent of about 12.5% of the overall universal farmland. In Africa, conservation agriculture was also seen to be on the rise amongst farmers with the total conservation agriculture area standing at 1.5 M ha in 2015/16 from 0.48M ha in 2008/09 (Kassam et al., 2018). It was taken up by 78 countries in 2015/2016, which signified a rise in adoption by 42 additional nations since 2008/2009 (Kassam et al., 2018).

2.2 Conservation Tillage

Tillage involves the mechanical manipulation of the soil. Through this process, tillage impacts the temperature of the soil, preservation of soil water, infiltration and evapotranspiration process consequently affecting the environment negatively (Busari et al., 2015). Conservation tillage (CT), a practice that was borne out of the American dust bowl of the 1930s (Hobbs et al., 2007), is key in minimizing soil degradation and achieving the rising urge for food for the skyrocketing human population. It encompasses a broad set of operations that aim at leaving a certain amount of crop residues on the surface of the soil in order to elevate water seepage and minimize soil erosion (Reicosky, 2015). CTIC (2004), also defines conservation tillage as any agricultural method that shelters 30% or more of the soil with crop remains after planting to minimize the washing away of soil by water. Retention of the crop residues on the surface of the soil helps to shield it from the direct impact of raindrops and sunlight whereas minimal soil disturbances maintain the movement of soil air and water as well as the enhancement of biological activities (Busari et al., 2015). Conservation tillage is therefore an essential practice in conservation agriculture.

Conservation tillage encompasses several tillage practices. They are: no tillage, strip tillage, mulching, ridging and contour tillage (Busari et al., 2015). No till systems keep more than 70% of the soil surface covered by plant residues and further ensures that from the harvesting period to the seeding, the soil is left unperturbed. The only disturbance carried out is a slender band made by a row cleaner attached to the planter or drill. No till systems have been found to have an impact on the weeds, in that they concentrate the weed seeds near the soil surface causing likely germination but also exposing them to greater mortality risks through weather variability and predation (Nichols et al., 2015). Mulch tillage, on the other hand is a tillage method that leaves 30% of the crop remnants on the land after sowing. The remnants are partially added using chisels or field cultivators. In this tillage system, the mulch suppresses the weed seeds, preventing their germination. However, the successful weed control by mulches is highly dependent on the presence of a substantial biomass (Reberg-Horton et al., 2012).

In ridge till, raised dams or seedbeds are constructed, and remade yearly during row cultivation. Crop residues are left on the surface in between the ridges which are used to grow crops. Ridge till protects the soil from erosion and prevents nutrients from leaching hence creating a conducive environment for crop development (Alagbo et al., 2022). In regards to weeds, ridge tillage pushes weed seeds 3 cm to 6 cm off the soil surface from the ridge to the inter-rows (Klein et al., 1996). These weed seeds can be suppressed by living mulches or cultivation using hand hoe in the inter rows or the ridges (Klein et al., 1996; Alagbo et al., 2022). Strip tillage applies tillage operations only to tinier strips or zones of soil where single rows will be planted for the next crop. It however, aids in rapid warming of the soil as a result of the removal of crop residues and disturbance of the soil in the berm (Morrison, 2002). Weed population dynamics under strip tillage are complex because of the ability of the weed propagules to move readily between the tilled and untilled zones as well as the potential interaction between the edaphic and biotic factors between the zones (Brainard et al., 2013). Depending on the amount of residue available, strip tillage leads to a higher survival and reproduction of weeds in the untilled between row zone (Brainard et al., 2012).

2.3 Weed Management in Conservation Agriculture

Vats (2015) defines weeds as unwanted, tenacious plants that damage and interfere with the growth of other crops which in turn affects agriculture, income and the economy of a country. Weeds are a major limitation in CA-based systems (Jena and Jena, 2017), due to the elimination of tillage activities. As such, there is minimal soil disturbance that leads to a change in the weed groups, weed growth dynamics and a concentration of about 60% - 90% of weed seeds in the top 5 cm of soil surface as opposed to the conventional tillage systems (Nichols et al., 2015; Rahman, 2017; Jena and Jena, 2017). Weed behavior and interaction with crops tends to be complex as CA often results to weed changes leading to a rise in the density of particular weeds especially those whose growth is not triggered by light (Jena and Meena, 2017). This is opposed to the conventional tillage systems, which can control weeds effectively by uprooting and burying them deep into the soil thereby hindering the emergence of weed seeds (Jena and Meena, 2017; Chauhan et al., 2012).

Weed pressure and crop yield are inversely related (Nichols et al., 2015; Rahman, 2017). The complexities of high weed density in CA leads to low crop yields if not properly controlled. Mashingaidze et al., (2012), noted that cowpea grain yield of less than 300 kg ha^{-1} was obtained in minimum tillage systems in comparison to the 413 kg ha^{-1} obtained from conventional tillage systems. Apart from weed management, waterlogging in soils, competing uses for crop residues, lack of experience by farmers in the initial years of CA adoption and a slow increase in soil fertility are also attributed to a decrease in crop yields (Mashingaidze et al., 2012; Rusinamhodzi et Al., 2011; Farooq et al., 2011). CA systems have also been shown to record higher yields than conventional systems. Kodzwa et al., 2020, reported that reduced tillage increased maize grain yield when compared when conventional tillage. Farooq et al. (2011) also found up to 80% yield increase from a range of CA systems compared to those of conventional systems. Similarly, Thierfelder et al. (2013) noted that yield benefits in CA over conventional tillage systems were greater especially from the 5th season although, in some instances, greater yields on CA were recorded almost immediately.

Weed management is therefore essential in reducing weeds and obtaining potential yield gains offered by CA systems. A number of agronomic practices that favor reduction of weed growth are employed in conservation agriculture systems (Rahman, 2017). These include practices such as the use cover crops and crop residues as mulch, stale seedbed practice, crop rotation, competitive crops, optimum sowing rate, date and row spacing and the use of post and pre-emergent herbicides (Eslami,2014; Chauhan et al., 2012). The removal and minimization of tillage operations in CA-based agricultural systems has made farmers to turn to herbicides for weed elimination as it saves on labor (Eslami, 2014; Pacanoski, 2007; Rahman, 2017). Herbicides play a critical role in controlling weeds during the initial years of CA adoption at least, in large cropping areas where hand weeding would be inefficient (Rahman, 2017). Non-selective post-emergence herbicides such as glyphosate, paraquat, and glufosinate are currently used to eliminate weeds prior to the planting of crop in conservation agriculture systems (Chauhan et al., 2012). Aside from being effective in weed control, herbicides also offer a wide array of benefits such as saving crop land from erosion, saving energy and increasing crop productivity (Pacanoski, 2007).

2.4 HERBICIDES AND THEIR CLASSIFICATION

Herbicides are the widely used pesticides in a larger array of countries with their origin pegged in the second World War (Vats, 2015). They are classified under pesticides and they are used to kill weeds and control their spread in cultivated and non-cultivated areas (Sanganyando, 2015; Vats, 2015). They vary in chemical arrangement, physicochemical properties and toxicity (Sanganyando, 2015). The Herbicide Resistance Action Committee (HRAC), classifies herbicides into groups according to their modes of action and chemical classes (HRAC, 2020). Herbicides can also be classified according to their method of application, target sites, time of application and specificity (Menne and Köcher, 2008; Vats, 2015).

Table 2.1: Classification by mode of action and chemical classes. Source: (HRAC, 2020)

LEGACY HRAC GROUP	MODE OF ACTION	CHEMICAL FAMILY
A	Inhibition of Acetyl CoA Carboxylase	Cyclohexanediones (DIMs), Aryloxyphenoxy-propionates (FOPs) Phenylpyrazoline
B	Inhibition of Acetolactate Synthase	Pyrimidinyl benzoates Sulfonanilides

		Triazolopyrimidine - Type 1 Triazolopyrimidine - Type 2 Sulfonylureas Imidazolinones Triazolinones
C1	Inhibition of Photosynthesis at PSll - Serine 264 Binders	Triazines Triazolinone Triazinones Uracils Phenlcarbamates Pyridazinone
C2	Inhibition of Photosynthesis at PSll - Serine 264 Binders	Ureas Amides
C3	Inhibition of Photosynthesis at PSll - Histidine 215 Binders	Nitriles Phenyl-pyridazines Benzothiadiazinone
D	PS I Electron Diversion	Pyridiniums
E	Inhibition of Protoporphyrinogen Oxidase	Diphenyl ethers Phenylpyrazoles N-Phenyl-triazolinones N-Phenyl-imides (procide acitive form)
F1	Inhibition of Phytoene Desaturase	Phenyl ethers N-Phenyl heterocycles Diphenyl heterocycles
F2	Inhibition of Hydroxyphenyl Pyruvate Dioxygenase	Triketones Triketones (procide) Pyrazoles (procide) Pyrazoles Isoxazoles
T	Inhibition of Homogentisate Solanesyltransferase	Pyridazinedione
F4	Inhibition of Deoxy-D-Xyulose Phosphate Synthase	Isoxazolidinone
G	Inhibition of Enolpyruvyl Shikimate Phosphate Synthase	Glycine
H	Inhibition of Glutamine Synthetase	Phosphinic acids
I	Inhibition of Dihydropteroate Synthase	Carbamate
K1	Inhibition of Microtubule Assembly	Dinitroanilines Pyridines Phosphoroamidates Benzoic acid Benzamides
K2	Inhibition of Microtubule Organization	Carbamates
L	Inhibition of Cellulose Synthesis	Triazolocarboxamide Benzamides Alkylazines Nitriles
M	Uncouplers	Dinitrophenols
K3	Inhibition of Very Long-Chain Fatty Acid Synthesis	Azolyl-carboxamides α-Thioacetamides Isoxazolines Oxiranes α-Chloroacetamides α-Oxyacetamides Thiocarbamates Benzofurans
O	Auxin Mimics	Pyridine-carboxylates Pyridyloxy-carboxylates Phenoxy-carboxylates Benzoates

		Quinoline-carboxylates Pyrimidine-carboxylates Phenyl carboxylates
P	ATI	Aryl-carboxylates
Q	Inhibition of Fatty Acid Thioesterase	Benzyl ether
R	Inhibition of Serine-Threonine Protein Phosphatase	Other
S	Inhibition of Solanesyl Diphosphate Synthase	Diphenyl ether
F3	Inhibition of Lycopene Cyclase	Triazole
Z	Unknown	Arylaminopropionic acid Acetamides Benzamide Chlorocarbonic acids Phosphorodithioate Trifluoromethanesulfonanilides

2.5 ATRAZINE, S-METOLACHLOR AND NICOSULFURON

Atrazine, S-metolachlor and Nicosulfuron herbicides are employed globally for weed elimination in crops such as maize, soybeans, and sunflower. Their use has risen recently particularly in lands under no-till (Bedmar et al., 2017).

2.5.1 ATRAZINE

Atrazine is a selective herbicide that is categorized under the triazine class of herbicides and falls under the legacy HRAC group C1, HRAC and WSSA group 5 (HRAC, 2020). It is the earliest of its kind and was brought to light by J.R. Geigy, Ltd. in Switzerland in 1958 (LeBaron et al., 2008). It works by inhibiting Photosynthesis at photosystem II - Serine 264 Binders and has a systemic action with residual and foliar activity (Heap, n. d.). It is commonly used as a pre-emergence herbicide for the control of broad-leaved weeds and grasses in maize systems (Rasool et al.,2020). It has a low aqueous solubility, is volatile, moderately mobile, it has the possibility of leaching to groundwater, it is moderately persistent and has an average half-life in soil of around 60-75 days (Lewis et al., 2016; Hanson et al., 2020). In humans, Atrazine is an endocrine disruptor and causes birth defects (Pathak and Dikshit, 2011), whereas in aquatic life, it has been found to lower survival rates and inhibit cortisol response in fish (Koakoski et al., 2014). It is also toxic to earthworms (Mosleh et al., 2003; Oluah et al., 2016) and bees (Araujo et al., 2020).

2.5.2 S-METOLACHLOR

It is an isomer herbicide mixture that is classified under the Chloroacetamide family (Zemolin et al., 2014). It falls in the legacy HRAC group K3, HRAC and WSSA group 15 and works by hindering cell division (Inhibition of Very Long-Chain Fatty Acid Synthesis) and elongation in plants due to interference with a number of enzymes (HRAC, 2020). It was first registered in 1997 and is used as a selective pre-emergent herbicide to control grasses and some broad - leaved weeds in a large range of crops such as Maize, Sunflower and Soybean (Meyer and Scribner, 2009; Rose et al., 2016).

Although S-metolachlor exhibits moderate to long persistence in soils, this varies based on soil factors, soil management and environmental conditions (Zemolin et al., 2014). It was found to have a half-life of 97 and 106 days within reduced tillage and no tillage systems respectively (Alleto et al., 2013). It has the possibility to contaminate ground water and surface water because of its moderate aqueous solubility of 488 mg/L at 20^{o}C (Senseman, 2007). It is volatile with a vapor pressure of 1.73×10^{-3} Pa at 20 ^{O}C (Zemolin et al., 2014), exhibits high toxicity to mammals on short term exposure (Lewis et al., 2016), and moderate toxicity to fish where it was found to cause delays in the ontogenic development and reduced growth of cray fish (Velisek et al., 2019).

2.5.3 NICOSULFURON

Nicosulfuron is a post emergent herbicide that belongs to the sulfonylurea's chemical family and is used to control annual grass weeds in maize crops. (Joly et al. 2013). It falls under legacy HRAC group B, HRAC and WSSA group 2 (HRAC, 2020). It works by inhibiting the action of the Acetolactate Synthase (ALS) enzyme also known as Acetohydroxyacid Synthase

(AHAS) which leads to the plant wilting and eventual plant death (Sherwani et al., 2015). It has a low volatility (Sondhia et al,.2013), a high aqueous solubility, high leachability, (Cueff, 2020) and non-persistent but mobile in soil (Lewis et al., 2016). Ahmadi et al. (2017), found Nicosulfuron to have a half-life of 14-20 days at different doses and depth in maize field soil. It is moderately toxic to mammals on short term exposure, birds, earthworms, honeybees, fish and aquatic invertebrates (Lewis et al., 2016).

2.6 HERBICIDE USE IN AGRICULTURAL PRODUCTION

The use of herbicides across the globe continues to rise due to the rising cost of labor and quick weed control in crop and non-crop areas (Sondhia, 2014). Between 2007 and 2015, herbicides constituted between about 40% and 50% of the total pesticides consumed globally (Sanganyando, 2015; Vats, 2015). FAO (2021) estimates that between 1990 and 2019, herbicide use on a global scale rose from 40 to 53 percent of the total pesticides used. On a regional basis, Africa's herbicide use rose from 23% between 1990 and 1999 to 32% between 2010 and 2019 (FAO, 2021). Kenya's demand for herbicides has been steadily increasing (Route to Food, 2019). In 2018, Kenya imported 17,803 tonnes of pesticides valued at US$ 128 million. Of these total pesticide imports, herbicides, insecticides, and fungicides accounted for about 87% in volume and 88% of the total cost of pesticide imports (Route to Food, 2019). As at 2020, Kenya's herbicide imports were Kshs. 3.6 billion, an increase from 1.8 billion in 2015 (Agrochemicals association of Kenya/Crop life Kenya, 2020). The increase in herbicide use in Kenya is attributed to the urge by more farmers to control weeds on their farms (Yeray 2012; Agrochemicals association of Kenya/Crop life Kenya, 2020).

2.7 HERBICIDE RESIDUES IN SOIL

The World Health Organization defines pesticide/herbicide residues as specified substance in food, agricultural commodities or animal feed resulting from the use of a pesticide and includes any derivatives of a pesticide, such as conversion products, metabolites, reaction products and impurities considered to be of toxicological significance. Sondhia (2014), refers to an herbicide residue as the quantity of a herbicide that exists in the soil for an extended period of time usually more than one planting season after its initial application, in its primary or a similar but phytotoxic form. Herbicides persistence in the soil is expressed as half-life (DT_{50}), which is the time needed for the dissipation of fifty percent of the initial applied herbicide molecules from the soil (Helling, 2005).

Herbicide residues in the soil are dependent upon several factors. These factors are: soil factors such as texture, organic matter content, and PH; climatic conditions such as temperature, sunlight and moisture; and herbicide properties such as water solubility and vapor pressure (Ying and Williams,2000; Curran, 2001; Helling 2005; Sondhia 2014;). The fate of herbicide in soil is dependent on processes such as volatilization, adsorption leaching, degradation by microbes, chemical processes and photodecomposition (Osgerby, 1973; Sondhia, 2014; Khan, 2016). There is also a variation in the ability of the different herbicide families to persist in the soil. Herbicide families such as the triazines (Jablonowski et al.,2011), uracils, phenylureas, sulfonylureas, dinitroanilines, isoxazolidinones, imidazolinones, and certain plant growth regulators belonging to the pyridine family mostly persist in the soil (Hager and Sprague, 2003).

2.8 Herbicide residues in soils under Conservation Agriculture systems

Herbicides have been shown to persist in soils within conservation agriculture systems. Despite their persistent nature, their adoption is underpinned by the estimate that agricultural losses would increase by about 50% without their use (Pacanoski, 2007). Curran (2001) notes that minimum tillage along with no tillage tend to leave a higher accumulation of herbicide near the surface zone. Prado et al. (2014) found that soils under conservation agriculture had higher atrazine herbicide retention potential than soils under conventional tillage. Similarly, Labad et al. (2019) observed an accumulation of glyphosate in conservation agriculture. Locke and Bryson (1997), observed that the sorption of herbicides was higher in surface soils within minimum tilled lands than from tilled lands. Similarly, in their study, Porfiri et al. (2015) showed that Imazapyr was only sorbed by no tillage soils with soil adsorption coefficient values ranging from 0.22 to 1.1 L kg^{-1}. Conservation agricultural practices also have the ability to modify herbicide dissipation behavior in soils. For example, Janaki et al. (2020) observed that the dissipation of pendimethalin was slow under CA practices as compared to conventional tillage practices. Other studies such as Bhagel et al. (2020), attribute the occurrence of herbicides in conservation agriculture systems to the engagement of soil microbes in crop residue breakdown for food or source energy which slowed down decomposition of herbicides leading to herbicide residues retention in the soil for extended period of time.

CHAPTER THREE: MATERIALS AND METHODS

3.1 Study area

The experimental site was at Kabete Field Station of the University of Nairobi (Figure 3.1). It is located about 10 km Northwest of Nairobi, in Kabete Sub-County, Kiambu County. It lies at 1°15′ S and 36° 44′ E with an elevation of 1941 meters above sea level (Karuku et al., 2012; Karuku et al., 2014; Onwonga et al., 2020). The area receives a mean annual rainfall of 1006 mm, in a bimodal pattern. The long rains occur in Mid-March to May and the short rains Mid October to December. The ratio of annual average rainfall to annual potential evaporation, r/Eo is 58% (Karuku et al., 2014). Between the months of April 2021 to March 2022, the area received an annual rainfall of 924.4 mm with the highest rainfall amount received in April 2021 being 272.2 mm (Kenya Meteorological department, 2022). Soils are classified as humic Nitisols. They are deep, well drained, red tropical soils that are strongly structured and with more than 30% clay (Gachene, 1989; WRB, 2006).

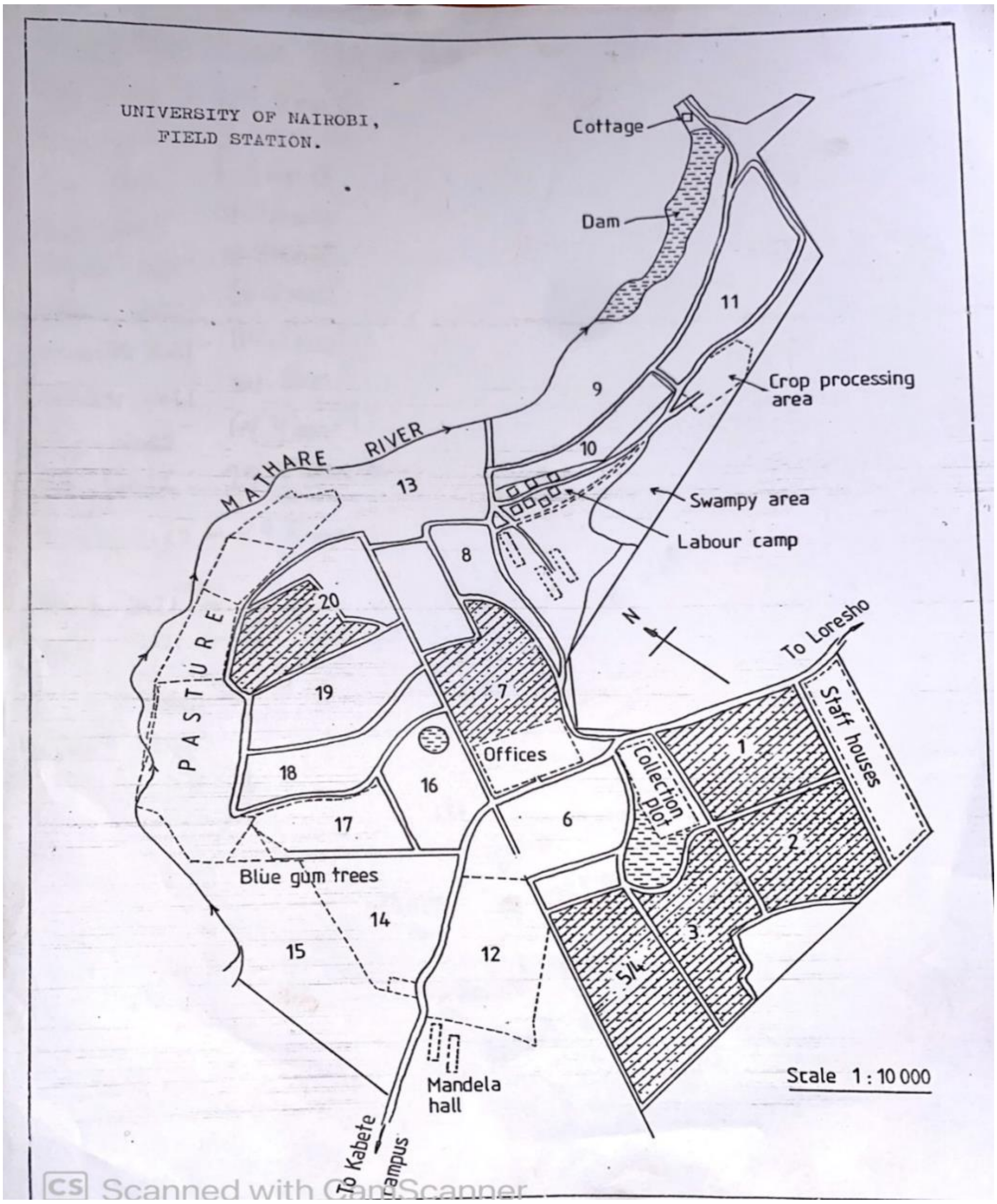

Figure 3.1: Map of the Kabete field station where the study was done (block 18-1).

3.2 EXPERIMENTAL LAYOUT AND DESIGN

The piece of land that was used in the study was under carrots with no pesticides used, before being left fallow for two years. This study was conducted over a period of two rainy seasons; the long rains season running from May – September 2021 and short rain season from October 2021 – February 2022. The treatments were a combination of herbicides and the type of tillage methods (Table 3.1). They included: (i) ripping + 290 g l^{-1} S-metolachlor + 370 g l^{-1} Atrazine

+ 240 g l^{-1} Nicosulfuron, (ii) jab planter + 290 g l^{-1} S-metolachlor + 370 g l^{-1} Atrazine + 240 g l^{-1} Nicosulfuron and (iii) hand hoeing as the control with no herbicides applied. The treatments were replicated four times in a randomized complete block design (RCBD).

Table 3.1: Treatments applied and their recommended rates of application

Tillage method	Herbicide application rate
Hand hoeing (HH)	No herbicides used
Ripping + 290 g l^{-1} S-metolachlor + 370 g l^{-1} Atrazine + 240 g l^{-1} Nicosulfuron	3 l ha^{-1} (290 g l^{-1} S-metolachlor + 370 g l^{-1} Atrazine) and 2 l ha^{-1} (240 g l^{-1} Nicosulfuron)
Jab planter + 290 g l^{-1} S-metolachlor + 370 g l^{-1} Atrazine + 240 g l^{-1} Nicosulfuron	3 l ha^{-1} (290 g l^{-1} S-metolachlor + 370 g l^{-1} Atrazine) and 2 l ha^{-1} (240 g l^{-1} Nicosulfuron)

3.2.1 LAND PREPARATION

Since the land had been fallow for two years, the weeds occurring on the land were collected and taken to the laboratory for identification before the commencement of the experiment. The land was then cleared by slashing and the residues left on the surface before the onset of rains. The piece of land was then divided into four blocks, and each block subdivided further into 3 plots, each measuring 25 m^2. A 2 m^2 path was left between the 25 m^2 blocks and a 1 m^2 path between the treatments.

A ripper attached to a tractor was used in ripping, with a distance between the furrows being 75 cm, and to a depth of 30 cm, and width of the furrow being 9 cm. The jab planter and hand hoe distance between the lines was 75 cm and the distance between the planting holes was 30cm.

Planting was done immediately after the onset of the rains. Hybrid maize variety SC Duma 43 (SC 403) was used as the test crop. Di-ammonium phosphate (DAP-18:46:0) fertilizer was applied at a rate of 125 kg ha^{-1} in all the plots. Calcium Ammonium Nitrate (CAN) was applied as the top dresser only in the second season at a rate of 60kg N ha^{-1}. Under ripping, planting was done in the ripped lines whereas in the jab planter and hand hoe it was done in the respective planting holes. The pre-emergence herbicides, S-metolachlor (290 g l^{-1}) + Atrazine (370 g l^{-1}) were applied at the recommended rate of 3 l ha^{-1} in the ripping and jab planter plots immediately after planting. Herbicide spraying was done after the rains to prevent the herbicides from being washed away. Weeding in the hand hoe plots was done 3 weeks after maize emergence. The post-emergence herbicide Nicosulfuron (240 g l^{-1}) was applied 30 days after germination of maize in the ripping and jab planter plots. It was applied at the recommended rate of 2 l ha^{-1}. The three herbicides are designed to control the growth of annual grasses and broad-leafed weeds in maize.

3.5 SAMPLE COLLECTION

3.5.1 WEED DATA COLLECTION

Weeds were collected and identified by their scientific names before the land was cleared. Weed identification was conducted at the University of Nairobi Laboratory of Plant Science and Crop Protection under the guidance of a proficient weed scientist and with reference to the book; Common weeds of East Africa (Terry & Michieka,1987). The data on weed abundance, was collected from 0 days, 14 days, 30 days, 50 days, and 120 days after planting. The weed count was done with the aid of 0.25 × 0.25 m quadrat which was tossed randomly at two places in each plot. The weeds were then counted, and the data recorded into a Microsoft Excel Spreadsheet.

3.5.2 SOIL SAMPLE COLLECTION

Soil samples were collected from five different points within each of the 12 plots, at two depths (0-15 cm and 15-30 cm). Approximately 200 g of each core was scooped using a soil auger. The cores were carefully mixed in an aluminium foil to form a composite sample. Initial soil samples were collected before spraying of the herbicides and this were used for reference

(Figure 3.2a). Soil sampling was done at 0 days, 30 days, and 120 days. Day zero and day 30 sampling was done two hours after the spraying of the pre- and post-emergence herbicides respectively to allow for the herbicides to settle in soil. Sampling was done over a period of 6 months; in May, June, and September 2021 (First Season) and the October, November 2021 and February 2022 (Second season).

Soil samples from the nearby maize and cabbage fields (500 m) were also collected to act as a second reference sample. Samples were then packed in sample bags, kept in cooler boxes and immediately transported to the University of Nairobi Pesticides laboratory, Chiromo, where they were immediately chilled and then stored by freezing to –20°C awaiting extraction, clean up and analysis.

Figure 3.2: Initial soil sampling (a) and sampling at day 120 (b).

3.6 SOIL SAMPLE EXTRACTION

Soil samples were removed from freezer and allowed to thaw for about 4 hours prior to extraction. Triplicates of 20 g samples were dried with activated anhydrous sodium sulphate

(Na_2SO_4) overnight before transferring to the soxhlet thimble and this was extracted with 175 ml of dichloromethane in a 200 ml round bottomed flasks for at least 16 hours in a soxhlet extractor set-up (Figure 3.3a). Two (2) ml of isooctane was added as keeper then concentrated to about 3 ml using LABCONCO rotary evaporator. The concentrated extracts were then put in vials and stored in a fridge at -4 ^{o}C a waiting clean-up process.

Figure 3.3: Soxhlet extraction of the soil samples (a) and clean-up of the extracts (b).

3.7 CLEAN-UP OF EXTRACTS

Clean-up of extracts was done using a column packed with 1 cm baked-out Na_2SO_4, and 15 g Al_2O_3 (Figure 3.3b.) Before use, the column was conditioned with 15 ml hexane after which the extracts were eluted with 170 ml hexane. Soil extracts were further taken through Sulphur removal using activated copper powder and the extracts further blown down to 0.5 ml by a gentle stream of nitrogen then analysis using Gas Chromatography with Mass Spectrometry (GC-MS).

3.8 SAMPLE ANALYSIS

3.8.1 INSTRUMENTAL ANALYSIS

The samples were analysed for the pesticides (S-metolachlor, Atrazine and Nicosulfuron) using gas chromatography (GC) (Agilent 6890N, Palo Alto, USA) coupled to a mass spectrometry (MS) (Agilent 5973, USA) equipped with a Thermo Scientific trace GOLD GC column (TG 5SILMS 30 m × 0.25 mm × 0.25 µm). The mass spectrometer was operated in selected ion monitoring (SIM) mode with the electron impact (EI+) ionization method in the resolution of >5000. The injection temperature was 280 ˚C and the detector temperature was 320 ˚C. Helium with a purity of 99.9999 % was used as the carrier gas at a flow rate of 1 mL min^{-1}. The GC oven temperature program was 90 ˚C (1 minute hold), then 40 ˚C min^{-1} to 180 ˚C, followed by 10 ˚C min^{-1} to 260 ˚C (2 minutes hold), and 25 ˚C min^{-1} to 320 ˚C (8 minutes hold). Split less injection mode was used and injection volume of 1 µL for all samples including the pesticides calibration standards, control samples and sample extracts (USEPA, 2010).

Identification of the targeted pesticide analytes was accomplished by comparing the retention time and mass spectra of analytes in samples to those of reference standards run following the same conditions. Confirmation of the compounds was carried out using the NIST mass spectral library, version 2.0 (Standard reference data program of the US National Institute of Standards and Technology). A specific pesticide was identified based on matching retention time to that of the reference standard (within a deviation of ±0.05 min) and the NIST library spectra (USEPA, 2010).

3.8.2 ATRAZINE, S-METOLACHLOR AND NICOSULFURON CALIBRATION CURVES

Quantitative analysis of S-metolachlor, Atrazine and Nicosulfuron was based on external calibration using multilevel calibrations curves of seven different concentrations of standards covering high, middle and lower bound limits. The correlation coefficient of calibration curves was greater than 0.99.

Determination of the concentration of Atrazine, S-metolachlor and Nicosulfuron in the soil samples was done based on calibration curves of Atrazine, S-metolachlor and Nicosulfuron standards of concentrations (mg/L). The concentration of each sample was obtained by calculating the peak areas obtained and plotting the curves which had straight lines through the equation y= mx + c, where Y was the peak area or instrument response, X was the analyte concentration, M was gradient, and C was a constant.

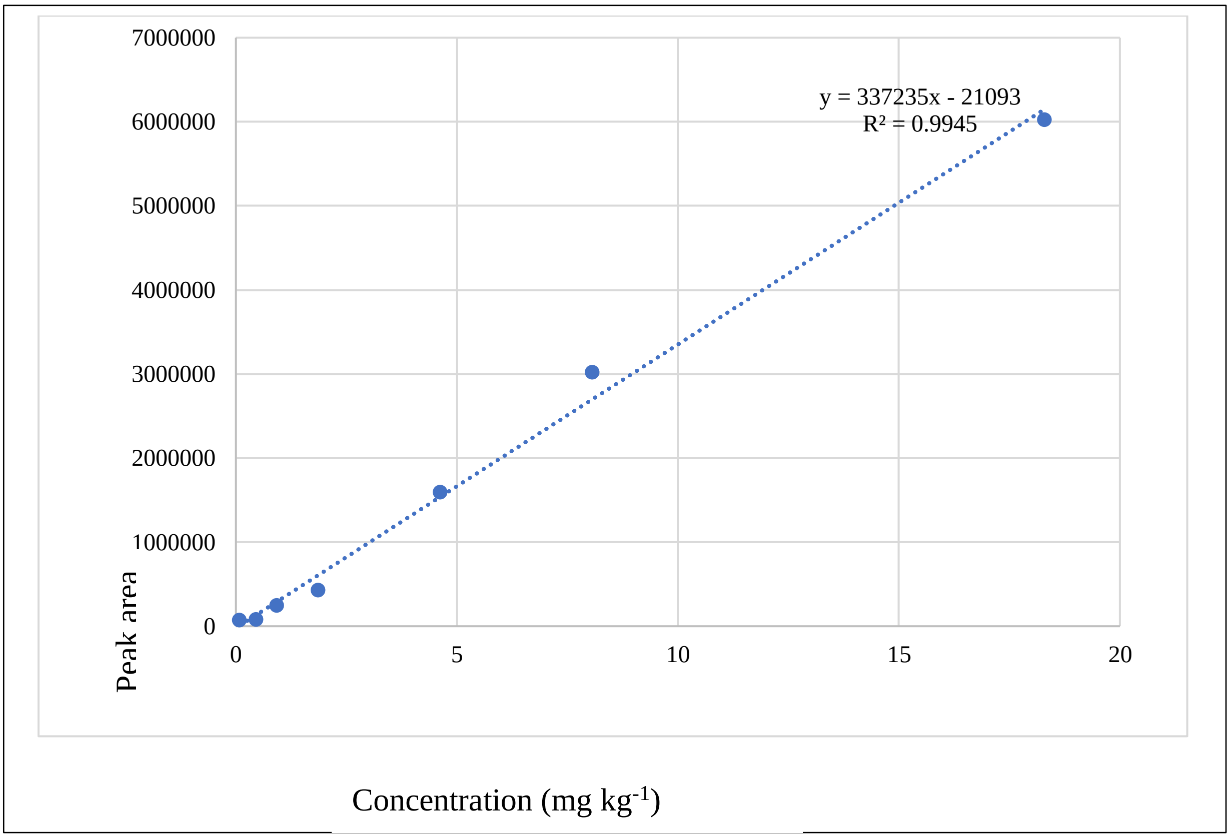

Figure 3.4 Calibration graph of S-metolachlor

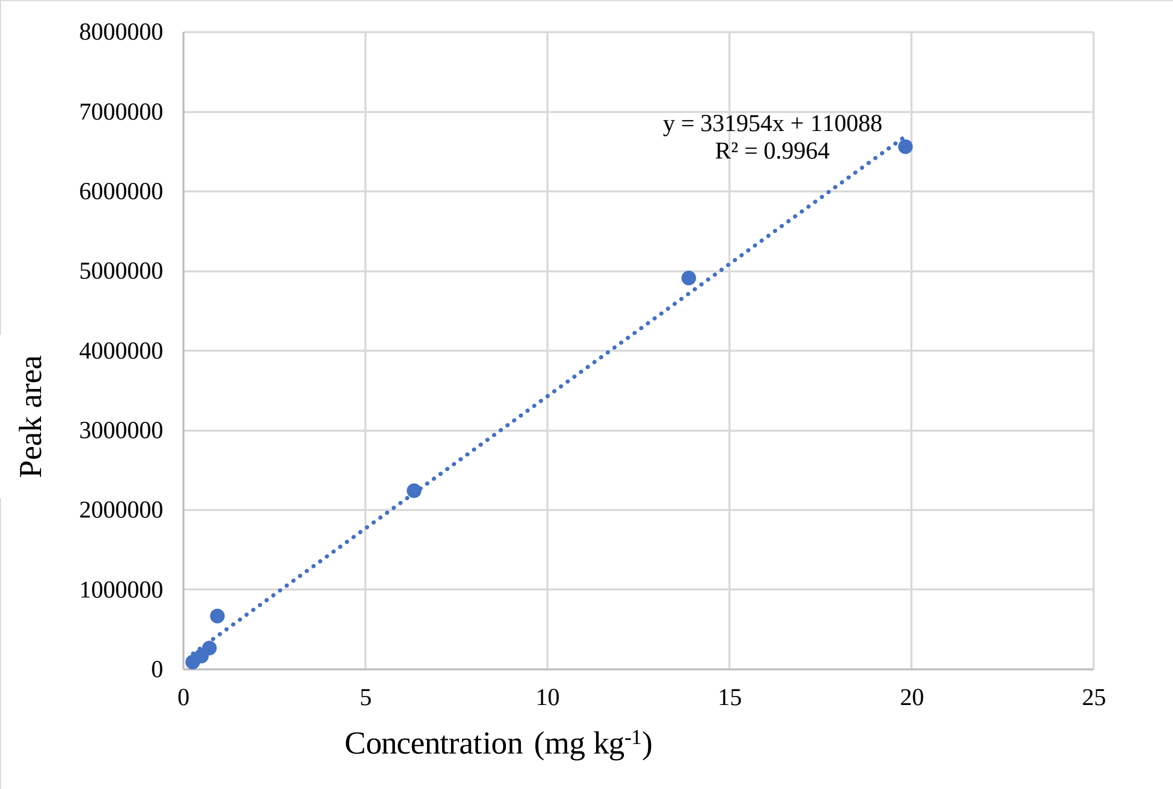

Figure 3.5: Calibration graph of Atrazine

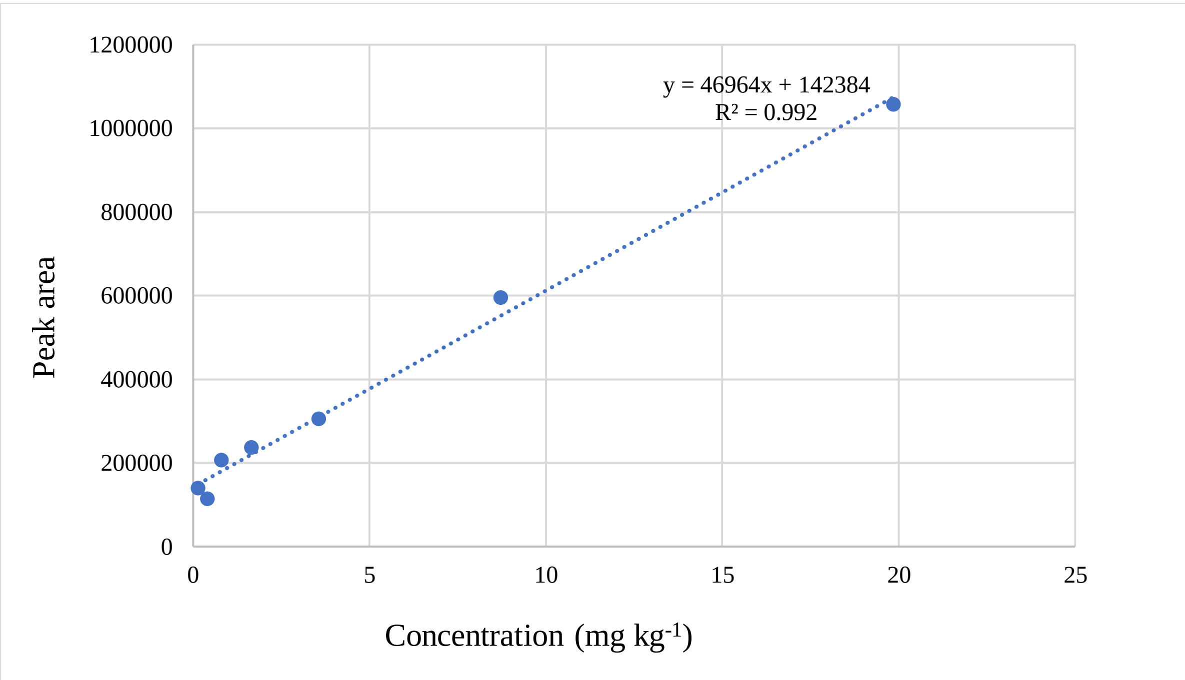

Figure 3.6: Calibration graph of Nicosulfuron

3.8.3 Quality Control and Quality Assurance

Quality assurance and quality control involved matrix spike with a surrogate standard prior to extraction to check extraction efficiency and recoveries, analysis of replicate samples, and field blanks. Field blanks consisted of anhydrous Na_2SO_4 and were carried along at every field trip. The field blanks were subjected to the entire analytical procedure as the samples. All sample and standard measurements were double checked using both volumes and weight measurements to minimise the possibility of errors. Confirmatory test of the sample analytes was conducted using a second capillary column of different polarity 35% Phenyl Polysilphenylene-siloxane (BPX 35) of dimensions 50 m x 0.25 mm x 0.25µm film thickness. The percent recoveries, limit of detection (LOD) and limit of Quantification (LOQ) for S-metolachlor were Atrazine and Nicosulfuron were as per Table 3.2.

Table 3.2: Percentage recoveries, LOD and LOQ for the three herbicides

Herbicide active ingredient	Percentage recoveries	LOD	LOQ
Atrazine	93.2%	0.011 µg/kg	0.11 µg/kg
S-metolachlor	89.6%	0.012 µg/kg	0.12 µg/kg
Nicosulfuron	85.7%	0.012 µg/kg	0.12 µg/kg

3.8.4 Statistical Analysis

The weed count data was keyed into a Microsoft Excel Spreadsheet. This data was then used to determine the weed diversity and species richness which were obtained using R statistical software, version 4.2.1 (R Core Team 2022). Means were separated using Tukey's honest significant difference (HSD) test ($p < 0.05$). The data on herbicide residues in the soil was modelled using linear mixed effects of regression as a function of tillage methods, time and soil depth using the package lme4 in R. Tukey's honest significant difference (HSD) test ($p < 0.05$) was used to separate the means.

CHAPTER FOUR: RESULTS

4.1 WEED TYPE IN THE STUDY AREA

The identified weed species in the study area before clearing was done were 24 (Table 4.1), out of which 20 (83%) were broad leaved and 4 (17%) were from the grass family.

Table 4. 1: Identified weed species in the study area before clearing

Scientific name	Common name
Abutilon mauritianum	Country Mallow
Amaranthus hybridus L.	Smooth pigweed
Bidens Pilosa	Blackjack
Commelina benghalensis	Wandering jew
Crotalaria incana	Rattlepod
Cynodon nlemfuensis	Star Grass
Cyperus rotundus L.	Nutgrass, purple nutsedge
Datura stramonium	Thorn apple
Desmodium unicinatum	Silverleaf Desmodium
Digitaria velutina	Velvet finger grass
Dichondra micrantha	Kidney weed
Erigeron sumatrensis	Broadleaf fleabane
Galinsoga parviflora	Gallant soldier
Lantana camara	Lantana, Tick-Berry
Leonitis mollissima	Lion’s ear,Lion’s Tail
Momordica foetida	Wild cucumber
Ocimum suave	Ocimum
Oxalis latifolia	Oxalis
Rumex pulcher	Fiddle dock
Rumex usambarensis	Dammer or Red Rumerx
Setaria verticillate	Bristly Foxtail, Love Grass
Tagetes minuta	Mexican marigold
Vernonia lasiopus	Vernonia, Bitter leaf
Xanthium pungens	Xanthium

4.2 EFFECT OF TILLAGE METHODS AND HERBICIDE APPLICATION ON ABUNDANCE AND DIVERSITY OF WEEDS

In the first season, the type of tillage method and herbicide application had significant effect on the abundance of *Amaranthus hybridus L.*, *Cynodon nlemfuensis*, *Desmodium unicinatum* and *Oxalis latifolia* but these differences varied with individual species (Table 4.2). For example, *A. hybridus* was significantly higher in plots where hand hoe was used at 11 counts m^{-2} compared to jab planter and ripping which had 1 count m^{-2} each. *C. nlemfuensis*, was significantly higher in ripping at 19 counts m^{-2}, while no weed of this species was recorded where jab planter and hand hoe were used. *D. unicinatum* also recorded a significant high count in ripping at 6 counts m^{-2} with jab planter at 1 count m^{-2} and hand hoe plots recording 0 counts m^{-2}. *O. latifolia* on the other hand was also more abundant in plots with ripping at 44 counts m^{-2}, followed by the hand hoe plots at 21 counts m^{-2} and jab planter at 14 counts m^{-2}. Tillage method did not have any effect on the abundance of *B. Pilosa, C. bengalensis, C. rotundus* L, *D. micrantha, D. velutina, E. sumatrensis, L. camara, M. foetida, T. minuta* and *X. pungens*.

Species richness significantly varied based on tillage and herbicide application with ripping recording the highest average number of 2.05 species m^{-2}, compared to jab planter at 1.78 species m^{-2} and hand hoe at 1.53 species m^{-2} (Table 4.2). Shannon diversity also significantly varied with ripping recording the highest average value of 0.59, followed by jab planter at 0.47 and finally the hand hoe at 0.37 (Table 4.2).

Based on the days after herbicide application, the abundance of *C. rotundus* and *D. micrantha* significantly varied in the jab planter tillage method with day 0 recording the highest value of 78 counts m^{-2} and 98 counts m^{-2} respectively. The abundance of the other weed species did not vary based on days after herbicide application. Species richness also significantly varied based on days after herbicide application in the hand hoe tillage method, with day 50 recording the highest number of 2.1 species m^{-2} (Table 4.2). It did not vary in the ripping and jab planter tillage methods. Shannon diversity on the other hand, significantly varied in the jab planter and hand hoe tillage methods with day 50 recording the highest values of 0.65 and 0.68 respectively (Table 4.2). Plots where ripper was used did not record any significant differences based on the days after herbicide application.

Table 4.2: Abundance (m^{-2}) and diversity of weeds as affected by tillage methods and herbicide application in season 1

Weed species	Tillage method																		*p*-value		
	Ripping						Jab planter						Hand hoe								
	Days after herbicide application (DAA)																				
	0	**14**	**30**	**50**	**120**	**Mean**†	**0**	**14**	**30**	**50**	**120**	**Mean**†	**0**	**14**	**30**	**50**	**120**	**Mean**†	**Tillage method**	**DAA**	**TM*DAA**
A. hybridus L.	0.0	0.0	0.0	0.0	2.0	**0.4**^{B}	0.0	2.0	0.0	0.0	0.0	**0.4**^{B}	0.0	12.0	28.0	14.0	0.0	**10.8**^{A}	**<0.001**	0.1461	0.0515
B. Pilosa	0.0	0.0	14.0	8.0	6.0	5.6	22.0	10.0	2.0	8.0	6.0	9.6	0.0	6.0	8.0	12.0	6.0	6.4	0.6969	0.9682	0.5900
C.bengalensis	0.0	0.0	2.0	0.0	2.0	0.8	2.0	0.0	6.0	6.0	0.0	2.8	12.0	8.0	6.0	2.0	0.0	5.6	0.1708	0.7174	0.4326
C. nlemfuensis	42.0	24.0	8.0	6.0	16.0	**19.2**^{A}	0.0	0.0	0.0	0.0	0.0	**0.0**^{B}	0.0	0.0	0.0	0.0	0.0	**0.0**^{B}	**<0.001**	0.4624	0.3112
C. rotundus L.	72.0	8.0	60.0	20.0	24.0	36.8	**78.0**^{a}	**12.0**^{b}	**8.0**^{b}	**8.0**^{b}	**10.0**^{b}	23.2	86.0	14.0	80.0	0.0	0.0	36.0	0.5787	**<0.001**	0.8278
D. unicinatum	10.0	16.0	0.0	2.0	2.0	**6.0**^{A}	0.0	4.0	0.0	0.0	0.0	**0.8**^{B}	0.0	0.0	0.0	0.0	0.0	**0.0**^{B}	**0.0046**	0.0648	0.1256
D. micrantha	56.0	10.0	0.0	8.0	2.0	15.2	**98.0**^{a}	**26.0**^{b}	**28.0**^{b}	**20.0**^{b}	**4.0**^{b}	35.2	72.0	60.0	0.0	4.0	0.0	27.2	0.3485	**<0.001**	0.7979
D. velutina	0.0	0.0	2.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3617	0.4263	0.4266
E. sumatrensis	2.0	4.0	0.0	4.0	0.0	2.0	4.0	0.0	0.0	2.0	0.0	1.2	0.0	0.0	0.0	2.0	0.0	0.4	0.4244	0.4537	0.8316
L. camara	4.0	0.0	0.0	0.0	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3617	0.5181	0.3625
M. foetida	2.0	2.0	0.0	2.0	0.0	1.2	2.0	2.0	0.0	2.0	0.0	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.1952	0.4692	0.9726
O. latifolia	38.0	20.0	106.0	28.0	28.0	**44.0**^{A}	32.0	6.0	20.0	6.0	4.0	**13.6**^{B}	38.0	18.0	22.0	16.0	12.0	**21.2**^{AB}	**0.0473**	0.1686	0.4032
T. minuta	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	0.0	0.0	0.4	0.0	2.0	0.0	4.0	0.0	1.2	0.2996	0.1680	0.6452
X. pungens	8.0	10.0	10.0	2.0	0.0	6.0	0.0	10.0	2.0	0.0	4.0	3.2	6.0	6.0	2.0	2.0	0.0	3.2	0.5597	0.4113	0.8790
Species richness (S)	2.13	2.00	2.00	2.25	1.88	**2.05**^{A}	1.88	1.75	2.00	2.00	1.25	**1.78**^{AB}	**1.25**^{bc}	**2.00**^{ab}	**1.63**^{ab}	**2.13**^{a}	**0.63**^{c}	**1.53**^{B}	**0.0038**	**<0.001**	0.0686
Shannon diversity (H')	0.58	0.67	0.49	0.70	0.54	**0.59**^{A}	**0.49**^{ab}	**0.56**^{ab}	**0.46**^{ab}	**0.65**^{a}	**0.21**^{b}	**0.47**^{AB}	**0.17**^{b}	**0.60**^{a}	**0.38**^{ab}	**0.68**^{a}	**0.00**^{b}	**0.37**^{B}	**0.0072**	**<0.001**	0.1068

† This mean gives aggregate effect of tillage method. Within rows, means in bold and followed by different letters in superscript are significantly different at $p < 0.05$. Uppercase letters indicate the differences based on tillage method while lowercase letters indicate differences based on days after herbicide application. Means were separated based on Tukey's honest significant difference (HSD) test.

In the second season, tillage coupled with herbicide application had significant effects on the abundance of *A. hybridus* L., *B. pilosa, C. nlemfuensis, D. unicinatum* and *D. micrantha* (Table 4.3). Similar to the first season, the abundance of *A. hybridus* was higher in hand hoe plots with 8 counts m^{-2} compared to the plots where the jab planter and ripping was used with 3 counts m^{-2} and 1 count m^{-2}, respectively. *B. pilosa* was more abundant in the hand hoed plots at 29 counts m^{-2} compared to 14 counts m^{-2} in ripping and 7 counts m^{-2} in the jab planter plots. *C. nlemfuensis* and *D. unicinatum* were more abundant in ripping plots at 16 counts $m^{-2}$and 7 counts m^{-2}. *D. micrantha* on the other hand was more abundant in the jab planter plots at 19 counts m^{-2}. Tillage alongside herbicide application had no notable effects on the abundance of the other weed species. Similarly, species richness and Shannon diversity were not significantly affected by tillage method or herbicide application.

Based on days after herbicide application, the abundance of some weed species significantly varied within the ripping and jab planter plots. For instance, *B. pilosa* and *O. latifolia* significantly varied in ripping plots, with the highest count of 54 counts m^{-2} recorded at 120 days and 126 counts m^{-2} at day 50 respectively. In jab planter plots, *C. rotundus, E. sumatrensis* and *X. pungens* recorded a higher number of counts; 328 counts m^{-2} at day 14, 188 counts m^{-2} at day 120, and 26 counts m^{-2} at day 50 respectively. In the hand hoe plots, the abundance of *B. pilosa* was highest at 62 counts m^{-2} at day 50. *C. rotundus* on the other hand had the highest abundance of 222 counts m^{-2} at day 14 while *D. stramonium* had its highest abundance of 16 counts m^{-2} at day 30. The abundance of the other species did not vary based on days after herbicide application in this season. Species richness significantly differed based on days after herbicide application within the ripping and jab planter methods. In both ripping and jab planter, species richness was higher after 120 days with 4.13 species m^{-2} and 4.25 species m^{-2}, respectively. Species richness was higher in hand hoe plots at day 50 with 3.38 m^{-2}. Shannon diversity significantly differed based on days after the application of the herbicides, with ripping and jab planter plots, having higher values 1.02 and 1.09 at day 120. In the hand hoe plots, Shannon diversity was high at day 50 with a value of 1.06.

Table 4.3: Abundance (m^{-2}) and diversity of weeds as affected by tillage methods and herbicide application in season 2

Weed species	Tillage method																		*p*-value		
	Ripping						Jab planter						Hand hoe								
	Days after herbicide application (DAA)																				
	0	**14**	**30**	**50**	**120**	**Mean†**	**0**	**14**	**30**	**50**	**120**	**Mean†**	**0**	**14**	**30**	**50**	**120**	**Mean†**	**Tillage method**	**DAA**	**TM*DAA**
A. hybridus L.	0.0	0.0	0.0	0.0	2.0	**0.4^{B}**	0.0	0.0	14.0	0.0	0.0	**2.8^{B}**	0.0	20.0	14.0	26.0	30.0	**18.0^{A}**	**0.002**	0.5224	0.4392
B. pilosa	**10.0^{b}**	**6.0^{b}**	**0.0^{b}**	**0.0^{b}**	**54.0^{a}**	**14.0^{AB}**	18.0	4.0	4.0	0.0	8.0	**6.8^{B}**	**38.0^{ab}**	**10.0^{b}**	**10.0^{b}**	**62.0^{a}**	**26.0^{ab}**	**29.2^{A}**	**0.005**	**0.0182**	**<0.001**
C. bengalensis	4.0	8.0	2.0	26.0	10.0	10.0	14.0	10.0	4.0	28.0	16.0	14.4	0.0	26.0	18.0	26.0	16.0	17.2	0.5146	0.0842	0.8736
C. nlemfuensis	14.0	16.0	10.0	34.0	6.0	**16.0^{A}**	0.0	2.0	0.0	0.0	0.0	**0.4^{B}**	4.0	0.0	0.0	0.0	0.0	**0.8^{B}**	**<0.001**	0.4727	0.4446
C. rotundus L.	2.0	152.0	90.0	50.0	150.0	88.8	**0.0^{b}**	**328.0^{a}**	**70.0^{b}**	**86.0^{b}**	**130.0^{b}**	134.0	**10.0^{c}**	**222.0^{a}**	**98.0^{b}**	**32.0^{bc}**	**46.0^{bc}**	81.6	0.1128	**<0.001**	**0.0377**
D. stramonium	0.0	0.0	0.0	0.0	8.0	1.6	0.0	0.0	0.0	0.0	0.0	0.0	**0.0^{b}**	**0.0^{b}**	**16.0^{a}**	**2.0^{ab}**	**0.0^{b}**	3.6	0.1125	0.0623	**0.001**
D. unicinatum	8.0	4.0	2.0	8.0	14.0	**7.2^{A}**	0.0	0.0	0.0	0.0	0.0	**0.0^{B}**	0.0	0.0	0.0	0.0	0.0	**0.0^{B}**	**<0.001**	0.5992	0.6785
D. micrantha	0.0	14.0	40.0	0.0	6.0	**12.0^{AB}**	36.0	10.0	0.0	14.0	36.0	**19.2^{A}**	0.0	0.0	0.0	0.0	10.0	**2.0^{B}**	**0.0375**	0.6218	0.1118
E. sumatrensis	2.0	2.0	0.0	0.0	6.0	2.0	**0.0^{b}**	**0.0^{b}**	**6.0^{b}**	**4.0^{b}**	**188.0^{a}**	39.6	6.0	0.0	0.0	6.0	0.0	2.4	0.0584	**0.0151**	**<0.001**
M. foetida	0.0	2.0	8.0	0.0	0.0	2.0	2.0	6.0	2.0	0.0	2.0	2.4	0.0	0.0	0.0	0.0	2.0	0.4	0.4204	0.4581	0.4434
O. latifolia	**20.0^{b}**	**12.0^{b}**	**26.0^{b}**	**126.0^{a}**	**22.0^{b}**	41.2	0.0	0.0	50.0	54.0	68.0	34.4	0.0	22.0	20.0	52.0	20.0	22.8	0.3826	**<0.001**	0.0571
R. pulcher	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.0	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.3617	0.3829	0.3585
T. minuta	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	0.4	0.3617	0.3829	0.3585
X. pungens	0.0	32.0	8.0	16.0	8.0	12.8	**0.0^{b}**	**0.0^{b}**	**4.0^{b}**	**26.0^{a}**	**2.0^{b}**	6.4	0.0	2.0	2.0	0.0	2.0	1.2	0.1466	0.3266	**0.0337**
Species richness (*S*)	**1.50^{b}**	**2.63^{ab}**	**2.63^{ab}**	**2.88^{ab}**	**4.13^{a}**	2.75	**2.13^{b}**	**2.25^{b}**	**2.50^{b}**	**3.00^{ab}**	**4.25^{a}**	2.83	**1.13^{b}**	**2.00^{ab}**	**3.25^{a}**	**3.38^{a}**	**3.25^{a}**	2.6	0.8241	**<0.001**	0.7175
Shannon diversity (*H′*)	**0.33^{b}**	**0.61^{ab}**	**0.84^{a}**	**0.86^{a}**	**1.02^{a}**	0.73	**0.51^{b}**	**0.34^{b}**	**0.65^{ab}**	**0.83^{ab}**	**1.09^{a}**	0.68	**0.09^{c}**	**0.38^{bc}**	**0.84^{ab}**	**1.06^{a}**	**0.87^{ab}**	0.65	0.9057	**0.0096**	0.8635

† This mean gives aggregate effect of tillage method. Within rows, means in bold and followed by different letters in superscript are significantly different at $p < 0.05$. Uppercase letters indicate the differences based on tillage method while lowercase letters indicate differences based on days after herbicide application. Means were separated based on Tukey's honest significant difference (HSD) test.

4.3. EFFECT OF TILLAGE METHODS ON THE DISTRIBUTION AND PERSISTENCE OF THE HERBICIDE RESIDUES IN THE SOIL

Based on the interaction between tillage methods, time and depth, the three herbicide residues significantly leached down the soil profile (Table 4.4). Where ripping was done, for example, an average of 14.7 mg kg^{-1} of Atrazine residues were found in the topsoil (0-15 cm) and 2.4 mg kg^{-1} in the subsoil (15-30 cm). Where jab planter was used, an average of 15.6 mg kg^{-1} residues of Atrazine were detected in the topsoil and 1.3 mg kg^{-1} in the subsoil. Similar differences were observed for S-metolachlor in both season 1 and 2. In ripping plots, an average of 5.6 mg kg^{-1} Nicosulfuron residues were detected in the topsoil and 1.4 mg kg^{-1} in the subsoil. Where the jab planter was used, an average of 6.2 mg kg^{-1} of Nicosulfuron residues were detected in the topsoil and 1.4 mg kg^{-1} in the subsoil. Similar differences for Nicosulfuron were observed in the second season.

Generally, herbicide residues of Atrazine, S-metolachlor and Nicosulfuron in the topsoil decreased with time in the two tillage methods (Table 4.4). For example, in the first season, where ripping was done, Atrazine residues significantly decreased from 25.5 mg kg^{-1} in the top 0-15 cm of the soil at 0 days to 1.0 mg kg^{-1} at 120 days after herbicide application. Similarly, S-metolachlor residues decreased from 34.9 mg kg^{-1} in the upper 0-15 cm of the soil at 0 days to 2.9 mg kg^{-1} at 120 days. Nicosulfuron also significantly reduced from 8.5 mg kg^{-1} in the topsoil at 0 days after application to 2.6 mg kg^{-1} at 90 days after herbicide application. Similar differences were observed where jab planter was used in both season 1 and 2. The herbicide residues significantly increased with time in the subsoil in the two tillage methods. For example, in the first season where ripping was done, Atrazine residues increased from 0.0 mg kg^{-1} on day 0 to 3.2 mg kg^{-1} on day 120. Similar differences were observed in the second season, except for Atrazine residues in the jab planter plots and S-metolachlor residues in the ripping plots which decreased with time.

Table 4.4: Atrazine and S-metolachlor persistence and distribution (mg kg^{-1}) in soil as affected by ripping and jab planter tillage methods

Herbicide AI	Depth	Tillage method								*p*-value					
		Ripping				Jab planter									
		Days after herbicide application (DAA)													
		0	**30**	**120**	**Mean**†	**0**	**30**	**120**	**Mean**†	**TM**	**DAA**	**D**	**TM*DAA**	**TM*D**	**TM*DAA*D**
						Season 1									
Atrazine	**0-15 cm**	**25.5**^{a}	**17.5**^{a}	1.0	**14.7**^{A}	**24.7**^{a}	**13.0**^{a}	9.0	**15.6**^{A}	0.9637	**0.0285**	**<0.001**	0.5186	0.5369	**<0.001**
	15-30 cm	**0.0**^{b}	**4.1**^{b}	3.2	**2.4**^{B}	**0.0**^{b}	**1.5**^{b}	2.4	**1.3**^{B}						
S-metolachlor	**0-15 cm**	**34.9**^{a}	**17.7**^{a}	2.9	**18.5**^{A}	**30.4**^{a}	**20.7**^{a}	1.3	**17.5**^{A}	0.9032	**0.0020**	**<0.001**	0.8138	0.7832	**<0.001**
	15-30 cm	**0.2**^{b}	**3.6**^{b}	3.3	**2.4**^{B}	**0.0**^{b}	**5.1**^{b}	2.4	**2.5**^{B}						
						Season 2									
Atrazine	**0-15 cm**	**19.1**^{a}	3.1	0.8	**7.6**^{A}	**25.1**^{a}	3.5	0.7	**9.8**^{A}	0.7379	**<0.001**	**<0.001**	0.7143	0.4275	**<0.001**
	15-30 cm	**0.1**^{b}	3.8	0.3	**1.4**^{B}	**0.3**^{b}	2.1	0.2	**0.9**^{B}						
S-metolachlor	**0-15 cm**	**32.8**^{a}	**15.1**^{a}	1.9	**16.6**^{A}	**31.1**^{a}	**13.6**^{a}	0.0	**14.9**^{A}	0.7905	**<0.001**	**<0.001**	0.9969	0.6955	**<0.001**
	15-30 cm	**0.1**^{b}	**2.6**^{b}	0.0	**0.9**^{B}	**0.0**^{b}	**1.6**^{b}	0.7	**0.8**^{B}						

† This mean gives aggregate effect of tillage method. Within rows, means in bold and followed by different letters in superscript are significantly different at $p < 0.05$. Uppercase letters indicate the differences based on tillage method while lowercase letters indicate differences based on days after herbicide application. Means were separated based on Tukey's honest significant difference (HSD) test.

Table 4.5: Nicosulfuron persistence and distribution (mg kg^{-1}) in soil as affected by ripping and jab planter tillage methods

Herbicide AI	Depth	Tillage method: Ripping (DAA) 0	90	Mean[†]	Jab planter (DAA) 0	90	Mean[†]	p-value TM	DAA	D	TM*DAA	TM*D	TM*DAA*D
Season 1													
Nicosulfuron	**0-15 cm**	**8.5**^{a}	2.6	**5.6**^{A}	**10.6**^{a}	1.7	**6.2**^{A}	0.8256	0.1748	**<0.001**	0.6755	0.8915	**<0.001**
	15-30 cm	**0.0**^{b}	2.7	**1.4**^{B}	**0.0**^{b}	2.8	**1.4**^{B}						
Season 2													
Nicosulfuron	**0-15 cm**	**11.8**^{a}	0.8	**6.3**^{A}	**8.7**^{a}	1.4	**5.1**^{A}	0.7253	**0.0158**	**<0.001**	0.5941	0.5498	**<0.001**
	15-30 cm	**0.0**^{b}	0.4	**0.2**^{B}	**0.0**^{b}	0.5	**0.3**^{B}						

[†] This mean gives aggregate effect of tillage method. Within rows, means in bold and followed by different letters in superscript are significantly different at $p < 0.05$. Uppercase letters indicate the differences based on tillage method while lowercase letters indicate differences based on days after herbicide application. Means were separated based on Tukey's honest significant difference (HSD) test.

CHAPTER FIVE: DISCUSSION

5.1 WEED TYPE IN THE STUDY AREA

Before undertaking the field experiment, there were a variety of weed species in the study area as the land had been left fallow for two years. Only 15 out of the 24 weed species initially identified occurred in the three tillage methods. Some initially identified weeds such as *Abutilon mauritianum, Galinsoga parviflora* and *Ocimum suave* did not appear completely after the application of the three tillage methods. Weed community composition and structure have been found to align with the tillage approach used (Derrouch et al.,2021). While their occurrence in this study, could be attributed to tillage methods, there is the possibility that their mode of dispersal, seed structure and growth pattern which were not monitored in this study could also have contributed to their occurrence.

5.2 EFFECT OF THE TILLAGE METHODS ON SPECIES RICHNESS AND DIVERSITY OF WEEDS

Minimum tillage operations have been found to increase total weed infestations in comparison to conventional tillage. This is because disruption of the soil in conventional tillage affects the various weed species in turn affecting their overall frequency and diversity (Steponavičienė et al., 2021; Woźniak, 2018; Kleijn, 1997). For example, Sekutowski (2009) reported that a reduction in tillage operations increased weed infestation by up to 37%. Conservation tillage therefore has a close correlation with higher weed diversity and richness because the elimination of tillage practices creates sustainable conditions for growth of some weed species (Travlos et al. 2018). The results obtained from this study support these earlier findings where species richness and diversity were found to be higher in the ripping and jab planter tillage methods and where herbicides had been applied compared to plots which hand hoe was used. Minimization of tillage operations in ripping and jab planter methods could have minimized soil disturbance, thus creating favorable conditions for germination of weed seeds and roots leading to higher species richness and diversity. The hand hoe tillage method on the other hand could have ensured complete uprooting of the weeds, unlike ripping and jab planter methods, which might have left the roots and seeds of the weeds below ground leading to their germination. This finding concurs with that of Montanya et al. (2013), and Govindasamy et al. (2020), who also found that weed abundance and diversity were significantly higher in the no tillage methods than in conventional tillage.

Contrary to these results, reduced tillage methods have been found to lead to less diverse weed communities as opposed to the more intensive tillage methods. Hossain et al. (2021), found that continuous conventional tillage practiced for two years increased weed diversity compared to strip tillage. Additionally, Derrouch et al. (2021) and Glemnitz et al. (2006) also found a decrease in weed flora diversity after adoption of conservation tillage. Alarcon et al. (2018), also showed that no tillage and minimum tillage methods had no consistent effects on species richness and diversity, which tallies with the findings of this study in the second season that tillage and herbicide application had no significant effect on species richness and diversity.

In regards to the effect of tillage and herbicides on individual weed species. They both had a significant effect on the abundance and diversity of a few individual species during the study period. For instance, in the first and second season, *A. hybridus.* was more abundant in hand hoe tillage methods which had no herbicide application compared to both ripping and jab planter methods that had herbicides applied to control weeds. *A. hybridus* has been found to have a high phenotypic plasticity and genetic variability which makes it easy for it to adapt to a wide variety of habitats, growing conditions and may enable its ability to resist pressure from different tillage methods (Costea et al., 2004; Mandumbu et al., 2012). This could then explain why in this study the abundance of *A. hybridus* differed in counts in the three tillage methods. However, other studies such as Tuesca et al. (2001) and Mandumbu et al. (2012) also found that tillage had no effect on *A. hybridus* density within the no tillage, minimum tillage, and conventional tillage methods.

C. nlemfuensis was also abundant in plots where ripping was done than in jab planter and hand hoe plots. *C. nlemfuensis* a perennial grass that is occasionally troublesome as a weed of arable land and perennial crops (Terry and Michieka, 1987), has previously been found to be obnoxious and to rapidly colonize in undisturbed areas, and form dense mats formed through resprouting of rooted runners and remnant stolons (FAO, 2013). In this study, its abundance could then be attributed to its obnoxious nature which may have contributed to it occurring in higher counts in plots where ripping was done than in the jab planter and hand hoe plots.

O. latifolia was also abundant in the first season in the ripping tillage method followed by hand hoe and jab planter tillage methods. *O. latifolia* tends to outdo several tillage methods both conventional and conservation as it has bulbils that continue to extend and grow into new bulbs that re-emerge after land tilling (Ivens,1989). Although these properties were not measured, there is a possibility that they may have influenced *O. latifolia's* differing abundance in the three tillage methods in this study. Other contrasting studies such as Kumar and Singh (1990) alluded that soil plowing provides better conditions for the dissemination of *O. latifolia* than leaving the soil untilled.

B. pilosa on the other hand was more abundant in hand hoed plots in comparison to the ripping plots and the jab planter plots. Travlos et al. (2018) found that annual weed species, such as *B. pilosa* tend to dominate under conventional tillage compared to conservation tillage because its mode of dispersal and suitability of its seed to thrive in the conventional tillage methods. These findings could therefore attempt to explain why in this study there was an increased abundance of

B. pilosa in the hand hoe plots than in the ripping and jab planter plots. The finding of this study, however, differs with that of Mhlanga et al. (2015) who suggested that *B. pilosa* tended to be favored by better soils which are always associated with minimal tillage.

In this study, the abundance of some weed species such as *C. rotundus* was found to have varied significantly based on days after herbicide application within ripping and jab planter tillage methods. The effectiveness of an herbicide in weed control depends on the weed species since certain species require complete removal from the soil (Klein et al., 1996). This is especially for perennial grassy weeds like *C. rotundus* with underground rhizomes that tend to dominate where weed control by minimum tillage is practiced (Terry and Michieka, 1987; Usman et al., 2013; Hossain et al., 2021).

Findings from this current study also corroborate those of Usman et al. (2013) who found that *C. rotundus* could not be controlled despite the application of post emergence herbicides in the zero tillage and reduced tillage methods. There is a possibility that the abundance of *C. rotundus* in this study, significantly reduced immediately after the application of herbicides and increased few weeks later because its rhizomes were buried deep within soil beyond the reach of herbicides. This then shows the significance of soil disturbance to weed species existence despite application of a weed control method (Travlos et al., 2018; Makokha et al., 2017). As such herbicide application is limited in control of weeds as it targets weeds in contact and not its seeds. Overall, these findings from a combination of vertical rooted annuals such as *B. pilosa* and *D. stramonium* and lateral rooted perennial such as *C. rotundus* explains the difference in patterns of weed abundance in relation to tillage as opined by Travlos et al. (2018).

5.3 EFFECT OF TILLAGE METHODS ON THE DISTRIBUTION AND PERSISTENCE OF THE HERBICIDE RESIDUES IN THE SOIL

This study detected Atrazine, S-metolachlor and Nicosulfuron residues in both the topsoil and subsoil in the ripping and jab planter tillage methods, an indication of their leaching down the soil profile. Increased pesticide leaching within conservation agriculture systems such as no tillage has been linked to improved macropore connectivity (Alleto et al., 2010; Malone et al.,2003). Conservation agriculture improves soil structure (Prado et al., 2014) and as such, preferential flows linked to macropore connectivity tend to speed the movement of atrazine through the soil (Shipitalo et al., 2000). This could be a possible explanation as to why the residues of the three herbicides were found in both the topsoil and subsoil in the ripping and jab planter tillage methods. The findings of this study are similar to those reported by Mahia et al. (2007) who observed that atrazine residues (observed as hydroxyatrazine) were detected in the cultivable layer (0–20 cm) one year after the herbicide application in no tillage systems. Sekutowski (2009) also observed rimsulfuron, a compound in the same family as Nicosulfuron, in the upper soil layer (0-20 cm) in the reduced tillage system. While the improved macropore connectivity within the ripping and jab planter tillage methods may have aided the herbicide residue leaching in the topsoil and subsoil in this study, initial intrinsic soil properties have been found to be more relevant for atrazine transport than those associated with tillage practices (Montoya et al., 2006) as well as climatic conditions (Alleto et al., 2010). In addition, chemical properties of these herbicides could have also affected their leaching to the subsoil. Nicosulfuron and Atrazine for instance have been found to have a high leachability and are extremely mobile in soil(Cueff, 2020; Lewis et al., 2016). Though these properties were not monitored in this study, this study cannot rule out the role of soil properties, environmental conditions, and herbicide properties in the movement of herbicide residues within the soil profile under conservation agriculture.

In terms of persistence in the soil, this study found that Atrazine, S-metolachlor and Nicosulfuron residues significantly persisted in both the top and subsoil at 120 days (Atrazine and S-metolachlor) and 90 days (Nicosulfuron) in ripping and jab planter tillage methods respectively. Herbicides such as Atrazine have been known to persist in the soil for a long time after their application (Stipičević et al., 2015). In soils under conservation agriculture, atrazine's retention is promoted by the high amount of soil organic matter regardless of the soil structure in a crop management system (Prado et al., 2014; Boivin et al., 2005). The findings in this study are similar to those of Amadori et al. (2016) who found that residual atrazine still existed in the soil after 180 days, in the no tillage methods. While the persistence of three herbicides residues in no tillage methods could be attributed to the high soil organic matter, herbicidal properties such as high sorption coefficient for Atrazine and S-metolachlor could have played a part in their persistence in the soil (Martins et al., 2018;Westra et al., 2015). This could be an area of study for herbicides applied under the no tillage and minimum tillage systems in conservation agriculture.

Whereas weed management through herbicide application has created much change in agricultural production, the presence of herbicide residues that persist after application remains a key concern. Some of these herbicides surpass their weed control phases, as noted by Curran (2016), and in several instances go beyond their expected phase of life, thus threatening subsequent productivity within the soils. Consequently, their extensive retention within the soil is a part of environmental pollution which is based on their presence in the water, soil and air upon application (Riyaz et al., 2021). S-metolachlor for instance has the ability to contaminate surface and ground water (Senseman, 2007). The persistence of these herbicide residues within the soil raises contamination concerns on soil functions, soil biodiversity and food safety (Silva et al., 2019). Mehdizadeh and Gholami (2018) reported that the accumulation of herbicide residues can inhibit beneficial soil micro-organisms due to their toxicity. Human health and biological diversity also remain at risk (Riyaz et al., 2021). Atrazine has the possibility of resulting in birth defects and disrupting the endocrine system in human beings (Pathak and Dikshit, 2011), while S-metolachlor has a moderate toxicity to cray fish resulting in delays in their ontogenic development and growth (Velisek et al., 2019). Nicosulfuron on the other hand is also moderately toxic to bees (Lewis et al., 2016). Despite the several concerns of environmental contamination and human health, the monitoring of herbicides residues in soil is scarcely carried out in Kenya and the information is often limited. This is not only in Kenya but also to the European Union where the monitoring of pesticide residues in soil is not required (Silva et al., 2019). Kenya has no quality standard of its own for the acceptable levels for herbicides residues in soil (MoALFC, 2020) water, and food and it therefore relies on international standards. For the recommended maximum residue levels in food, the Pest Control and Products Board of Kenya cites the European Union (Pest Control Products Board, 2023). Based on this, Atrazine is currently not approved for use in plant protection products in the European Union based on its toxicity. Despite this the European Union Pesticides Database expects that that for soils with pH above 6 concentrations of atrazine and its breakdown products should not exceed 0.1 μg/l (European Commission, 2003). The atrazine residues obtained in this study surpassed the above the recommended concentrations in soil and could pose a threat to the environment and health for Kenyans. While data on the recommended residue levels in the soil for S-metolachlor and Nicosulfuron is unavailable. Their recommended residue levels in maize/corn is 0.05mg/kg for S-metolachlor and 0.01mg/kg for Nicosulfuron (European Commission, 2023).

CHAPTER SIX: CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

In this study, a total of 24 weed species were identified in the study area prior to any clearing activities. Among these, 20 (83%) were categorized as broad-leaved weeds, while the remaining 4 (17%) belonged to the grass family. When examining the impact of three different tillage methods, it was observed that 15 out of the initially identified 24 weed species were present across all three methods. Certain weed species that were initially identified, such as *Abutilon mauritianum*, *Galinsoga parviflora*, and *Ocimum suave*, did not fully reappear after the implementation of the three different tillage methods. This suggested that weed community composition and structure tend to align with the tillage approach used (Derrouch et al.,2021).

The findings of this study also revealed the significant effect of tillage methods and herbicide application on species richness and weed diversity. In the first season, ripping tillage method had the highest species richness with an average number of 2.05 species m^{-2}, followed by jab planter at 1.78 species m^{-2} and hand hoe at 1.53 species m^{-2} (Table 4.2).Similarly, Shannon diversity also significantly varied with ripping recording the highest average value of 0.59, followed by jab planter at 0.47 and finally the hand hoe at 0.37 (Table 4.2).This observed trend was attributed to the creation of sustainable conditions for growth of weed species and minimum disturbance of the weed roots within the minimum and no tillage methods species (Travlos et al. 2018). Conversely, in the second season of this study, tillage was found to have no effect on species richness and weed diversity.

This study also found that tillage methods, time and depth had a significant effect on the distribution and persistence of herbicide residues in the soil. Trends from this study showed that

Atrazine, S-metolachlor and Nicosulfuron residues significantly leached down the soil profile in both ripping and jab planter tillage methods with higher residue concentrations detected in the topsoil 0-15 cm of the two tillage methods. Where ripping was done, for example, an average of 14.7 mg kg^{-1} of Atrazine residues were found in the topsoil (0-15 cm) and 2.4 mg kg^{-1} in the subsoil (15-30 cm). Where jab planter was used, an average of 15.6 mg kg^{-1} residues of Atrazine were detected in the topsoil and 1.3 mg kg^{-1} in the subsoil. Similar differences were observed for S-metolachlor in both season 1 and 2. In ripping plots, an average of 5.6 mg kg^{-1} Nicosulfuron residues were detected in the topsoil and 1.4 mg kg^{-1} in the subsoil. Where the jab planter was used, an average of 6.2 mg kg^{-1} of Nicosulfuron residues were detected in the topsoil and 1.4 mg kg^{-1} in the subsoil.

Atrazine, S-metolachlor and Nicosulfuron residues significantly increased with time in the subsoil in the two tillage methods. For example, in the first season where ripping was done, Atrazine residues increased from 0.0 mg kg^{-1} on day 0 to 3.2 mg kg^{-1} on day 120. For jab planter Atrazine residues increased from 0.0 mg kg^{-1} on day 0 to 2.4 mg kg^{-1} on day 120.

Whereas this study only assessed the effect of tillage methods in the leaching and the persistence of Atrazine, S-metolachlor and Nicosulfuron residues in the soil profile, other factors such as their chemical properties, soil properties, and environmental conditions that surrounded the herbicides could also have aided in their leaching and persistence in the soil.

6.2 RECOMMENDATIONS

While protecting the soil from destructive tillage operations is commendable, application of herbicides takes away the protective value of conservation agriculture. For Atrazine, S-metolachlor and Nicosulfuron herbicides used in this study, the recommended maximum residue limits in soil were not outlined on the Pest Control Products Board of Kenya website neither were they listed on the manufacturer's website (PCPB, 2023; Syngenta, 2023; Juanco,2023). Based on this, this study recommends that; if herbicides are to be used in agricultural operations in Kenya, policies should be passed that require that the information on the herbicide properties, maximum residue limits in the soil, their dissipation rates, and effects on the environment, human health, and biodiversity to be availed to the public regularly by the Pest Control Products board and the Herbicide manufacturers.

There is a need for a harmonized soil quality standard for Kenya in relation to herbicides as well as constant monitoring and evaluation of the residues in soil, water and food by the Kenya Plant Health Inspectorate and the Pest Control Products Board.

There is also a need for further studies to show the effect of the herbicide residues to the soil and soil microorganisms. Further studies are also needed on the uptake of these herbicide residues by plants which has the possibility of impacting human health through consumption. By virtue of their leaching potential there is a need for further studies on the contamination of underground aquifers and water bodies and policy directive against the use of soluble herbicides near important water resources.

To reduce the risks associated with herbicide residues in the soil, it is imperative for the government of Kenya to make available biopesticides through the Pest Control and Products Board. For the Ministry of Agriculture to deploy agricultural extension officers to work with farmers to embrace alternative ways of weed control such as use of biopesticides, use of agronomic practices like mulch and crop residues, push pull technique, crop rotation, and intercropping of crops with allelopathic properties such as sorghum that inhibit growth of weeds.

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