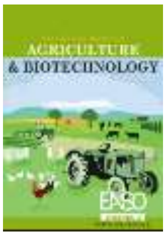

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Original Article

Minimum Tillage and Soil Surface Cover Reduced Weed Density but Not Diversity Over Four Growing Cycles

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ABSTRACT

This study investigated use of cultural practices to address weed challenges that present one of the highest costs to farmers. The parameters explored included the effects of tillage and soil cover practices on weed density and diversity, evaluated in a split plot experimental design. Increasing rainfall amounts significantly increased weed density and weed diversity. Minimum tillage significantly suppressed weeds with a density of 80/m2 compared to conventional tillage density of 124/m2. Soil cover practices similarly suppressed weed density ($p<0.05$) compared to sole crops without soil cover intervention. Maize with mulch had the lowest density (64/m2) followed by maize intercropped with one line of soybean between maize being more effective in weed suppression (92/m2 vs 113/m2). Sole maize and sole soybeans treatment both had a density of ~121/m2. Weed diversity, as measured by Shannon-Weiner index and Simpsons index were not statistically different across treatment ($p>0.05$). However, weed species count was higher in minimum tillage by 05% compared to conventional tillage, hence it calls for investment in minimum tillage and intercropping practices to allow a more diverse weed community that will be less competitive, less prone to dominance by highly adapted weeds, hence promoting ecological sustainability.

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INTRODUCTION

Weeds are notorious yield reducers that are economically more harmful than insects, fungi, or other crop pests (Gharde et al., 2018; Liu et al., 2021). The cost of controlling weeds has a significant economic impact on net returns to farmers, worsening with invasive alien weed species (Eschen et al., 2021; Soltani et al., 2017; Tataridas et al., 2023). In sub-Saharan Africa (SSA), smallholder crop producers commonly realize as low as 30% of the yield potential (Gianessi & Williams, 2011a; Tittonell & Giller, 2013) due to a number of factors such as use of inferior crop varieties and due to poor agronomic practices. However, yield losses of 25% have been attributed to farmers being unable to weed crops at optimal time (Chikoye et al., 2007). The key crop management practice to improve such low crop yields from smallholder farmers is timely weeding (Munialo et al., 2020). Smallholder farmers spend 50-70% of their total labour time hand weeding (Chikoye et al., 2007; Gharde et al., 2018; Gianessi & Williams, 2011a; Woyessa, 2022). Therefore, the ability of smallholders to carry out weeding is a key determinant of farm size (Gianessi & Williams, 2011b).

Cultural weed control that involves practices such as crop rotation, diversified cropping, timely planting, cover cropping has been practiced by farmers for centuries (Basch et al., 2020). Currently, weeds are managed through intensive tillage practices and herbicides (Hussain et al., 2021; Perotti et al., 2020). However, the two methods of weed control have led to land degradation through soil loss due to erosion (Hussain et al., 2018). Also, herbicides have caused environmental pollution and health safety issues (Scavo & Mauromicale, 2020; Ustuner et al., 2020).

Manual weeding in SSA is done by mostly women and children (Gianessi & Williams, 2011b), in a study done in Ethiopia invasive alien weeds had gender impacts on everyday life that disproportionately affected the less powerful (Christie et al., 2023). Cultural weed control therefore presents an opportunity as a sustainable practice (MacLaren et al., 2020) and utilizes cropping systems to reduce weed pressure (Rosset & Gulden, 2020). It involves non-chemical crop management practices ranging from variety selection for cultivar competitiveness to land preparation, soil cover, manipulation of plant density, crop diversification, nutrient and water management, allelopathy, harvest and postharvest processing (Gabryś & Kordan, 2022). These practices can be integrated with resistant crop varieties, biological control agents, judicious use of herbicides, minimum tillage (Hussain et al., 2021). Bioherbicides is an emerging technology in sustainable weed management, bioherbicides are extracted from plants containing phytotoxic allelochemicals or certain disease-carrying microbes that can suppress weed populations and are currently in the market (Hasan et al., 2021). In most instances, cultural control methods are generally cheaper than chemical control methods and provide additional benefits to the soil, such as the addition of organic matter and biologically fixed nitrogen (Bhaskar et al., 2021; Chaudhary, 2022; Sharma et al., 2021).

The long-term effects of applying integrated weed management (IWM) practices can be realized through shifting research on IWM from a descriptive to a predictive phase (Swanton & Murphy, 1996). This can be possible through linking management changes with crop-weed modelling that includes such components as weed population dynamics and the ecophysiological basis of competition (Swanton & Murphy, 1996). Therefore, it will help predict future weed problems and solutions and the economic risks and benefits of intervention (Chauhan et al., 2017; Swanton & Murphy, 1996). Long term benefits of IWM would be clear such as improved soil

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quality, crop productivity, and water quality (Scavo & Mauromicale, 2020); all of these are related to the rationale of IWM, hence IWM can be linked to agroecosystem health.

Despite the above weed challenge in SSA, weeds are still underestimated, with plant pathology and entomology taking precedence (Mvula, 2016). Weed science discipline in the 21st century must transform to encompass an integral complex system like weed ecological management, physiology of weed traits among others rather than narrow focus on herbicides and tillage (Davis et al., 2009; Monteiro & Santos, 2022). The complex weed management strategy may be more desirous in conservation agriculture (CA) systems with often higher weed pressure resulting to higher costs of weeding and yield losses (Kuyah et al., 2021; Mhlanga et al., 2022). The core CA practices namely minimum tillage, surface cover and crop diversity singly or in combination affects weeds differently and may be region-specific (Strauss et al., 2021). Actually, crop management practices that conserve a more diverse weed community will make that environment less competitive for individual weeds, hence less prone to dominance by highly adapted weeds and may indicate a more sustainable cropping system (Anwar et al., 2021; MacLaren et al., 2020; Storkey & Neve, 2018).

An ecological approach to weed management, which integrates knowledge of weed population dynamics with cultural tactics and long-term planning, has enabled producers to control weeds with 50% less herbicides (Anderson, 2005; Westwood et al., 2018). No single weed control method can provide season-long and effective weed control (Brunharo et al., 2020). Herbicide-resistant and tolerant weed populations are evolving rapidly as a natural response to selection pressure imposed by modern agricultural management activities (Norsworthy et al., 2012). Minimum and no tillage plots were found to have the highest number of weed seed species (weed diversity) in the soil layer of 0-5 cm (Auškalnienė & Auškalnis, 2009). However, Vasileiadis et al. (2016) found higher seed densities (total number of seeds combined) in the mould board plough system. In the minimum tillage systems, seeds remain near the soil surface, thus are more likely to germinate due to exposure to favourable conditions (Mulugeta & Stoltenberg, 1997). The diversity and density of weeds at a particular location is determined by different abiotic and biotic factors such as soil characteristic, cropping system, and rainfall (Mhlanga et al., 2022; Pyšek et al., 2002). However, these factors do not affect weed occurrence independently, but interact, and thus there's not much information available on the role played by each one of them (Anwar et al., 2021; MacLaren et al., 2020; Pyšek et al., 2002).

Crop residue retention as a surface mulch has been recommended for reducing early season labour requirements for weeding in minimum tillage in Zambia (Giller et al., 2009) and globally (FAO, 1997). Likewise, using cover crop as a soil cover contributes significantly to weed management (Bàrberi & Mazzoncini, 2001; Kocira et al., 2020; Kumar et al., 2020; Teasdale et al., 1998). Unfortunately, most smallholders in SSA including in Zimbabwe, Zambia and Uganda are practicing minimum tillage without crop residue retention or crop rotation (Mashingaidze et al., 2009; Kaweesa et al., 2018). In temperate regions, mulching with crop residues has been observed to reduce both weed density and biomass (Bilalis et al., 2009). Although there is limited literature on weed suppression by mulching in SSA, there is some evidence from work done in southern Africa that maize residue has suppressive effects on weed mass in minimum tillage systems (Mashingaidze et al., 2009). Research findings suggested hay mulches applied at 15 to 24 t ha^{-1} several weeks after tomato planting substantially reduced the growth of annual weeds (Schonbeck, 1999). Also, Uwah and Iwo, 2011, recommended mulch application rate of 6 t ha^{-1} to control weeds and maintain an ideal soil temperature, aeration and moisture for normal maize growth. This lower rate may be more consistent with the minimum soil cover of 30% suggested by FAO (FAO, 2023) given the often-limited quantities of residue in SSA due to competing uses.

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Conservation agriculture has become very popular in recent years (Locke et al., 2002) with proponents asserting that weeds are only a major problem where minimum tillage (MT) is adopted without crop residue mulching and diverse crop rotations (Mashingaidze *et al.*, 2009). However, small-scale farmers in SSA may adopt one or two of the CA principles (Kaweesa et al., 2018; Mashingaidze et al., 2009; Rodenburg et al., 2021; Wekesah et al., 2019). Weed management is perceived by smallholder farmers, extension workers, and researchers as one of the main limiting factors for the widespread adoption of CA in southern Africa (Lee & Thierfelder, 2017; Mashingaidze et al., 2012). In fact, in Zimbabwe, despite the yield benefits associated with the minimum tillage packages such as planting basins and ox-ripping, the majority of smallholders' fields are still under conventional plough tillage (Mazvimavi et al., 2008). An understanding on integrated weed management or multi-tactic approach to effectively manage weeds is therefore a necessity (Melander et al., 2017). The objective of the study is to determine the effect of tillage and soil cover practices on weed density, diversity, and crop performance

This study hypothesizes that residue cover will have a greater effect than cover crop in reducing weed density and diversity. Also, ox-ripping will have a greater effect than ox-ploughing in reducing weed density, diversity in maize crop. All the tillage and soil cover practices are expected to interact with meteorological conditions with wetter conditions resulting to greater weed abundance and diversity during the four experimental seasons from 2019 to 2021. Weed diversity is better assessed using the Shannon-Weiner index (H), which is more sensitive to species richness and rear species, while Simpsons index (D) gives more weight to evenness, pays more emphasis on abundance and common species. Use of both diversity indices improves output information from the data sets that is unique for each sample population. This study uniquely integrates how various tillage and soil cover practices affect weeds while incorporating seasonal effects. The generated information therefore has great implications for agroecologists and agronomists in designing sustainable weed management strategies for enhanced crop yields.

MATERIALS AND METHODS

Site Description

An experimental study was conducted on-station at one of the public agricultural research stations mandated to conduct research in the northern agroecological zone of Uganda. The study was implemented during four growing seasons 2019B, 2020A, 2020B and 2021A. Season A refers to the first rains (March-June) and season B refers to the second rains (Aug-Nov). The station is located at 02°.29573'N; 032°.92092'E at 1180 meters above sea level and experiences an average daily temperature of 25 °C and a maximum temperature of 29 °C (Kumakech et al., 2014). The climate is described as moist, sub-humid, with a mean annual rainfall of 1,639 mm, bi-modally distributed from March-June and August-December (Kumakech et al., 2014). The soil at the experimental site is sandy loam (Sand 73%, Silt 11%, Clay 16%), average pH of 6.4, organic matter content of 2.5%, P 20 ppm, K 506 ppm, Ca 1089 ppm, Mg 317 ppm (Anyoni et al., 2023).

Experimental Design

The study was implemented in afield experiment laid down in a Randomized Complete Block Design (RCBD) with a split plot treatment structure. Ox-ploughing and ox ripping were considered as main plot treatments and soil cover practices were the sub plot treatments. The test crop was Maize (Water Efficient Maize for Africa(WEMA 2115)) planted 75 cm by 25 cm (between rows and plants respectively) with mulch at 6t/ha, maize planted at 75 cm by 25 cm with no mulch, Two rows of soybean planted in between maize row at a spacing of 50 cm by 10 cm, one row of soybean planted in between a maize row at a spacing of 50 cm by 10 cm, Sole soybean was planted at a spacing of 50 cm by 10 cm between rows and plants respectively, under conventional tillage and lastly sole soybean planted at a spacing of 75 cm by 10 cm between rows and plants

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respectively, under minimum tillage. Plot size was 4 m by 4 m with a 2 m border in between plots, 2.5 m between blocks and the treatments were replicated three times

The land preparation methods were chosen based on the common practices conducted in Uganda and in this study two methods were chosen, namely, the use of ox-plough for conventional tillage and by placing ripper in the position of the mould board plough for minimum tillage. Weeding was done by hand hoeing and no fertilizer was used; pest control was by application of striker pesticide (Thiamethoxam 141g/L + Lambda-cyhalothrin 106g/L) at a rate of 10ml/20L of water to control fall armyworm. The maize-soybean intercropping patterns was justified because 52.9% of Ugandan small-scale farmers are intercropping (UBOS, 2001).

The minimum tillage component of the experiment was conducted by clearing the plots by slashing and allowing the weeds to sprout and at attainment of 4-5 leaves, glyphosate was applied at four litres per acre. The plots were then prepared for planting by ripping during dry season (July and December) for first and second season planting respectively. Ripping was done at a depth of 30-40 cm at a pacing of 75 cm between rows and maize was planted at the onset of rain (August for season B and April for season A). Weeding was done by hand pulling.

For the conventional tillage plots the land was prepared by Ox- drawn inverted mouldboard plough at a depth of 15-25 cm with first and second ploughing conducted within the month of February-March for season A and June-July for season B, respectively. Maize was planted at the onset of rain August for season B and April for season A) at a spacing of 75 cm by 25 cm intra row and inter plant respectively. Weeding of the experiment was performed by hand hoeing at the depth of 10-15 cm and conducted three times in the maize growing season. The experiment was carried out for two years in the season of August 2019B, April 2020A, August 2020B and April 2021A in the respective year and season A (First season) and B (Second season).

Data Collection

Data was collected on weed density and diversity, daily rainfall, minimum and maximum temperature during the experimentation period. Weed density and diversity was measured at three phases, just before first and second weeding, and one week before harvesting as described by Evans (1972) and Peltzer (2019). Weed density was determined by randomly placing 1 m by 1 m quadrat three times in each plot and weeds enumerated every time a quadrat is placed. An average of the three weed counts was calculated and recorded to determine weed density (number per sq. meter). For weed diversity, a standard flora reference book was used to aiding weed identification (Botha, 2001). In addition to other weed identification resources such as locally generated weed album. Weed diversity was measured using the Shannon-Weiner Index, (H) and Simpsons index, (D) as illustrated in the equations below.

$$H = -\sum_{1=i}^{s} p_i \ln p_i$$

$D = \sum$(Sum) of Pi ^{2}

Where, H = The Shannon diversity index, D = Simpson index, P_i = Fraction of the entire population made up of the species i (proportion of a species i relative to total number of species present, not encountered) and s = numbers of species encountered. Here, a high value of H would be representative of a diverse and equally distributed community and lower values represent less diverse community. A value of 0 would represent a community with just one species. Simpson's diversity index (D) measures community diversity, where: High scores indicate high diversity.

Metrological data (daily rainfall, maximum and minimum temperature) during the crop season were obtained from the office of the National Metrological Authority station located at Ngetta ZARDI to enrich the research findings and discussion. Data on maize and soybean yield was recorded and computed per hectare. The land

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equivalence ration (LER), defined as the relative land area required as sole crops to produce the same yields as intercropping (Willey, 1979). LER, calculated according to the equation below, was used to express the yield advantage or disadvantage of intercropping.

$$LER = L_A + L_B = \frac{Y_A}{S_A} + \frac{Y_B}{S_B}$$

where LA and LB are the LERs for the individual component crops, YA and YB are the individual crop yields in intercropping, and SA and SB are their yields under sole cropping.

Statistical Analysis

Data on weed density and diversity was analysed using GenStat's 16th edition statistical software and Analysis of Variance (ANOVA) was performed with means separated at 5% using Least Significant Difference (LSD). In addition, analysis of Variance was used to evaluate the effect of soil cover, tillage, seasons and their interaction on weed density and diversity. Also, ANOVA was used to analyse rainfall and temperature data and relate the effect of the number of rainy days per month on weed density and diversity within the four seasons. The results across the four seasons were grouped together in their respective tillage and soil cover practices as explained in section 2.2 above. Where the F-test was significant, a least significant difference (LSD) test was performed at $P \leq 0.05$, for mean separation. Weed species frequencies were analysed using Pareto analysis, this is a very useful technique to determine the contribution of each weed species to overall community population in descending order.

RESULTS

Effect of Rainfall Amount and Number of Rainy Days on Weed Density and Diversity

Increase in the rainfall amount significantly increased weed density (p<0.001). Every extra 100 mm of rainfall increased weed numbers in a square meter area by 17 individuals. Likewise, the number of rainy days was highly significant in influencing weed density, where for every 2 additional rainy days, the number of weeds increased by 3 individuals. Just like for weed density, the amount of rainfall also significantly influenced weed diversity estimated using Shannon Wiener index (p<0.05; *Table 1*). However, Simpsons' diversity index (p>0.05) was not significantly affected since the additional weed species due to increased rainfall were not abundant. Overall, for all the four seasons, number of rainy days didn't significantly influence weed diversity as estimated by Shannon Weiner index (H) and Simpson's index (D), unlike rainfall amount that significantly influenced Shannon Weiner index.

Table 1: Mean values of weed density, weed diversity estimate by both Shannon Weiner index (H) and Simpsons index (D) across four seasons.

Source of variation	Weed density	Weed Diversity	
		Shannon Weiner index (H)	Simpsons index (D)
Rainfall amount (mm)	19.03***	3.28**	2.16NS
Rainy days (No. of days)	21.06***	2.57NS	2.72NS
Rainfall x Rainy days	20.78***	3.35**	2.26NS

*Note: *** Highly significant at the p< 0.01 level ** significant at the P < 0.05 level, NS not significant at p>0.05 level*

Rainfall amount and number of rainy days were significantly different between seasons (F*igure 1*). For example, within the second rains, rainfall amount was highest in September 2020B at 384 mm and 21 rainy days, whereas in the same month of 2019B, rainfall amount was the lowest at 22.6 mm with 17 rainy days. In the first rains of 2020A, the month of May had the highest rainfall amount at 221 mm and 23 rainy days, compared to season 2021A where rainfall amount was highest in the month of April with 140 mm and 15 rainy days. Generally, both rainfall amount and rainy days per month decreased through 2019B season to 2021B season. Season 2020B however, received high

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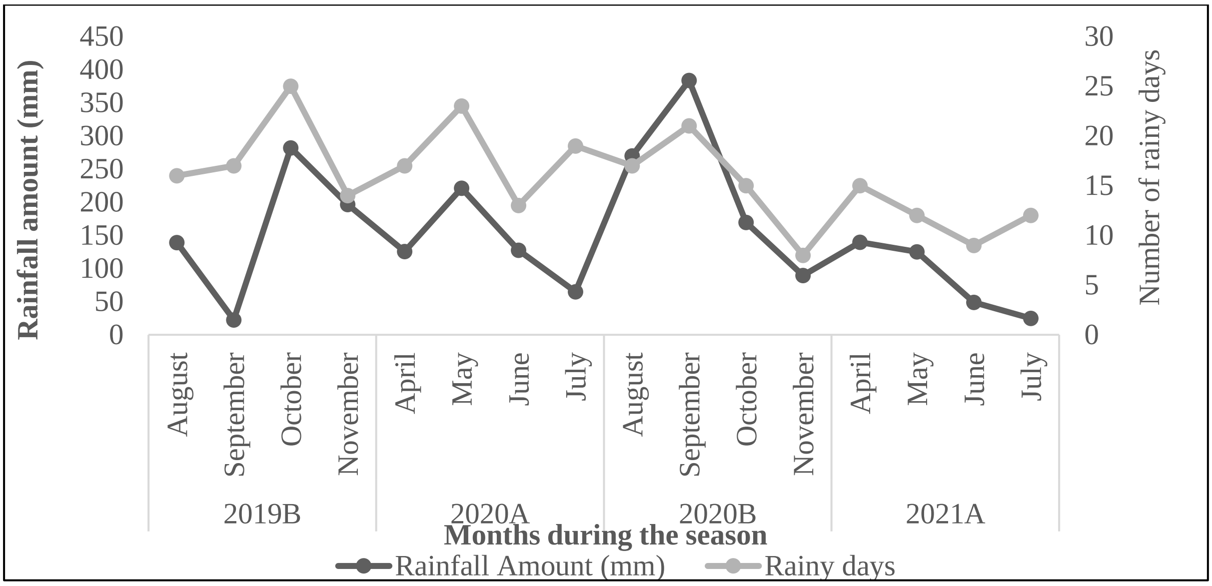
rainfall amount with smaller number of rainy days compared to 2019B, 2020A, 2021A. Hence, in 2020B, despite high amount of rainfall compared to other seasons weed density was lower due to reduced number of rainy days. Therefore, the number of rainy days per month was very crucial in determining weed density.

Figure 1: Rainfall amount and rainy days' distribution in the four growing seasons.



Note: Rainfall amount and number of rainy days were significantly different within season.

Effect of Tillage and Soil Cover Practice on Weed Density

Tillage method had a significant influence on weed density, defined as the total number of weeds per square meter ($p<0.05$). Conventional tillage plots prepared through ox-ploughing had a mean weed density of 124 per m^2 while minimum tillage plots had a lower mean weed density of 80 per m^2 (*Table 2*). In this study a total of thirty-eight weed species were observed in the minimum tillage plots compared to thirty-four weed species in the conventional tilled plots. *Figure 2*; shows the weed density (weed count) by season and treatment.

Soil cover practice had a significant effect on weed density (*Table 2*). The five soil cover practices had the following mean weed densities; maize with mulch - 64/m^2, sole maize - 121/m^2, maize with two lines of soybean in between - 113/m^2, maize with one line of soybean in between - 92/m^2 and sole soybean - 121/m^2. Weed density was higher in sole maize without mulch, compared to mulched and intercropped maize with one line of soybean between maize lines by at least 47% and 30%, respectively. Soil cover by mulching was much more effective in reducing weed density compared to intercropping. Maize intercropped with one line of soybean had significantly lower weed density than two lines of soybean in between maize.

Table 2: Mean values of weed density, weed diversity estimate by both Shannon Weiner index (H) and Simpsons index (D) across four seasons.

Source of variation	Total number of weeds	Diversity Index	
		Shannon Weiner index	Simpsons index
Tillage method			
Conventional tillage	124***	1.90 NS	5.14 NS
Minimum tillage	80***	1.97 NS	5.56 NS
Soil cover practice			
Sole maize with mulch	64***	1.97 NS	5.81 NS
Sole maize	121***	1.88 NS	4.95 NS

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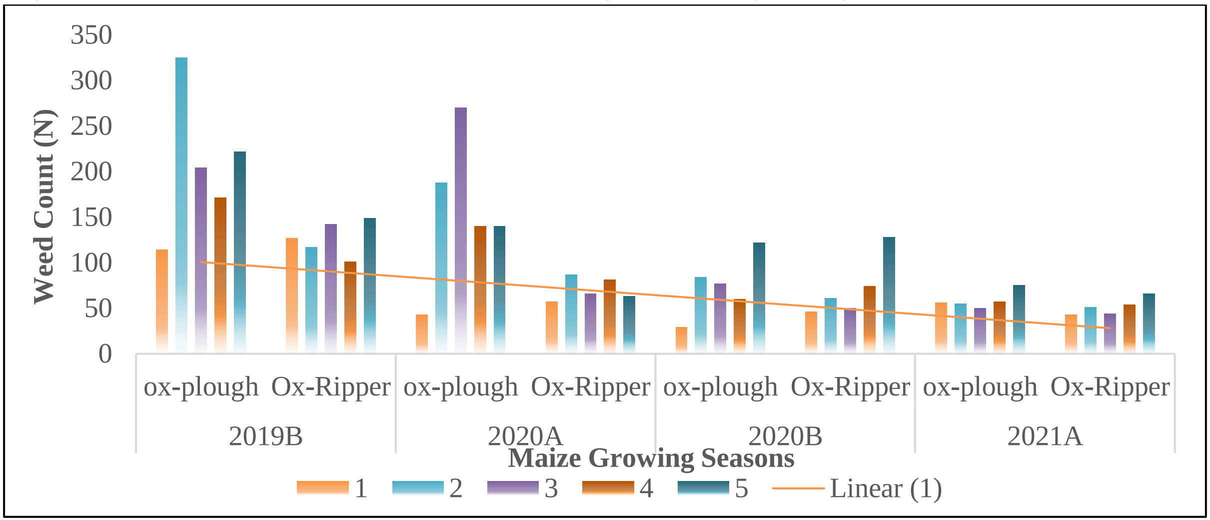
Two lines of soybean in between one line of maize	113***	1.98 NS	5.69 NS
One line of soybean in between one line of maize	92***	1.92 NS	5.16 NS
Sole soybean	121***	1.91 NS	5.14 NS
Tillage method X soil cover practice	***	NS	NS

*Note: *** Highly significant at the p< 0.01 level, NS not significant at p>0.05 level.*

Figure 2: Total number of weed count (n) during the maize growing season 2019B-2021A.



***Note:** Mean weed density during the four seasons. 1- Sole maize with mulch, 2-Sole maize, 3-Two lines of soybean in between maize, 4- One line of soybean in between maize, 5-Sole soybean. Weed count decreased along 2019B-2021A.*

Effect of Tillage and Soil Cover Practice on Weed Diversity Using Shannon Weiner Index

Shannon Weiner index (H) is a measure of diversity that takes into account species richness at different levels. Tillage and soil cover practice did not significantly influence weed diversity as measured using the Shannon Weiner index (*Table 2*). In this study, a total of forty-five above ground weed species were observed consisting of 27 broad-leaved weed species, 17 grasses and one sedge weed (*Figure 3* and *4*). The top ten with high weed densities ranging from 04 to 12 per square meter are *Richardia bransiliensis*, *Amaranthus hybridus*, *Panicum maximum*, *Commenlina benghalensis*, *Bidens pilosa*, *Vulpia myuros*, *Tropical ricardia*, *Amaranthus thunbergii*, *Desmodium intortum*, *Euphobia heterophylla*, *Cyperus rotundas* (8 Broad-leaved weeds, 1grass, 1 sedge). It's important to note that thirty-eight weed species were observed in the plots tilled with ox-plough consisting of 16 grasses, 1 sedge, and 21 broad-leaved weed species (*Figure 3*). Forty weed species (14 Grasses, 1 Sedge, 25 Broad-leaved weed species) were observed in the minimum tillage plots. Despite suppressing weeds better, minimum tillage had more diverse weed species composition. The weeds in minimum tillage plots not observed in conventional tillage plots include *Rottboellia cochninchinensis*, *Asclepias incanata*, *Boerhavia diffusa*, *Synedrelia nodiflora*, *Hairy Euphorbia heterophylla*, *Cleome*, *Axonopus compressus*, *Sesamum calycinum* ("Agilo"-Luo). This study also observed that *Tagetes minuta*, *Bracharia eruciforms*, *Panicum maximum*, *Sorghum drummondi and Erigeron canadensis* grass weed species was only found in conventional tillage plots. In the first experimental season of 2019B, the following weed densities were observed: grasses constituted 30%, broad-leaved weeds 60% and sedges 10%. However, at the end of the trials in 2021A, grasses constituted 10%, broad leaved 80% and sedges 10%. There was an increase of broad-leaved weeds in both tillage practices. Grasses were fewer in the minimum tilled plots than conventional plots at 7% and 15%, respectively.

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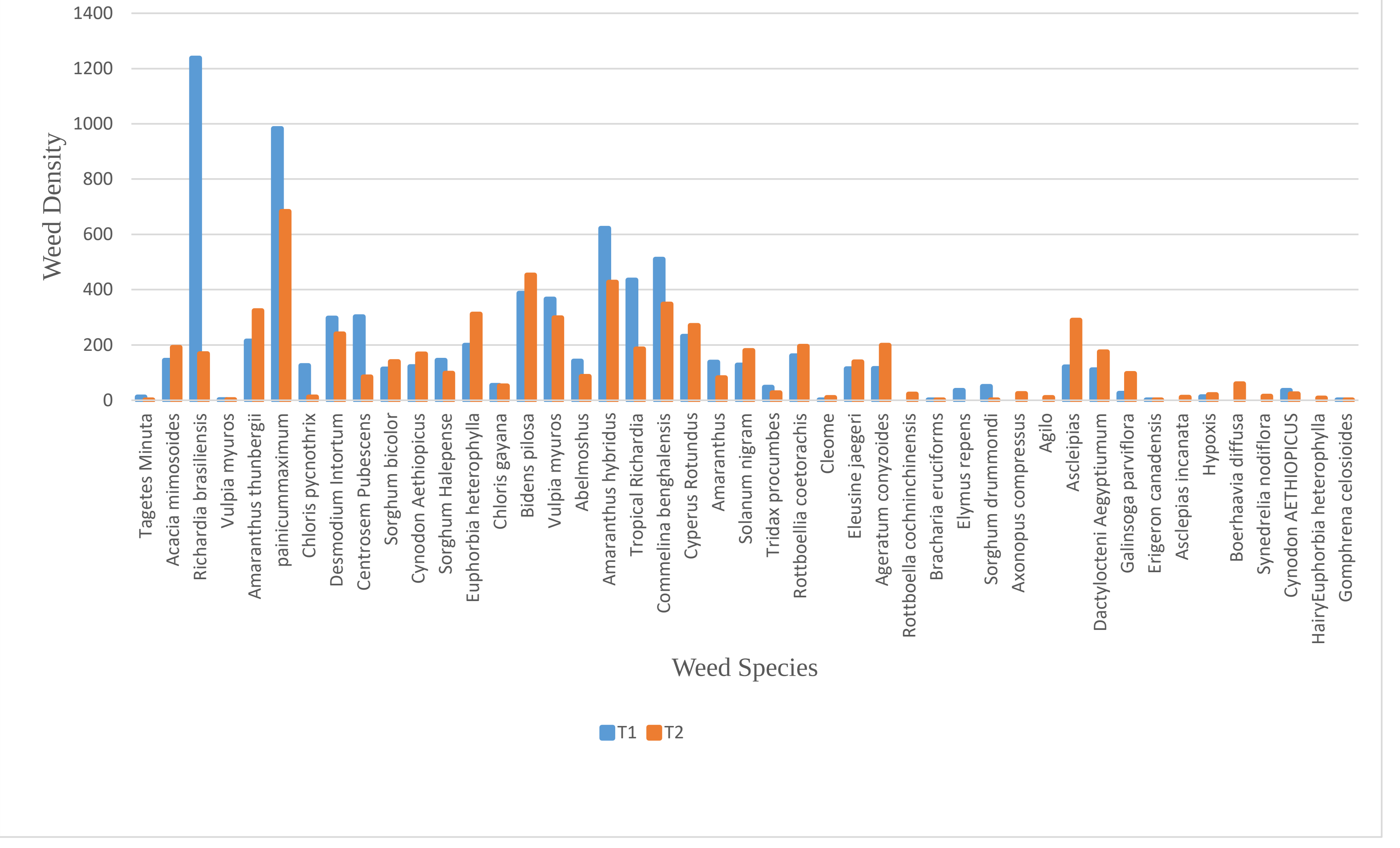
Figure 3: Effect of tillage methods on weed density and diversity.



NOTE : *T1: Conventional tillage, T2: Minimum tillage.*

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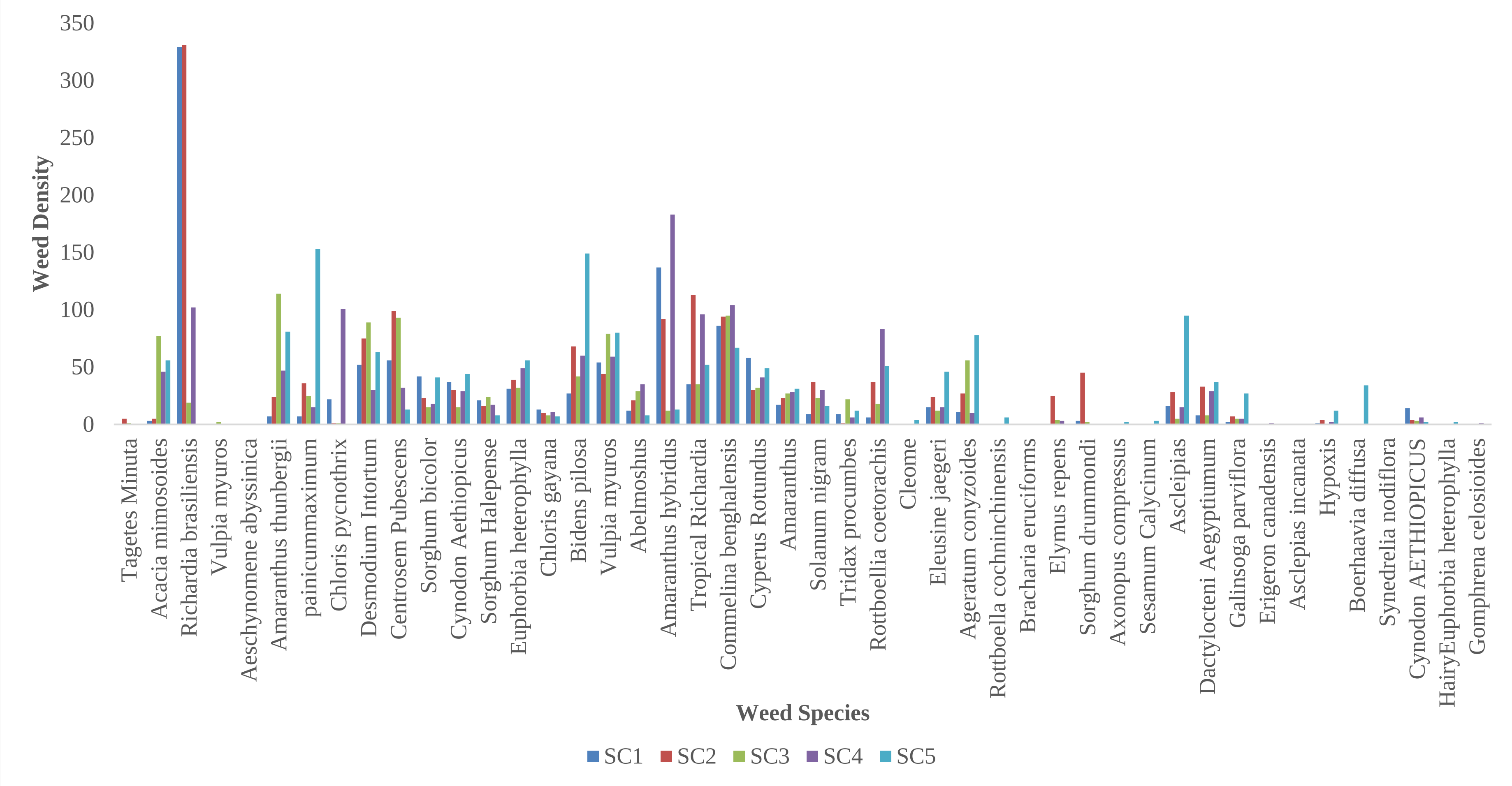
Figure 4: Effect of five soil cover practices on weed density and diversity



Note: SC1- Sole maize with mulch, SC2-Sole maize, SC3-Two lines of soybean in between maize line, SC4- One line of soybean in between maize line, SC5-Sole soybean

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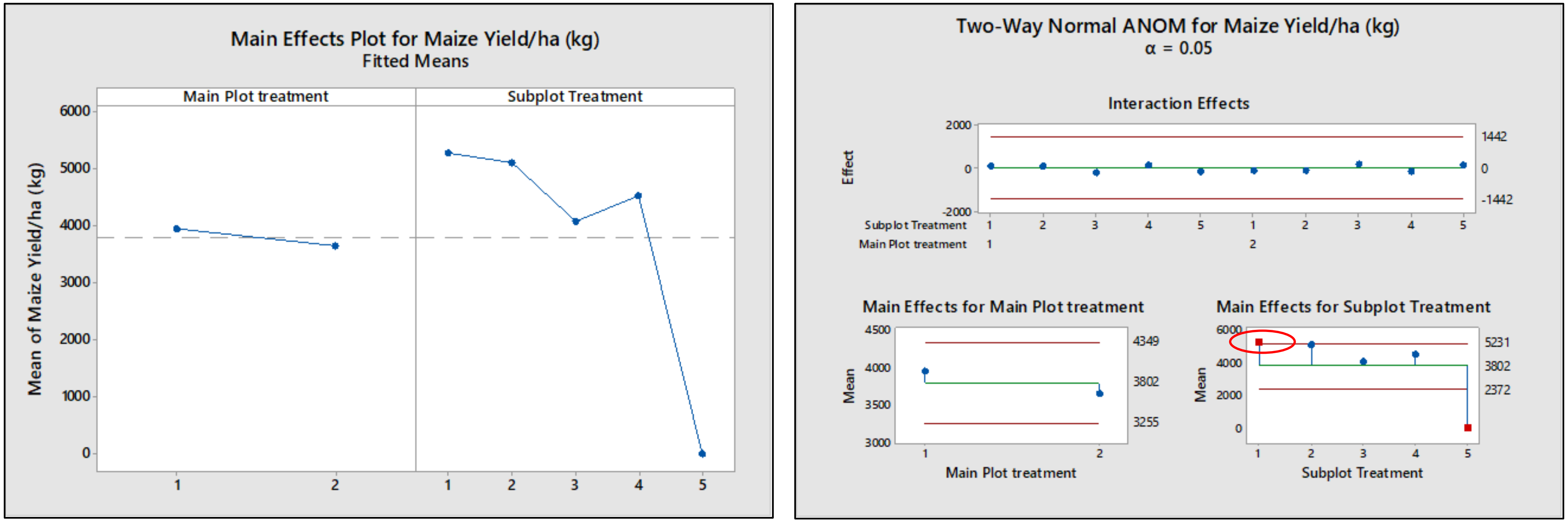
Figure 5: Interaction effects between tillage and soil cover practices



Note: Main Plot treatment (1-Conventional tillage, 2-Minimum tillage). Subplot treatment (1- Sole maize with mulch, 2-Sole maize, 3-Two lines of soybean in between maize, 4- One line of soybean in between maize, 5-Sole soybean)

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Effect of Tillage and Soil Cover Practice on Weed Diversity Using Simpsons Diversity Index

Simpsons diversity index (D) is a measure of diversity that takes into account the number of species present, as well as the relative abundance of each species. Tillage practice had no significant influence on Simpsons index (*Table 2*). Soil cover practices had no significant effect on weed diversity as measured by Simpson's index (*Table 2*).

Effect of Tillage and Soil Cover Practice on Yield

In the main effects plot (*Figure 5*), there were no significant difference in yield between conventional and minimum tillage plots. However, soil cover practices significantly affected maize yield ($p<0.05$). The computation of the land equivalence ratio for both intercropping patterns in the soil cover practices offered the advantage to intercropping. Soil cover improves soil moisture availability by decreasing evaporation, improves infiltration, prevents leaching and helps preserve water from the unreliable rainfall, its suited for areas receiving inadequate rainfall. In addition, soil cover controls soil erosion, prevents leaching, and if practiced with crop cover fixes nitrogen (Antosh et al., 2020; Unger & Vigil, 1998).

DISCUSSION

Conservation agriculture has been promoted in the last few decades as a sustainable approach to increase crop production. It was and is still expected to address key production challenges including soil degradation, crop pest and diseases, and agricultural labour challenges amongst others (Kassam et al., 2020). In most of the studies on sustainable agriculture, little emphasis is placed on pest management (weeds inclusive) (Giller et al., 2021). One of the key challenges to implementation of CA are weeds, which can cause up to 100% crop failure (Daramola et al., 2020). In this study, the effect of minimum tillage and soil cover, which are two of the three principles of CA on weeds over four growing seasons were assessed. Our main result is that minimum tillage and soil surface cover reduced weed density and not weed diversity based on the H and D indices used, in comparison to conventional ploughing without soil cover. Over the four growing seasons, there was a shift in the weed's composition from more grass type weeds to predominantly broad-leaved weeds with overall lower density. The overall lower weeds density signify that CA can be a sustainable approach to increasing production, more especially in SSA where crop yields are often very low. In regard to weed species count, the minimum tillage plots had 05% more weed species than the conventional tillage plots, though this was insignificant for weed diversity parameters as measured by Shannon Wiener and Simpson index. However, it's important to note that a single weeds species could easily become dominant in unbalanced weed community and cause serious economic losses. This calls for more sensitive parameters when comparing the effect of farming practices on weed species. The broader implication is that agricultural practices that promote a more diverse weed community will be less competitive, less prone to dominance by highly adapted weeds or herbicide resistant weeds, and gives an indication of an agronomic and environmental sustainability (MacLaren et al., 2020). Also, a high number of arable weed species supports insect diversity contributing to sustainable pest management (Armengot et al., 2016; Marshall et al., 2003).

Effect of Rainfall Amount and Number of Rainy Days on Weeds

Results of our study show that weed density and diversity is influenced by not just the amount of rainfall, but also the number of rainy days per month. In season 2020B it was observed a high amount of rainfall, but fewer rainy days, hence weed density remained lower than 2019A and 2020A due to less rainy days as indicated in *Figure 2*. Data for all the four seasons show that weed diversity species richness as measured by H, was significantly influenced by rainfall amount and not the number of rainy days (*Table 1*). Farmers in the study area depend on rainfall typically as the only source of

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soil moisture, hence studying effect of rainfall amount and number of rainy days is important to support them in making key decisions on farm. The use of soil cover supports conservation of water supplied by the erratic rainfall (fewer rainy days), which can improve crop yield. The use of more than two crops can help preserve diversity of fauna as compared to monocropping (Raven & Wagner, 2021). Intercropping is practiced by 40% of Ugandan farmers (UBOS, 2001, p. 200), hence it would be easily adopted as a weed management practice compared to soil cover through mulching that was not adopted by CA farmers (Kaweesa et al., 2018).

Effect of Tillage Method on Weeds

Tillage practice had a significant effect on weed density, but not weed diversity as measured by H and D indices (*Table 2*). Also, the number of weed species count in conventional tillage were 05% lower compared to the number of weed species in minimum tillage plots (*Figure 3*). This percentage difference should not be ignored even if not detected by the diversity indices, as a single additional weed could become dominant and cause enormous crop destruction. The reason for more weeds species in the minimum tillage systems could be because, seeds remain near the soil surface within 0-5 cm soil layer, thus are more likely to germinate due to exposure to favourable conditions (Chauhan et al., 2006). Similar studies indicated the same trend (Adeux et al., 2022; Armengot et al., 2016; Nandan et al., 2020). This knowledge could contribute to development of integrated weed management programs which are responsive to an overall balance of agroecosystems while managing serious and noxious weeds (Travlos et al., 2018). An integrated weed management approach developed based on functional agricultural biodiversity can open up possibilities of establishing a resilient system where both food production and nature can develop. Minimum tillage using ox-drawn ripper influenced a shift to broad leaved species (dicots) where four broad-leaved species observed in minimum tilled plots were not seen in the conventional tillage. The weed density of broad-leaved weeds also increased in minimum tillage plots. An earlier study on the effect of reduced tillage noted a shift in weed species towards dicots, with higher weed density observed in *Tridax procumbens* L and *Euphorbia hirta* L (G et al., 2021). In our study, there was an observed shift to the following broad-leaved weeds *Rottboellia coelorachis g. Forst, Asclepias Incarnata, Boerhavia diffusa, Synedrelia nodiflora, Sesamum calycinum* due to influence of minimum tillage and a reduction in grass weed density, including absence of *Eymus repens* found in plots tilled conventionally. Also, minimum tillage plots showed less weed infestation compared to conventionally ploughed plots using ox-drawn plough. This is similar to several reports that indicated the same effect of reduced tillage and zero tillage (Dorn et al., 2015; Jat et al., 2021; Nyagumbo, 1999). However, Mavunganidze et al. (2020) evaluated effect of no till on weed density in the short run (after 3 weeks) on different soil types and found out that no till didn't influence weed density in sandy soils, but had a higher weed density than conventional plots in clay and loam soil, eventually increasing the weed problem, if early weeding is not done. It must be noted that tillage effect on weeds is largely location specific. This is because it is influenced by the crop being tested, weed types, soil properties and texture, available water capacity and soil carbon (Pätzold et al., 2020).

Effect of Soil Cover Practice on Weeds

Soil cover improves soil moisture availability by decreasing evaporation, improves infiltration, prevents leaching and helps preserve water from the unreliable rainfall, its suited for areas receiving inadequate rainfall. In addition, soil cover controls soil erosion, prevents leaching, and if practiced with crop cover fixes nitrogen (Antosh et al., 2020; Unger & Vigil, 1998).

Use of mulching as a soil cover significantly suppressed weed density by 65% compared to un-mulched maize but maintained high weed diversity.

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Soil cover through intercropping soybean in maize significantly reduced weed density but did not significantly influence weed diversity. Weed density was influenced by the type of crop with soybean sole crop having a higher weed infestation than sole maize. Mulched plots had the lowest weed infestation followed by intercropping one line of soybean between maize line, which was even better at suppressing weed density than two lines of soybean in between maize (*Table 2*). Intercropping reduces weeds possibly by taking away resources that could be available for the weeds to thrive (Ferreira et al., 2018). In several studies, intercropping significantly suppressed weed density and maintain diversity, however, these depended much on the environmental conditions and presence of a cereal crop among the intercrop (Dorn et al., 2015; Guerra et al., 2022; Stefan et al., 2021; Szumigalski and Van Acker, 2005; Travlos et al., 2018). This is because cereals are greater competitors due to their physiological advantage of fast growth at early stages and a well-developed root and shoot system. This enables cereals capture the most resources above (light) and below (water and nutrients) ground (Amanullah, 2015).

CONCLUSION

Although CA has been found to recurrently encounter weed problems, some of its practices if implemented correctly can reduce weed problems and increase crop yields. In particular, minimum tillage through ripping and maintenance of soil surface cover over several seasons was found to reduce weed density in the current study by up to 65% and 53%, respectively. This study has demonstrated that soil cover can suppress weeds under conservation agriculture and can be necessary tool for integrated weed management system with a direct relationship with improved yield. Weed diversity on the other hand was not significantly affected by ripping and soil surface cover. Such unaltered diversity in weed composition may prevent dominance by noxious weeds. Hence, the study hypothesis is accepted. Rainfall amount and rainy days during the four seasons further confirms that we are experiencing climate variability with rain fall amount within a season that may be sufficient for crop production, but not evenly distributed based on fewer number of rainy days. This calls for adoption of soil cover practices to conserve the scarce water from unevenly distributed rainfall. Overall, minimum tillage when applied together with surface cover under wetter conditions can maintain diversity with implication that a more diverse weed community can be less competitive and less prone to dominance by a more competitive weed species ensuring higher crop yields.

AUTHOR CONTRIBUTIONS

Otim Godfrey Anyoni developed the concept note, implemented and conducted data analysis. Dr. Obia Alfred and Associate professor Susan Tumwebaze contributed to the review of the research concept note and write up of manuscript, Ekwangu Joseph contributed to the revision of manuscript. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare that they have no conflicts of interest.

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