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Strip Crops and Intercrops Outperform Crop Rotations for Weed Management Under Conservation Agriculture in Zimbabwe

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ABSTRACT

High weed infestation remains a major constraint on crop productivity for smallholder farmers practising Conservation Agriculture (CA). Fewer, more diverse weeds are desirable to reduce competition and provide ecosystem services. Crop diversification can help, but it is not yet clear which species combinations and layouts are most effective for smallholder CA. Here, we conducted an experiment in sub-humid Zimbabwe at two research stations with contrasting soils, and over two growing seasons (2021–2022 and 2022–2023). We evaluated weed community responses to maize monoculture, maize rotated with cowpea or pigeon pea, maize-pigeon pea intercropping and maize-cowpea and maize-pigeon pea strip cropping under moderately fertilised versus unfertilised conditions. Data were collected on weed abundance (number and biomass), diversity (species richness, Pielou evenness and Shannon diversity) and community composition. There were significant differences between sites and, to a lesser extent, between growing seasons. More substantial impacts of cropping systems on weeds were observed at the more fertile site. On average across both sites, seasons and fertiliser levels, maize-pigeon pea strip cropping performed best, resulting in the lowest weed number (23.2 weeds m^{-2}) and biomass (99.2 $g\,m^{-2}$) and the highest weed species diversity (Shannon index = 1.35), while the maize-cowpea rotation performed worst (number = 31.3 weeds m^{-2}, biomass = 179.3 $g\,m^{-2}$ and Shannon index = 1.12). Cropping system biomass was associated with lower weed biomass, but had no consistent effect on weed numbers or diversity. Fertilisation had weak and inconsistent effects. Overall, our results suggest that high biomass cropping systems, such as maize-pigeon pea strip cropping, could contribute to sustainable weed management in Zimbabwe. However, more research is needed to develop strategies for less fertile sites, where weeds seem less susceptible to crop competition.

1 | Introduction

Weeds are commonly considered a threat to crop and animal production because they compete with crops and pastures for water, light and nutrients. Uncontrolled weeds lead to yield losses averaging 30% globally, with 100% yield losses also possible in some cases (Benjamin et al. 2024; Oerke 2006). However, diverse weed communities can also be beneficial by providing ecosystem services in agricultural landscapes (MacLaren et al. 2020).

To manage weeds, smallholder farmers tend to rely on ploughing before the crop is planted, followed by hand hoeing and/or pulling for weed control throughout the season (Mhlanga et al. 2016). These practices can be costly for farmers and for their fields. Regular ploughing can result in soil erosion and degradation, compromising soil health and its functions (Hobbs et al. 2008). Manual weeding is labour-intensive and often results in delayed weed management during peak labour demand periods, leading to reduced crop yields. Weeding may be necessary up to four times during the growing season, demanding substantial labour, and weeding is a task often primarily undertaken by women and children (Mashingaidze et al. 2012).

Conservation Agriculture (CA), a farming system based on minimum soil disturbance, surface crop residue retention and crop diversification, among other complementary practices, has been proposed to help farmers avoid soil degradation while maintaining crop yields (Thierfelder et al. 2018). Without ploughing, alternative weed control methods need to be found (Lee and Thierfelder 2017; Nichols et al. 2015). Herbicides are one alternative that is becoming more common in smallholder farming systems in southern Africa due to labour shortages for manual weeding (Chauhan 2020; Muoni et al. 2013). However, the continued use of herbicides as the primary method of weed control can lead to herbicide-tolerant species becoming dominant and to herbicide resistance in some weed biotypes (MacLaren et al. 2020; Nichols et al. 2015). Herbicides can also cause environmental pollution and human health risks (Marin-Morales et al. 2013).

Crop diversification, one of the pillars of CA, may offer more sustainable opportunities for weed management. Crop diversity has been shown to regulate weed abundance while maintaining biodiversity (Liebman and Staver 2001). Diversification can be achieved temporally, by rotating different crops over time, which also leads to spatial diversity with different crops planted in different fields in each growing season. Spatial diversity at the within-field scale can also be achieved by combining crops in intercrops and mixtures (Liebman and Dyck 1993). Previous research suggests that crop rotations are most effective for weed management when they involve substantial management differences between crops or changes in planting and harvesting dates (MacLaren et al. 2020; Weisberger et al. 2019). These changes create an unstable environment for weeds, limiting abundance and increasing diversity by altering the species that can survive in each year (Liebman and Dyck 1993; Smith and Gross 2007). However, such rotations may not always be possible. For instance, smallholder farmers in Zimbabwe face a strong unimodal rainfall pattern, with planting and harvest dates constrained by rainfall. Furthermore, smallholder farmers tend to have limited access to tools and resources and must rely on more uniform management practices across crop rotations. Consistency can diminish the weed-suppressive benefits of rotation (MacLaren et al. 2020).

In contrast to rotations, intercropping can suppress weeds through a mechanism that may be less sensitive to smallholder conditions: more effective resource capture (Bybee-Finley et al. 2017; Isbell et al. 2017). Growing different crop species together with complementary resource use patterns in space and over time within the season enhances the use of available resources, thus reducing resource availability for weeds (Brooker et al. 2015).

The effects of crop diversity on weed communities in smallholder farming systems are still understudied, so it remains unclear which cropping systems have the most potential to alleviate weed pressure. Indeed, even in international literature, we could not find any comparisons between rotations and intercrops for weed suppression, though global meta-analyses suggest that both have the potential to reduce weeds by around 50% compared to sole crops (Gu et al. 2021; Weisberger et al. 2019). To begin addressing this knowledge gap, we investigated weed communities in three cropping systems commonly used by smallholder farmers in Zimbabwe: monoculture, crop rotation and intercropping. We also included strip cropping, a less common system that involves growing crops in alternating strips of multiple rows. Strip cropping may have more potential to balance productivity and ecosystem services than other cropping systems (Kinyua et al. 2023; Thierfelder et al. 2024).

We tested the effects of these cropping systems both with and without fertiliser, given that smallholders often have inconsistent or insufficient access to fertilisers (Falconnier et al. 2023) and that fertiliser is known to influence weeds (Little et al. 2021; Storkey et al. 2021). The nutrients supplied by fertiliser often favour weeds, enabling them to grow more vigorously and compete more strongly with crops (MacLaren et al. 2020). However, in some cases, fertiliser instead provides a greater competitive advantage to crops (Little et al. 2021). Typically, fertiliser reduces weed diversity (Storkey et al. 2021), but nitrogenous fertilisers can also break some weed species' seed dormancy, resulting in changes in weed community composition (Pyšek and Lepš 1991).

We hypothesised that (1) crop rotations typical of Zimbabwean smallholders do not have substantial effects on weed abundance or diversity compared to monocultures, but (2) intercrops and strip crops reduce weed abundance and increase diversity compared to monocultures due to greater resource capture. We also expected to find that (3) applying fertiliser increases weed abundance while decreasing weed diversity.

2 | Materials and Methods

2.1 | Study Sites

The study was conducted in Zimbabwe at the University of Zimbabwe farm (UZ) and the Domboshava Training Centre (DTC) research stations. UZ is located 12.5 km north of Harare (17.73°S, 31.02°E) and DTC 30 km northeast of Harare (17.62°S, 31.17°E), both in the sub-humid region of Zimbabwe. This area experiences a unimodal rainfall pattern with an average of around 800 mm from November to April. The climate is warm temperate to tropical, with hot, wet summers (November–April) and dry winters (May–October) (Manatsa et al. 2020). Rainfed crops can only be grown in the wet summer, with land left fallow in winter. The soils at UZ are xanthic Ferralsols derived from dolerite (Schad 2023), characterised by a sandy clay loam texture with 34% clay in the top 20 cm of soil and 38% clay in the 20–40 cm subsoil layer. In contrast, DTC has granitic abruptic Lixisols (Schad 2023), which are sandy loams with a light texture, containing 15% clay in the topsoil and 30% clay in the subsoil (Shumba et al. 2023).

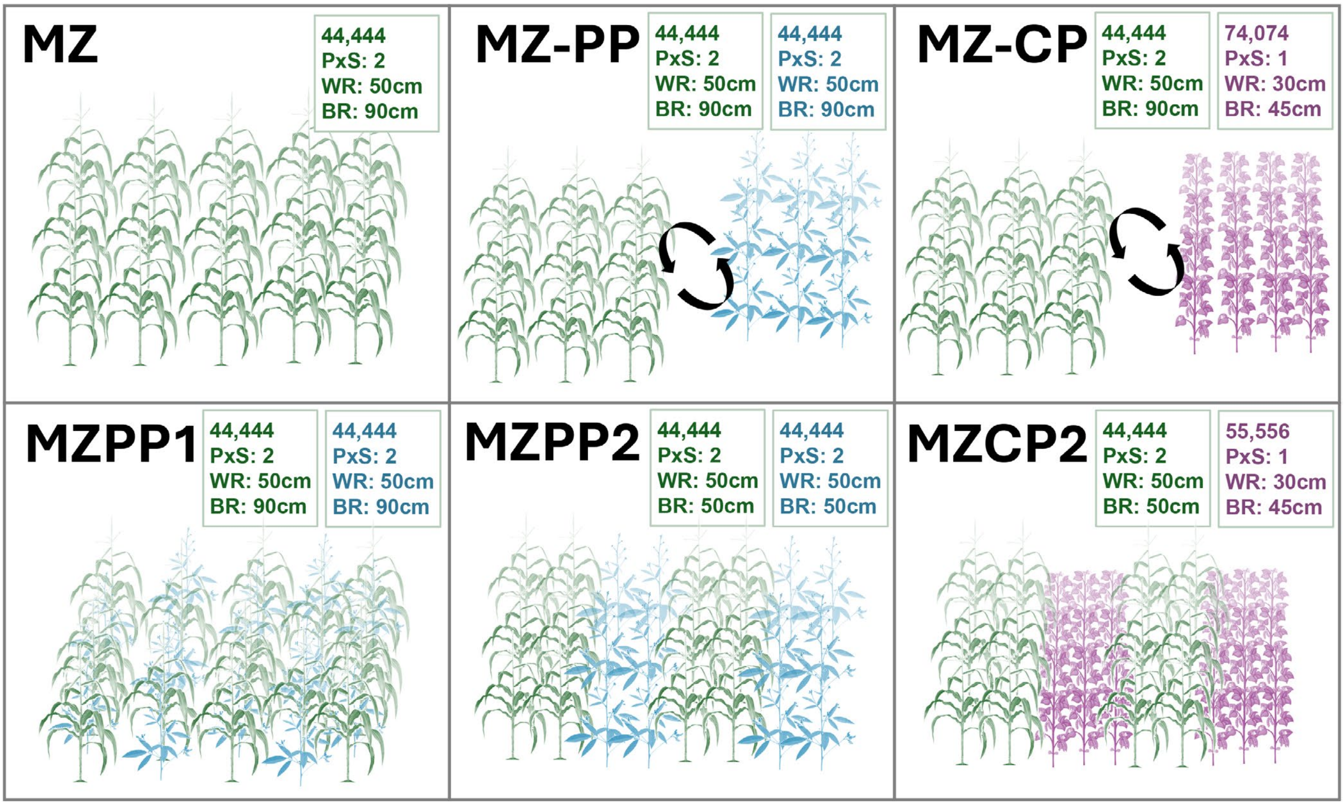

FIGURE 1 | Illustrations of the six cropping systems tested in this study (not to scale), with green symbols for maize, blue for pigeon pea and purple for cowpea. Boxes inset into the upper right corners of each panel indicate (1) the plant population of each species in each plot of each system (note that the rotation has one plot per crop), (2) the number of plants per station (PxS), (3) the within-row spacing between stations (WR) and (4) the between-row (BR) spacing. In the traditional intercrop, maize and pigeon pea are planted in alternating stations within the same row. In MZPP2, the spacing between strips (i.e., between rows of maize and pigeon pea) was 40 cm, and in MZCP2 it was 35 cm. MZ = sole maize; MZ-CP = maize–cowpea rotation; MZ-PP = maize–pigeon pea rotation; MZCP2 = maize–cowpea double-row strip cropping; MZPP1 = traditional alternate maize intercropping with pigeon pea; MZPP2 = maize–pigeon pea double-row strip cropping.

2.2 | Experiment Design and Crop Management

Two identical experiments were established during the 2019–2020 summer growing season at UZ and DTC. Data included in our analysis were from the second cropping season 2021–2022 to the 2022–2023 season (allowing the first year for the systems to establish). The experiments followed a strip plot design: each site had four replicates, and each replicate was split lengthwise into two fertiliser treatment main plots and perpendicularly into eight cropping system main plots. Treatments were randomly assigned to each main plot. This design resulted in 16 plots per replicate, each 8 m long by 6 m wide.

The six cropping systems tested were (1) continuous sole maize (MZ), (2) a maize-cowpea (*Vigna unguiculata* (L.) Walp.) rotation (MZ-CP), (3) a maize-pigeon pea (*Cajanus cajan* (L.) Millsp.) rotation (MZ-PP), (4) a maize-cowpea two-row strip crop (MZCP2), (5) a maize-pigeon pea traditional intercrop (MZPP1) and (6) a maize-pigeon pea two-row strip crop (MZPP2) (Figure 1). The two legumes, cowpea and pigeon pea, have different morphological and physiological characteristics that may influence their effects on weeds. Cowpea establishes quickly with broad leaves and a spreading canopy, which may rapidly shade weeds and limit light availability, while pigeon pea grows taller with woody stems and a deep root system, potentially competing more strongly with weeds later in the season despite slower initial growth (Moolendra et al. 2018; Yadav et al. 2021). In the rotations, a single crop is grown in the wet summer growing season each year, with crops rotated between years. Two plots were allocated to each rotation treatment so that both crops were present in the experiment each growing season. In all treatments, maize was planted at 44 400 plants ha^{-1}, a relatively low density typical for smallholder farming in Zimbabwe, which aims to minimise competition between maize plants and thus mitigate the impact of the region's frequent droughts. The intercrops and strip crops were arranged in an additive design, given that smallholders tend to be reluctant to reduce maize populations in favour of legumes. Layouts for each cropping system are shown in Figure 1.

The two fertiliser treatments were fertilised and unfertilised. The fertilised plots received a basal application of compound fertiliser (12 kg N ha^{-1}, 14 kg P ha^{-1} and 8 kg K ha^{-1}), applied to all crops. Maize (*Zea mays* L.) also received a top dressing of ammonium nitrate (52 kg N ha^{-1}), split between applications at 4 and 7 weeks after planting, leading to a total of 64 kg N ha^{-1} applied to each plot over the season.

Medium-maturity varieties of maize (PGS 63), cowpea (CBC2) and pigeon pea (ICEAP 01551) were grown at both sites in both seasons. Both legumes were determinate varieties. All crops were planted on the same date, after the first effective rains (defined as 3 consecutive days with at least 30–50 mm rainfall), that fell between 15 November and 25 November in both seasons. Cowpea and pigeon pea were sown without Rhizobium inoculation, as most smallholders in Zimbabwe do not have access to inoculant. Crops were sown in planting basins 'stations' dug with a hand hoe to the approximate dimensions 15 cm length × 15 cm width × 15 cm depth. Crop residues were retained in situ from the previous cropping season at a rate of 2.5–3 t ha^{-1}. During each season, pests and diseases were controlled with recommended pesticides if they reached economically damaging levels.

2.3 | Weed Management, Sampling and Calculations

2.3.1 | Weed Management and Sample Timing

Weed management followed typical practices for smallholder farmers implementing CA, with weed sampling adapted to fit into this weeding regime. At sowing, existing weeds were sprayed with glyphosate [N-(phosphono-methyl) glycine] at a rate of 1025 g active ingredient ha^{-1}. Thereafter, weeds were removed with hand hoes when they reached approximately 10 cm in height or 10 cm in circumference for stoloniferous weeds, which occurred at least three times each season. Manual weeding was undertaken as the first plots exceeded this threshold, and all plots within a site were weeded on the same day. Weeds were sampled a day before each manual weeding event during the growing season.

2.3.2 | Weed Sampling and Calculations

In each plot at each sampling event, the weed species present, the number of weeds and weed biomass were measured in quadrats: three 0.5 m ×0.5 m quadrats were randomly placed in each subplot, avoiding outer crop rows to avoid edge effects and ensuring a representative sample of the weed population within the plot. All weeds within the quadrats were identified according to the guidelines of Botha (2001) and Makanganise and Mabasa (1999). The weeds were counted by species, recorded and uprooted. The day after weed sampling, all plots in the experiment were weeded with hand hoes to ensure sampling would not affect future weed numbers or biomass.

All weed samples collected from the quadrats, including roots, were oven-dried at 70°C for 48 h, and the dry weight of weed biomass was measured. We acknowledge that uprooting rather than cutting weeds was not an ideal method and is likely to have introduced unnecessary noise into our data. Although weeds are typically pulled free of the soil with their large roots intact, smaller roots may have broken off, meaning we may have captured a different proportion of each plant's biomass. Given that the approach was used consistently across the experiment, it would have introduced noise but not bias; it may have obscured some trends, but would not have altered them.

The metrics of the weed community used in our study were total weed number (mean number of weeds per m^2 across all quadrats and sampling events per plot), total weed biomass (mean dry weight g m^{-2} across all quadrats and sampling events per plot), weed species richness (total number of weed species present across all quadrats and sampling events per plot), weed species diversity (Shannon index) and weed species evenness (Pielou index). These metrics were calculated by summing the weed numbers, biomass and species richness in the three quadrats (total area 0.75 m^2) in each plot at each sampling point, and then summing again across all sampling events per season. This method captured the total potential weed pressure that would be encountered by farmers when following typical weeding practices throughout the season, and indicates the overall burden of repeated weeding and the associated labour demands (but does not represent an actual field weed community at any one time point). For weed number and biomass, we converted the total sum from per 0.75 m^2 to per m^2. Weed species richness was not converted (due to the species-area relationship) and is the number of weed species encountered within 0.75 m^2 across all sampling events.

The Shannon diversity index was calculated as follows:

$$\text{Shannon index} = -\sum \left(P_i \times \ln\left(P_i\right)\right) \tag{1}$$

where P_i is the relative abundance of each group of weed species (summed across the three quadrats), and ln is the natural logarithm. A Shannon index of 0 indicates no diversity (a single species), while the greater the value, the greater the diversity.

The Pielou index was calculated using the following formula:

$$\text{Pielou index} = H / \ln(S) \tag{2}$$

where S is the weed species richness, ln is the natural logarithm, and H is the Shannon weed diversity index. The Pielou index ranges from 0 to 1. Values closer to 1 indicate a uniform distribution of plants among weed species, and values closer to 0 indicate that most plants present belong to just one or a few weed species. Both the Pielou and Shannon indices were calculated using the *vegan* package (Oksanen et al. 2020) in R (R Core Team 2024).

2.3.3 | Total Crop Biomass Sampling

Crop harvesting was done by hand when each crop had reached physiological maturity, with cowpea, maize and pigeon pea harvested separately. One sample was harvested per plot for each of the three crops. For maize and pigeon pea, samples were taken from 4 central rows by 5 m, while 2 central strips (4 rows) of 5 m length were harvested for double row strip cropping. For cowpea, 8 central rows by 5 m were harvested in sole crops, and 2 central strips for strip cropping.

Harvested material was separated into plant biomass (stalks and leaves) and cobs/pods, and fresh weights for each crop were recorded. To determine the fresh to dry weight ratio, sub-samples of approximately 500 g of plant material (stems and leaves), 10 maize cobs, and approximately 500 g of cowpea or pigeon pea pods were used. These sub-samples were separated into grain, cob cores and pod shells, air-dried, then weighed separately. Grain yields were standardised to 12.5% moisture. Total crop biomass was obtained by first using the fresh to dry weight ratios to convert the fresh weight of plant material, cobs, pods and grain in each plot into dry weight. These values were then summed per plot to obtain the dry weight of total crop biomass, and this value was then expressed on a per m^2 basis. For systems with two crops, the biomass of both crops was summed to obtain total system biomass. Only the dry weights were used for analysis.

2.4 | Statistical Analyses

2.4.1 | Weed Abundance and Diversity

All analyses were conducted in R (R Core Team 2024). We used mixed models to investigate treatment effects on the five metrics of the weed community: weed number, biomass, species richness, Pielou evenness and Shannon diversity. A separate model was created for each of these response variables. In all models, the fixed effects were cropping system, crop type nested within cropping system, fertiliser level, site, season and all interaction terms between these variables. Crop type was included to account for the different crops in the rotations, potentially having other effects, but in the intercrops and strip crops, there was only a single level of this factor because weeds were measured under both crops together. The models also included random effects for fertiliser plot and cropping system plot, and their interaction, to account for the strip plot design and the non-independence of data collected in the same plots across different seasons. Mixed models based on a normal distribution were created using function *lmer* in package *lme4* (Bates et al. 2015). To meet the assumptions of normality and homoscedasticity in the residuals, weed number and biomass were log transformed. The Pielou evenness index was logit transformed (given it is bounded between 0 and 1), using the equation as follows:

$$\text{Logit}\_P = \log\left(P / (1 - P)\right) \quad (3)$$

where P is the Pielou evenness index. All results have been back-transformed and are reported on the original scale.

The significance of model terms was tested using Type III ANOVA (Satterthwaite F-tests) using packages *pbkrtest* (Halekoh and Højsgaard 2014) and *lmerTest* (Kuznetsova et al. 2017). The variance explained by each model was described using the marginal R^2 (fixed effects only) and the conditional R^2 (fixed plus random effects), both calculated using the *MuMIn* package (Bartoń 2022). The package *emmeans* (Lenth et al. 2023) was used to calculate estimated marginal means and conduct pairwise comparisons (using a Tukey correction for multiple tests). The means and comparisons shown for each response variable depended on which interactions were significant in the ANOVA; however, results are always averaged across crop types within rotations to show cropping system rather than crop effects.

2.4.2 | Effect of Total Crop Biomass on Weed Metrics

We also investigated whether differences in cropping system biomass could explain differences in weed responses across cropping system treatments. To do so, we used the same mixed-model procedure described above, but we replaced the crop type and cropping system terms with total crop biomass. The fertiliser treatment variable was retained to examine whether crop biomass differed between fertilised and unfertilised conditions. In these models, the responses for weed number and biomass were log-transformed. Still, the Pielou index was not (residuals from a model with the non-transformed response met all necessary assumptions).

One point with an outlier value for the cropping system biomass was removed from these models. This point had the highest value for weed biomass in our dataset and was well outside the range of other values collected from the same treatment, site and season, so it seems likely that this point was an error. It fell at the end of the range of cropping system biomass values and so was highly influential in most models, with a much higher Cook's distance than all other points. To avoid our results being substantially altered by a single and suspect datapoint, we excluded it from the models.

2.4.3 | Weed Community Composition

To explore differences in weed community composition across the experiment, we used a non-metric multidimensional scaling (NMDS) ordination. First, we checked the number of dimensions required to achieve a result with a stress value below 0.2 using the function *dimcheckNMS* in package *goeveg* (Von Lampe and Schellenberg 2024), then ran the ordination using *metaMDS* in package *vegan* (Oksanen et al. 2020). We used the Bray–Curtis dissimilarity index.

3 | Results

3.1 | Weed Number and Biomass

The cropping system and fertiliser treatment affected both weed numbers and biomass (Table 1). For weed number, there was also a significant interaction between cropping system and fertiliser. Significant effects of site and season, and interaction terms containing them, indicated that mean weed number and biomass both differed between sites and seasons, and that treatment effects on these responses also differed between sites and seasons (Table 1). Across both seasons, DTC had higher weed numbers and biomass than UZ, whereas treatment effects were much more pronounced at UZ (Figures 2 and 3). At DTC, the only significant difference observed was a lower weed number in unfertilised MZ-CP than in fertilised MZ-PP. At UZ, MZ-CP tended to have higher weed biomass than other cropping systems, while MZPP2 had the lowest. Fertiliser had variable effects on weed number, depending on the cropping system, site and season, and little effect on weed biomass, except to reduce weed biomass across all cropping systems in the 2021–2022 season.

3.2 | Weed Species Richness, Evenness and Diversity

Cropping system and fertiliser interacted in their effect on weed species richness, although this effect differed between seasons,

TABLE 1 | The p values alongside numerator (N.DF) and denominator degrees of freedom (D.DF) for each model term from Type III ANOVA F tests of mixed models testing the effects of treatment, site and season on each weed response variable: weed number, weed biomass, weed species richness, weed species evenness (Pielou index) and weed species diversity (Shannon index).

	Number			Biomass			Species richness			Pielou evenness index			Shannon diversity index		
	N.DF	D.DF	p	N.DF	D.DF	p	N.DF	D.DF	p	N.DF	D.DF	p	N.DF	D.DF	p
Cropping system	5	51.26	**< 0.001**	5	56.97	**< 0.001**	5	54.66	0.975	5	56.06	**< 0.001**	5	54.94	**0.006**
Fertiliser	1	6.41	0.841	1	6.25	0.127	1	6.37	0.052	1	6.49	0.663	1	6.48	0.415
Season	1	96	**< 0.001**	1	96	**< 0.001**	1	96	**< 0.001**	1	96	**< 0.001**	1	96	**< 0.001**
Site	1	6.36	**< 0.001**	1	6.12	**< 0.001**	1	6.13	0.016	1	6.49	**< 0.001**	1	6.48	**0.001**
Cropping system: crop	2	96	**0.004**	2	96	0.669	2	96	0.518	2	96	0.078	2	96	0.069
Cropping system: fertiliser	5	57.57	**0.048**	5	57.57	0.615	5	57.57	0.188	5	56.06	0.955	5	54.94	0.917
Cropping system: season	5	119.96	**< 0.001**	5	119.68	0.086	5	120.49	0.502	5	120.09	0.089	5	120.43	0.051
Fertiliser: season	1	96	**0.002**	1	96	**0.017**	1	96	0.068	1	96	0.988	1	96	0.699
Cropping system: site	5	51.26	**< 0.001**	5	56.97	**0.001**	5	54.66	0.111	5	56.06	**< 0.001**	5	54.94	**0.008**
Fertiliser: site	1	6.41	0.514	1	6.25	0.649	1	6.37	**0.048**	1	6.49	0.472	1	6.48	0.108
Season: site	1	96	**< 0.001**	1	96	**< 0.001**	1	96	**< 0.001**	1	96	0.175	1	96	**< 0.001**
Cropping system: crop: fertiliser	2	96	0.556	2	96	0.376	2	96	0.518	2	96	0.357	2	96	0.509
Cropping system: crop: season	2	42	**0.004**	2	42	0.708	2	42	0.506	2	42	**0.036**	2	42	0.147
Cropping system: fertiliser: season	5	119.36	0.316	5	119.36	0.956	5	119.36	0.854	5	120.09	0.359	5	120.43	0.527
Cropping system: crop: site	2	96	**0.014**	2	96	0.376	2	96	0.325	2	96	0.280	2	96	0.581
Cropping system: fertiliser: site	5	57.57	0.492	5	57.57	0.326	5	57.57	0.816	5	56.06	0.938	5	54.94	0.961

(Continues)

TABLE 1 | (Continued)

	Number			Biomass			Species richness			Pielou evenness index			Shannon diversity index		
	N.DF	D.DF	*p*	N.DF	D.DF	*p*	N.DF	D.DF	*p*	N.DF	D.DF	*p*	N.DF	D.DF	*p*
Cropping system: season: site	5	119.96	0.176	5	119.68	0.067	5	120.49	0.222	5	120.09	0.288	5	120.43	0.240
Fertiliser: season: site	1	96	**0.031**	1	96	**0.007**	1	96	1.000	1	96	**0.001**	1	96	**0.003**
Cropping system: crop: fertiliser: season	2	42	**0.071**	2	42	0.300	2	42	**0.046**	2	42	0.185	2	42	0.625
Cropping system: crop: fertiliser: site	2	96	0.607	2	96	0.197	2	96	0.370	2	96	0.686	2	96	0.169
Cropping system: crop: season: site	2	42	0.076	2	42	0.071	2	42	0.922	2	42	0.393	2	42	0.461
Cropping system: fertiliser: season: site	5	119.36	0.821	5	119.36	0.866	5	119.36	0.198	5	120.09	0.699	5	120.43	0.571
Cropping system: crop: fertiliser: season: site	2	42	0.920	2	42	0.534	2	42	0.114	2	42	0.169	2	42	0.499
Model marginal (m) and conditional (c) R^2	$mR^2 = 0.88$, $cR^2 = 0.91$			$mR^2 = 0.86$, $cR^2 = 0.87$			$mR^2 = 0.40$, $cR^2 = 0.51$			$mR^2 = 0.52$, $cR^2 = 0.56$			$mR^2 = 0.46$, $cR^2 = 0.54$		

Note: p values < 0.05 are emphasised in bold text to highlight which terms were significant at the 5% level for each response variable.

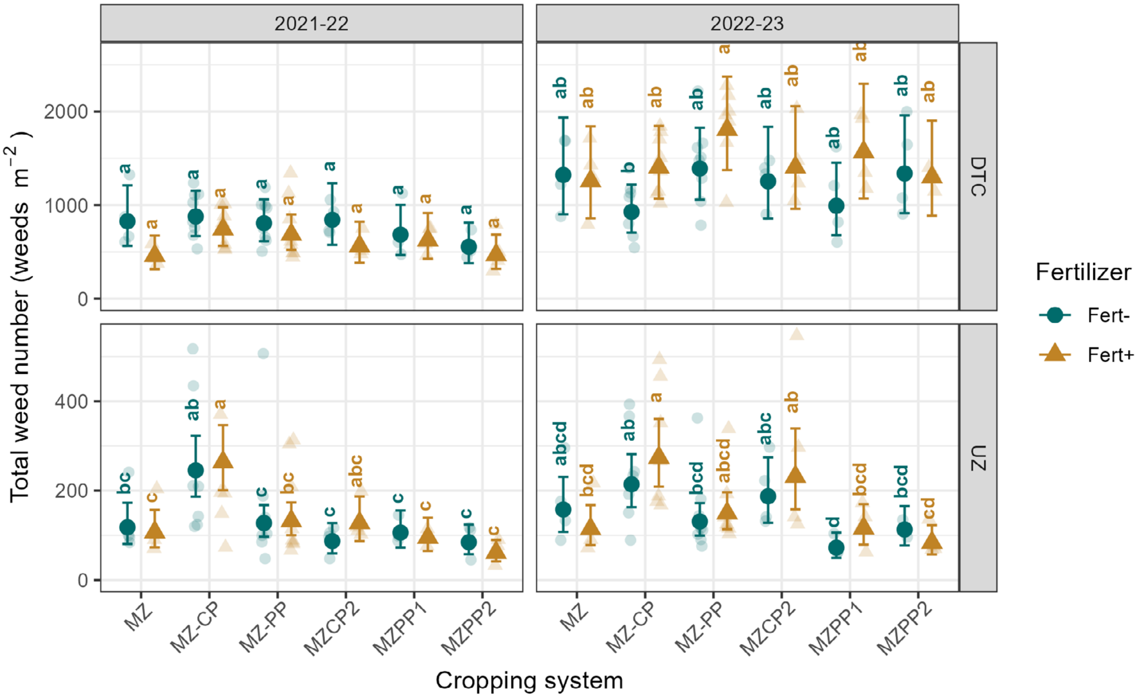

FIGURE 2 | Mean weed number per m^2 across all sampling events in each treatment in each site and season, indicated by the large dark points, with error bars showing 95% confidence intervals. The small pale points indicate observations from each plot. Means and pairwise comparisons for each combination of cropping system (*x*-axis) by fertiliser (colour and shape) treatment are shown for each site and season, given significant interactions among cropping system, fertiliser, site and season (Table 1). Lowercase letters indicate significant differences between treatments within sites and seasons: Means that do not share a letter are significantly different. Note the different y-axis scales between sites and seasons. See Figure 1 for treatment abbreviations.

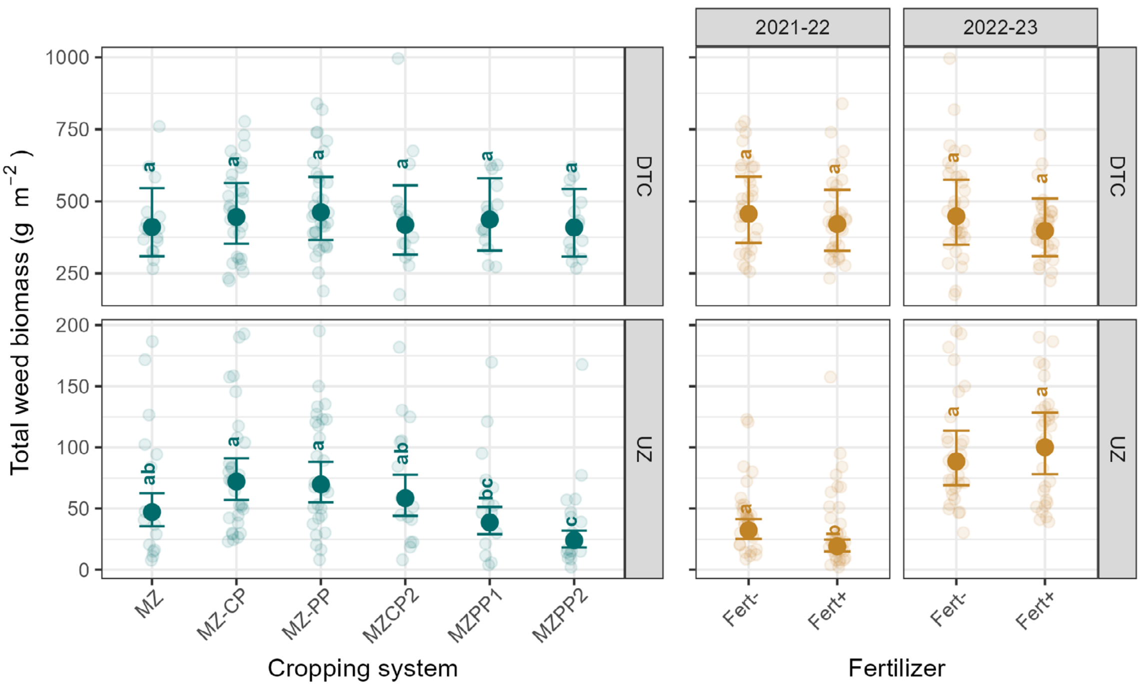

FIGURE 3 | Mean weed biomass per m^2 across all sampling events in each treatment, indicated by the large dark points, with error bars showing 95% confidence intervals. The small pale points indicate observations from each plot in each season. In the left panels, overall means for each cropping system are shown for each site (significant cropping system by site interaction; Table 1), and in the right panels, overall means for each fertiliser treatment in each site and season are shown (significant interactions between fertiliser, site and season; Table 1). Lowercase letters indicate significant differences between treatments within sites and seasons; treatments that do not share a letter are significantly different. Note the different y-axis scales. See Figure 1 for treatment abbreviations.

and mean weed species richness also differed between sites and seasons (Table 1). However, few significant differences between treatments were detected, with only fertilised MZ-PP (9.125 species) significantly higher than unfertilised MZPP2 in the 2021–2022 season at UZ (5.5 species; Figure S1). In contrast, multiple differences between treatments were observed for the Pielou index of weed species evenness in both seasons at UZ, with MZ-CP consistently lower than MZPP2 and MZ, by 0.1–0.2 in the 2021–2022 season and by 0.2–0.3 in the 2022–2023 season (Figure S2). At DTC, no cropping system effects on the Pielou index were observed, but the addition of fertiliser was found to reduce the Pielou index by 0.07 in the 2022–2023 season. The Shannon diversity index is calculated from both richness and evenness, and so the results reflect both (Table 1). As with the Pielou index, the Shannon diversity index differed between cropping systems at UZ but not DTC. At UZ, the Shannon index in MZ-CP was lower by 0.3–0.4 than the Shannon index in MZ, MZ-PP, MZPP1 and MZPP2 (Figure 4). The Shannon index was lower in unfertilised than fertilised treatments at UZ in the 2022–2023 season.

3.3 | Relationship Between Cropping System Biomass and Weed Metrics

Cropping system biomass varied within and between treatments (Figure S3). Across sites and seasons, cropping system biomass had a consistent negative effect on weed biomass (Table 2, Figure 5). The effect on weed numbers, however, differed between seasons (Table 2), with no effect observed in 2021–2022 but an increase in weed numbers associated with an increase in cropping system biomass in 2022–2023 (Figure 5). Weed species richness was not affected by cropping system biomass (Table 2). Pielou evenness and Shannon diversity responded similarly to cropping system biomass, but the patterns differed between sites and seasons (Table 2). In the 2021–2022 season, cropping system biomass was not significantly associated with either weed species evenness or diversity, whereas in the 2022–2023 season, it was positively associated with weed evenness and diversity at UZ but negatively associated with both at DTC (Figure 6 and Figure S4).

3.4 | Weed Community Composition

Thirty-five weed species were observed across sites and seasons. The observed species belonged to 18 families, with the Asteraceae family having the most extensive composition of 28%, followed by Poaceae with 17% (Table 3). Almost 71% were annual weeds, 26% were perennials, and 3% were biennials. Broad-leaved weeds constituted about 83% of the total weeds, while 17% were grasses. After summing up all the weeds for the two seasons and sites, *Galinsoga parviflora* CAV. (gallant soldier) had the largest total weed number, followed by *Richardia scabra* L. (Mexican clover) and *Bidens pilosa* L. (black jack) (Table 3).

The occurrence and abundance of weed species varied across sites and seasons. For instance, species such as *Ageratum conyzoides* L. (billy goat), *Oxalis latifolia* Kunth (purple garden sorrel), *Alternanthera pungens* Kunth (khaki weed) and *Cyclospermum leptophyllum* (Pes.) (marsh parsley) only occurred at UZ, whereas *Cyperus esculentus* L. (yellow nutsedge), *Acanthospermum hispidum* DC (Upright starbur), *Desmodium uncinatum* (Jacq.) DC. (silver leaf), *Cynodon nlemfuensis* Vanderyst (star grass) and *Datura stramonium* L. (thorn apple) were only observed at DTC (Table 3). Some species were season-dependent, with 24 weed species recorded at UZ in the 2021–2022 season and 26 in the 2022–2023 season, and 17 then 20 species recorded at DTC in those seasons, respectively. Notable differences in the counts of specific species between the 2021–2022 and 2022–2023 seasons included, at UZ, an increase in *B. pilosa* (from 45.30 ± 10.60 to 77.64 ± 9.75 individuals per plot) and a decrease in *Conyza bonariensis* L. (from 36.64 ± 4.17 to 22.13 ± 1.83 individuals per plot). At DTC, *R. scabra* increased (248.2 ± 17.70 to 307.20 ± 17.90 individuals per plot), while *G. parviflora* decreased (from 666.8 ± 35.60 in 2021/2022 to 106.80 ± 10.70 individuals per plot). An NMDS ordination confirmed that site and season were major drivers of weed community composition, with little variation in community composition imposed by cropping system and fertiliser treatment (Figure 7).

4 | Discussion

Our study investigated the effects of different cropping systems and fertiliser applications on weed communities over two growing seasons at two sites in central Zimbabwe with contrasting soil types: clay-rich at UZ and sandy at DTC. Differences between sites and seasons played a strong role in determining mean weed abundance, diversity and community composition, but we also observed significant effects of cropping system and fertiliser treatments. Treatment effects were more substantial and more prevalent at UZ than at DTC, aligning with other studies showing that cropping system and fertiliser effects on weed abundance and diversity are context-specific (Koocheki et al. 2009; Mhlanga et al. 2015).

At DTC, weed numbers, biomass and species richness were higher, while at UZ, species evenness was higher. Crops produced less biomass at DTC than at UZ, suggesting that at DTC, the weeds had the advantage over crops and were therefore less susceptible to cropping system and fertiliser effects. Although the crop varieties used in our experiment have been bred for low-input, smallholder conditions, DTC is a particularly challenging environment, with sandy, low-pH soils and a high nematode population. The resident weed community may be better adapted to these conditions and more able to compete with crops at DTC, whereas in the more fertile soils at UZ, crops are more competitive and can influence weed abundance and diversity.

4.1 | Weed Number and Biomass

The results from UZ suggest that pigeon pea is more effective for weed suppression than cowpea, and that strip crops and intercrops are more effective than rotations, with the maize monoculture falling in between. In particular, MZPP2 had the lowest weed biomass and among the lowest weed numbers, while MZ-CP had the highest weed biomass and numbers. These results suggest that efficient resource capture by intercrops and strip crops could present a more effective mechanism for weed

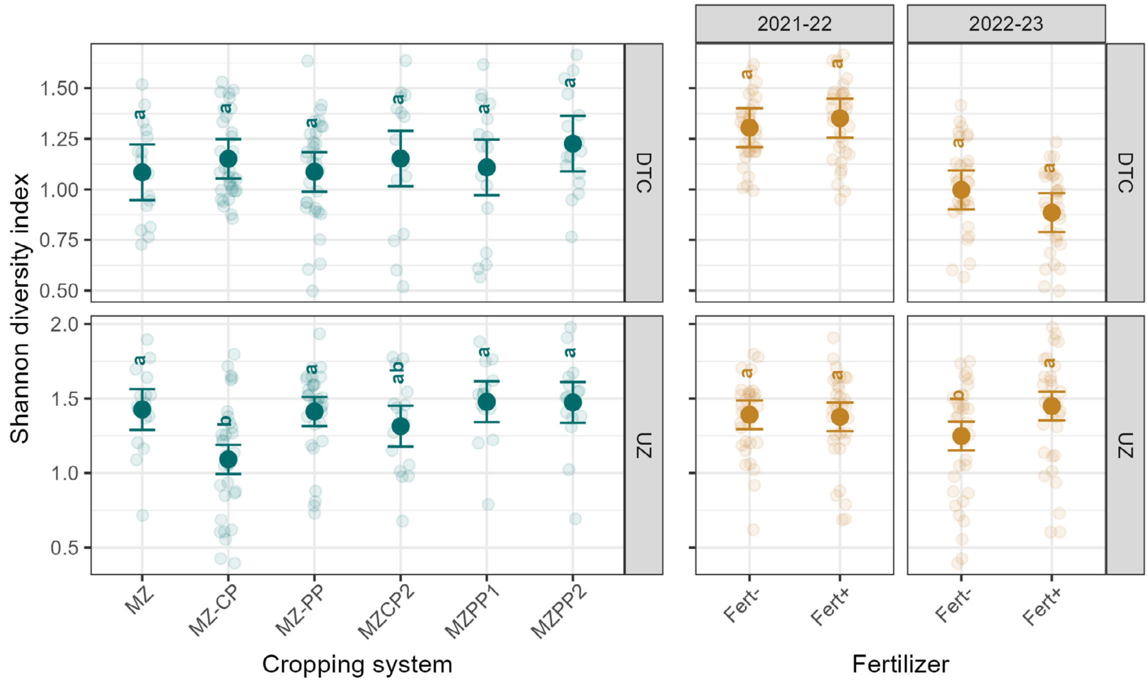

FIGURE 4 | Mean weed species diversity (Shannon index) observed over the season in each treatment, indicated by the large dark points, with error bars showing 95% confidence intervals. The small pale points indicate observations from each plot in each season. In the left panels, overall means for each cropping system are shown for each site (significant cropping system by site interaction; Table 1), and in the right panels, overall means for each fertiliser treatment in each site and season are shown (significant interactions between fertiliser, site and season; Table 1). Lowercase letters indicate significant differences between treatments within sites and seasons; treatments that do not share a letter are significantly different. Note the different *y*-axis scales. See Figure 1 for treatment abbreviations.

suppression than the changing conditions imposed by rotations. Rotating maize with a less competitive crop, such as cowpea, may even increase weed pressure compared with monoculture. This result counters much of the literature, with crop rotations generally considered an essential component of sustainable weed management (MacLaren et al. 2020) and globally reported to decrease weed density by 49% and weed biomass by 22% on average (Weisberger et al. 2019).

On smallholder farms in Zimbabwe, in-season weed management is limited to hand-hoeing and pulling, and crops are consistently sown at the onset of the rains in November and harvested after the rains end in May. This consistency in management and timing could limit the potential of rotations to suppress weeds via imposing varying conditions on weeds. Potentially, in regions with longer growing seasons, or for wealthier farmers who may have access to a greater variety of weed management tools, rotations would be more advantageous (MacLaren et al. 2020). It is also possible that our experiment did not allow sufficient time for rotation effects to build up; our study encompassed the growing seasons in the second and third years after system establishment, but many weed seeds can persist for extended periods in the soil.

In the context of our experiment, one possibility to increase the change in conditions imposed by rotation could have been to use pigeon pea as a bi-annual crop instead of an annual crop, given that pigeon pea can survive the dry season and produce grain for (at least) two seasons (Snapp et al. 2019). Pigeon pea can also be effectively managed by ratooning the crop after the first cropping season (Rusinamhodzi et al. 2017). However, we did not test this strategy because it would be challenging to implement widely in Zimbabwe; livestock are allowed to range across crop fields in the dry season and consume crop residues and would also browse on pigeon pea.

The benefit of intercrops and strip crops for weed suppression in our study could have arisen from the higher crop plant densities in these systems compared with the monoculture and rotations. Among Zimbabwean smallholders, maize is typically grown at relatively low densities to minimise competition between maize plants, but this practice may also lead to underutilised light and soil resources, creating opportunities for weeds. Adding an intercrop or strip crop while maintaining maize density helps to suppress weeds through capturing these resources. The same goal may also be achieved by increasing the maize density in a monoculture. However, intercropping and strip cropping are expected to be more effective than increasing maize density, given the differences in resource acquisition strategies between maize and legumes. The resulting resource complementarity between crop species would be expected to better suppress weeds through more complete resource capture, while also minimising the competition experienced by each maize plant due to contrasting resource niches between maize and legumes (Brooker et al. 2015; Mhlanga et al. 2016).

In our study, we observed that higher cropping system biomass was associated with lower weed biomass, suggesting that greater resource capture by crops did indeed reduce the resources available for weed growth. The intercrops and strip crops tended to produce more biomass than the monoculture and rotations, presumably due to the higher crop plant density, while pigeon pea

TABLE 2 | The p values alongside numerator (N.DF) and denominator degrees of freedom (D.DF) for each model term from Type III ANOVA *F*-tests of mixed models testing the effect of cropping system biomass, fertiliser, site and season on each weed response variable: weed number, weed biomass, weed species richness, weed species evenness (Pielou index) and weed species diversity (Shannon index).

	Number			**Biomass**			**Species richness**			**Pielou evenness index**			**Shannon diversity index**		
	N.DF	**D.DF**	***p***	**N.DF**	**D.DF**	***p***	**N.DF**	**D.DF**	***p***	**N.DF**	**D.DF**	***p***	**N.DF**	**D.DF**	***p***
Cropping system biomass	1	209.92	0.103	1	216.39	**0.001**	1	194.93	0.745	1	216.51	0.563	1	206.63	0.331
Fertiliser	1	80.04	0.785	1	71.84	0.110	1	67.25	0.316	1	77.85	0.579	1	75.8	0.969
Season	1	160.58	0.316	1	183.39	**< 0.001**	1	190.41	0.093	1	184.58	0.051	1	186.77	**0.015**
Site	1	33.86	**< 0.001**	1	27.87	**< 0.001**	1	24.78	0.093	1	66.96	**0.024**	1	70.35	0.286
Cropping system biomass: fertiliser	1	156.42	0.566	1	166.43	0.181	1	175.32	0.994	1	170.24	0.911	1	179.49	0.989
Cropping system biomass: season	1	176.22	**0.009**	1	201	0.338	1	203.22	0.963	1	202.48	0.746	1	202.54	0.962
Fertiliser: season	1	176.99	0.608	1	184.28	0.502	1	188.86	0.982	1	185.34	0.541	1	186.81	0.505
Cropping system biomass: site	1	209.92	0.158	1	216.39	0.231	1	194.93	0.470	1	216.51	0.102	1	206.63	0.096
Fertiliser: site	1	80.04	0.655	1	71.84	0.336	1	67.25	0.968	1	77.85	0.481	1	75.8	0.442
Season: site	1	160.58	0.152	1	183.39	**< 0.001**	1	190.41	**0.004**	1	184.58	0.273	1	186.77	0.947
Cropping system biomass: fertiliser: season	1	178.86	0.169	1	188.16	0.704	1	195.41	0.398	1	190.55	0.517	1	194.99	0.594

(Continues)

TABLE 2 | (Continued)

	Number			Biomass			Species richness			Pielou evenness index			Shannon diversity index		
	N.DF	**D.DF**	***p***	**N.DF**	**D.DF**	***p***	**N.DF**	**D.DF**	***p***	**N.DF**	**D.DF**	***p***	**N.DF**	**D.DF**	***p***
Cropping system biomass: fertiliser: site	1	156.42	0.475	1	166.43	0.249	1	175.32	0.240	1	170.24	0.548	1	179.49	0.826
Cropping system biomass: season: site	1	176.22	0.537	1	201	0.298	1	203.22	0.999	1	202.48	**0.032**	1	202.54	**0.017**
Fertiliser: season: site	1	176.99	0.425	1	184.28	0.972	1	188.86	0.766	1	185.34	0.385	1	186.81	0.343
Cropping system biomass: fertiliser: season: site	1	178.86	0.654	1	188.16	0.164	1	195.41	0.903	1	190.55	0.884	1	194.99	0.982
Model marginal (m) and conditional (c) R^2	$mR^2 = 0.82$, $cR^2 = 0.87$			$mR^2 = 0.79$, $cR^2 = 0.90$			$mR^2 = 0.35$, $cR^2 = 0.46$			$mR^2 = 0.32$, $cR^2 = 0.44$			$mR^2 = 0.31$, $cR^2 = 0.41$		

Note: p values < 0.05 are emphasised in bold text to highlight which terms were significant at the 5% level for each response variable.

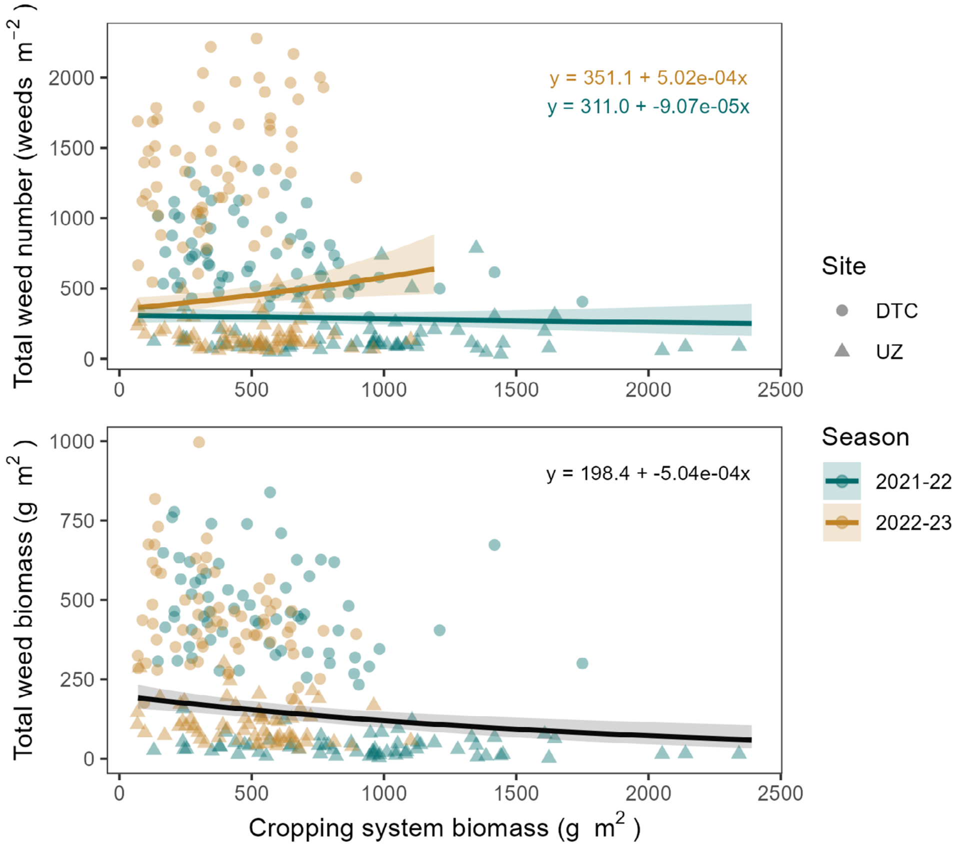

FIGURE 5 | Weed number (top panel) and weed biomass (bottom panel) in relation to cropping system biomass. For weed number, the lines show the estimated relationship between weed number and crop biomass for each site (significant crop biomass by site interaction; Table 2), while in the bottom panel, the line shows the overall estimated relationship between weed biomass and crop biomass (no significant interactions, Table 2). Ribbons show 95% confidence intervals. The equations give the intercept and regression coefficients (slope) for cropping system biomass (x). The points are measurements from each plot, with colours indicating the seasons and shapes indicating the sites.

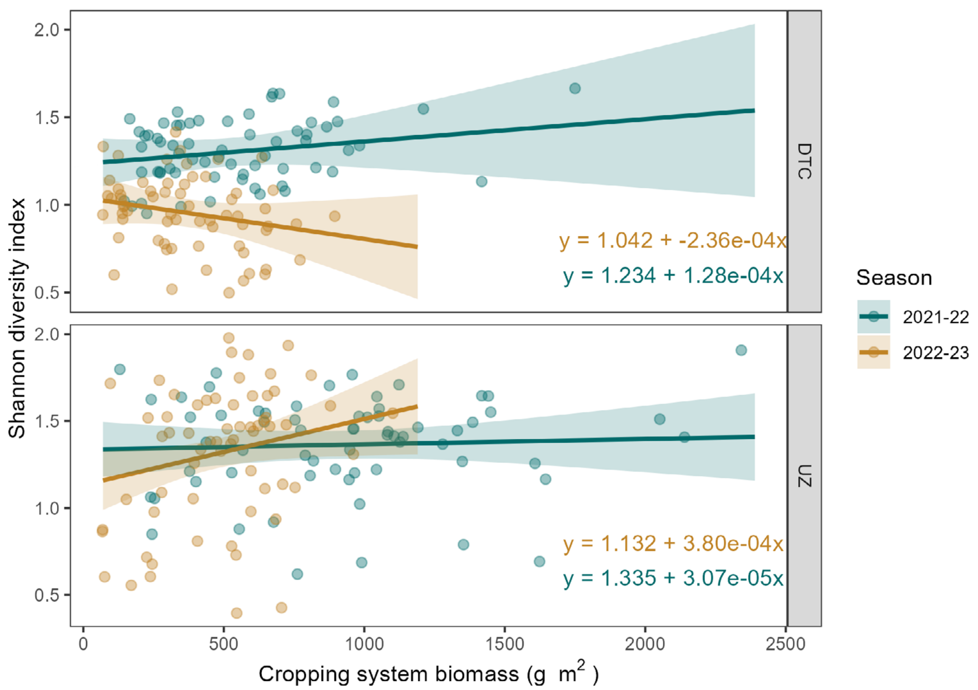

FIGURE 6 | Weed Shannon diversity in relation to cropping system biomass. The lines show the estimated relationship between the Shannon diversity index for weeds and crop biomass for each site and season (significant biomass by site and season interactions; Table 2). Ribbons show 95% confidence intervals. The equations give the intercept and regression coefficients (slope) for cropping system biomass (x). The points are measurements from each plot, with colours indicating the seasons and shapes indicating the sites.

TABLE 3 | The scientific name, family and common name of all weed species observed within the experiment.

Family	Common name	Scientific name	Total count	Mean counts			
				UZ 2021–2022	UZ 2022–2023	DTC 2021–2022	DTC 2022–2023
Asteraceae	Gallant soldier	*Galinsoga parviflora* Cav.	50 312	7.81 ± 2.66	4.75 ± 1.14	666.8 ± 35.60	106.80 ± 10.70
Rubiaceae	Mexican clover	*Richardia scabra* L.	36 441	7.63 ± 5.70	6.39 ± 1.43	248.2 ± 17.70	307.20 ± 17.90
Asteraceae	Black jack	*Bidens pilosa* L.	16 552	45.30 ± 10.60	77.64 ± 9.75	76.89 ± 8.68	58.77 ± 6.02
Asteraceae	Fleabane	*Conyza bonariensis* (L.) Cronquist	3799	36.64 ± 4.17	22.13 ± 1.83	0.22 ± 0.13	0.38 ± 0.14
Asteraceae	Silver heads	*Helichrysum argyrosphaerum* DC.	2377	12.34 ± 1.71	0.00 ± 0.00	0.00 ± 0.00	24.80 ± 3.65
Poaceae	Rapoko grass	*Elusine indica* (L.) Gaerth	1510	0.22 ± 0.16	0.05 ± 0.04	10.45 ± 3.55	12.88 ± 2.48
Amaranthaceae	Pigweed	*Amaranthus hybridus* L.	1179	1.02 ± 0.70	1.39 ± 0.82	7.91 ± 2.22	8.11 ± 0.88
Poaceae	Garden Urochloa	*Urochloa panicoides* P. Beauv.	1074	0.58 ± 0.16	0.86 ± 0.23	4.47 ± 0.84	10.88 ± 1.20
Lamiaceae	Bobbin weed	*Leucas martinicensis* (Jacq.) W. T. Aiton	1043	3.86 ± 1.63	0.91 ± 0.30	11.34 ± 4.87	0.19 ± 0.12
Apiaceae	Marsh parsley	*Cyclospermum leptophyllum* (Pes.) Sprague ex Britton & P. Wilson	656	2.45 ± 1.25	7.80 ± 1.24	0.00 ± 0.00	0.00 ± 0.00
Commelinaceae	Tropical spiderwort	*Commelina benghalensis* L.	560	0.06 ± 0.03	0.19 ± 0.08	4.08 ± 0.75	4.42 ± 0.54
Orobanchaceae	Witch weed	*Striga densiflora* (Benth.) Benth.	350	0.00 ± 0.00	5.47 ± 0.63	0.00 ± 0.00	0.00 ± 0.00
Asteraceae	Upright starbur	*Acanthospermum hispidum* DC.	308	0.00 ± 0.00	0.00 ± 0.00	3.27 ± 2.72	1.55 ± 0.47
Amaranthaceae	Khaki weed	*Alternanthera pungens* Kunth	190	2.94 ± 0.63	0.03 ± 0.03	0.00 ± 0.00	0.00 ± 0.00
Asteraceae	Billy goat	*Ageratum conyzoides* L.	178	1.66 ± 0.50	1.13 ± 0.33	0.00 ± 0.00	0.00 ± 0.00
Convolvulaceae	Morning glory	*Ipomoea purpurea* (L.) Roth	176	0.14 ± 0.06	0.30 ± 0.08	0.00 ± 0.00	2.31 ± 0.60
Solanaceae	Thorn apple	*Datura stramonium* L.	174	0.00 ± 0.00	0.00 ± 0.00	0.73 ± 0.41	1.98 ± 0.55
Poaceae	Star grass	*Cynodon nlemfuensis* Vanderyst	172	0.00 ± 0.00	0.00 ± 0.00	1.94 ± 0.69	0.75 ± 0.39
Onagraceae	Water purslane	*Ludwigia palustris* (L.) Elliott	134	0.00 ± 0.00	2.09 ± 0.66	0.00 ± 0.00	0.00 ± 0.00
Asteraceae	Mexican daisy	*Tridax procumbens* L.	133	1.23 ± 0.47	0.84 ± 0.34	0.00 ± 0.00	0.00 ± 0.00
Poaceae	Couch grass	*Cynodon dactylon (L.) Pers.*	126	0.34 ± 0.17	0.00 ± 0.00	0.00 ± 0.00	1.63 ± 0.52
Fabaceae	Silver leaf	*Desmodium uncinatum* (Jacq.) DC.	94	0.00 ± 0.00	0.00 ± 0.00	0.22 ± 0.09	1.25 ± 0.30
Portulacaceae	Common purslane	*Portulaca oleracea* L.	88	0.02 ± 0.02	0.05 ± 0.04	0.19 ± 0.08	1.13 ± 0.30
Euphorbiaceae	Wild poinsettia	*Euphorbia heterophylla* L.	78	0.41 ± 0.12	0.81 ± 0.15	0.00 ± 0.00	0.00 ± 0.00
Cyperaceae	Yellow nutsedge	*Cyperus esculentus* L.	68	0.00 ± 0.00	0.00 ± 0.00	0.48 ± 0.18	0.58 ± 0.18

(Continues)

TABLE 3 | (Continued)

Family	Common name	Scientific name	Total count	Mean counts			
				UZ 2021–2022	UZ 2022–2023	DTC 2021–2022	DTC 2022–2023
Solanaceae	Apple of Peru	*Nicandra physalodes* (L.) Gaertn.	39	0.05 ± 0.04	0.00 ± 0.00	0.00 ± 0.00	0.56 ± 0.13
Euphorbiaceae	Asthma weed	*Euphorbia hirta* L.	25	0.00 ± 0.00	0.39 ± 0.10	0.00 ± 0.00	0.00 ± 0.00
Asteraceae	Khaki weed	*Tagetes minuta* L.	18	0.13 ± 0.08	0.16 ± 0.05	0.00 ± 0.00	0.00 ± 0.00
Poaceae	Crabgrass	*Digitaria sanguinalis* (L.) Scop.	14	0.00 ± 0.00	0.22 ± 0.06	0.00 ± 0.00	0.00 ± 0.00
Malvaceae	Wild stockrose	*Hibiscus meeusei* Exell	13	0.03 ± 0.02	0.08 ± 0.03	0.03 ± 0.02	0.06 ± 0.05
Malvaceae	Common wireweed	*Sida acuta* Burm.f.	8	0.06 ± 0.03	0.02 ± 0.02	0.05 ± 0.03	0.00 ± 0.00
Asteraceae	Common sowthistle	*Sonchus oleraceus* L.	8	0.00 ± 0.00	0.13 ± 0.04	0.00 ± 0.00	0.00 ± 0.00
Oxalidaceae	Purple garden sorrel	*Oxalis latifolia* Kunth	7	0.03 ± 0.03	0.08 ± 0.06	0.00 ± 0.00	0.00 ± 0.00
Poaceae	Cat's tail	*Sporobolus pyramidalis* P.Beauv.	4	0.06 ± 0.04	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
Asteraceae	Groundsel	*Senecio cacaliaster* Lam.	1	0.00 ± 0.00	0.02 ± 0.02	0.00 ± 0.00	0.00 ± 0.00
—	Other	—	617	4.41 ± 0.45	0.00 ± 0.00	0.00 ± 0.00	2.27 ± 0.51

Note: The ‘total count’ column is the total number of observations of each species across both sites and seasons, while the ‘mean counts’ column is the mean number of individuals of each species per plot across all sampling events within each site and season.

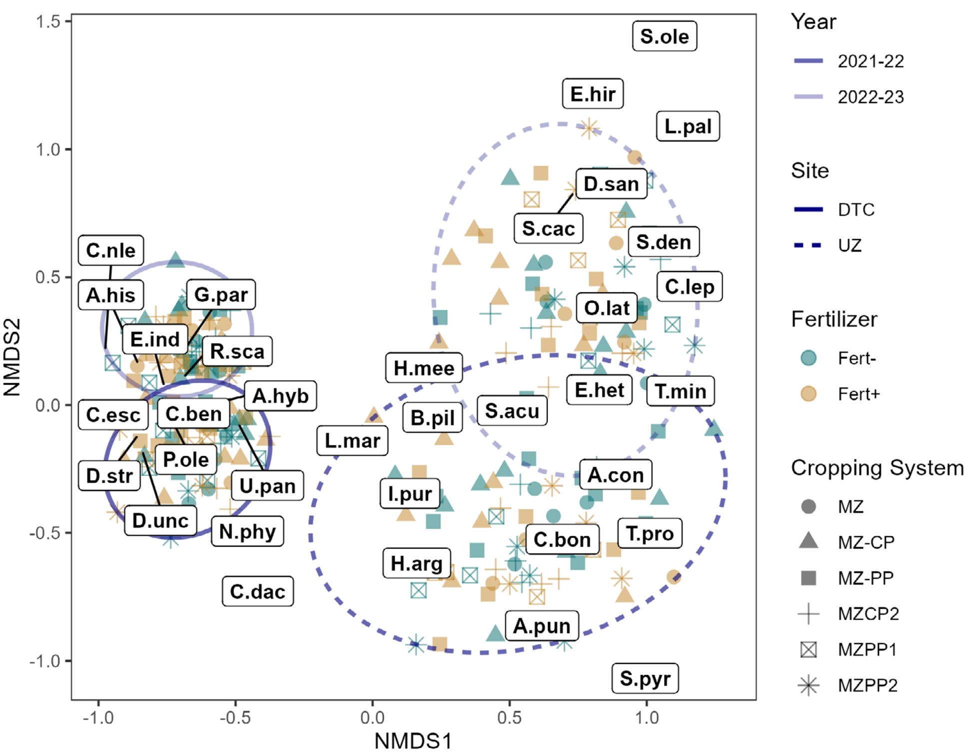

FIGURE 7 | A bi-plot of the NMDS ordination of the weed community (counts of each species) observed within each plot in each site and season of this study. Plots are indicated by points and species by labels. Points close to one another in ordination space indicate plots with similar weed communities to one another, and points close to a species label contain a higher abundance of that species (see Table 3 for species abbreviations). Colours indicate the different fertiliser treatments, and shapes indicate different cropping systems. The four ellipses contain all points within each site by season combination. Overall, this figure demonstrates that the weed community is more distinct between sites and seasons (ellipses) than between cropping system and fertiliser treatments (symbols and colours).

also produced more biomass than cowpea. Pigeon pea grows more slowly than cowpea, but eventually grows taller and with deeper roots (Mugi-Ngenga et al. 2023; Njira et al. 2021).

Integrating high-biomass-producing cropping systems, such as MZPP2, into maize-based systems could thus improve weed management for Zimbabwean smallholders. However, there are two caveats to this conclusion. First, the cropping system biomass did not reduce weed numbers in our study. Second, although crop biomass was associated with reduced weed biomass at both sites, weed biomass at DTC was much higher for a given quantity of crop biomass than at UZ. Farmers using high-biomass cropping systems under conditions similar to DTC could still face a high weed burden.

In our study, we observed inconsistent effects of fertiliser on weed numbers and biomass, and no clear picture emerged of its role in weed dynamics. A moderate fertiliser rate was used (64 kg N ha^{-1}, 14 kg P ha^{-1} and 8 kg K ha^{-1}), so its effects may have been outweighed by other sources of variation in weed numbers and biomass.

4.2 | Effects of Cropping System and Fertiliser on Weed Diversity

Cropping system affected weed evenness more clearly and consistently than species richness, although, as before, only at UZ and not at DTC. At UZ, weed evenness was lowest in MZ-CP and highest in MZPP2, mirroring the reverse trend in weed numbers and biomass across cropping systems. This pattern suggests that weed-suppressive systems disproportionately suppressed dominant weed species but tended not to eliminate rare weed species. Consequently, the relative abundance of all species became more balanced.

Weed species evenness is desirable because it helps to maintain ecological balance and biodiversity within agroecosystems. Avoiding dominance by just one or a few competitive species reduces the risk of intense competition with crops and helps to sustain ecosystem services such as natural pest control and pollination (Adeux et al. 2019; MacLaren et al. 2020). Moreover, even and diverse weed communities are less likely to develop herbicide resistance, making long-term weed management more sustainable (Storkey and Neve 2018).

We observed only small, inconsistent effects of fertiliser on species richness and evenness, but where we observed effects, fertiliser tended to increase species richness while decreasing evenness. Previous studies have found that high fertiliser rates tend to favour a few dominant weed species (Storkey et al. 2021), but the moderate rate used in our study may have allowed a broader range of weed species to coexist (Blackshaw and Brandt 2008). In addition, our fertilisation method may have ensured that fertiliser was used efficiently by maize, and little was available to weeds. We used a split application to avoid applying more fertiliser than could be readily used by the maize, and we applied fertiliser by hand, placing a small amount either in each planting station (basal application) or directly above the roots of each maize plant (top dressing).

4.3 | Weed Composition

The weed community composition in our study differed strongly between sites, and to a lesser extent between seasons. Resilient weed species, such as *G. parviflora* and *R. scabra*, could thrive under the more stressful conditions found at DTC, a sandy location characterised by low pH, low organic carbon, low moisture and low nutrient retention capacity. *G. parviflora* adapts easily to harsh conditions (Areington et al. 2024) while *R. scabra* thrives well in depleted soils with poor water and nutrient retention capacity (Mavunganidze et al. 2009; Mhlanga et al. 2016). Previous studies undertaken at the same sites also reported that *R. scabra*, *Urochloa panicoides* and *Eleusine indica* were common on the low-nutrient soils at DTC, while *B. pilosa* and *C. bonariensis* were associated with the fertile soils at UZ (Mhlanga et al. 2015; Muoni et al. 2014).

The differences in weed composition between DTC and UZ likely contributed to the fact that we observed stronger effects of cropping system, crop biomass and fertiliser at UZ than at DTC. The more fertile conditions at UZ seem to have increased the crops' capacity to compete with weeds. At the same time, the dominance of stress-tolerant species at DTC, such as *G. parviflora* and *R. scabra*, may have reduced the influence of cropping systems. Stress-tolerant species would be expected to be less sensitive to the resource limitation imposed by intercrops and strip crops (MacLaren et al. 2023). Our findings thus suggest that site-specific environmental factors and inherent weed community traits can change the effectiveness of cropping system interventions for weed management. Specifically, this study highlights the need for further research to identify effective weed management tactics for farming systems on sandy soils in Zimbabwe.

5 | Conclusions

This study investigated the effects of different cropping systems and fertiliser application strategies on weed communities at two sites with contrasting soil types (clayey vs. sandy). Our results suggest that high crop biomass is the most critical feature of cropping systems for weed suppression under smallholder farming conditions in central Zimbabwe. However, the potential for crops to suppress weeds was much greater on the richer clay soils found at UZ than on the poor sandy soils at DTC. Intercrops and strip crops tended to increase overall cropping system biomass and lead to greater weed suppression, whereas rotations were less effective than reported by other studies (Weisberger et al. 2019). We infer that rotations should not be relied on to improve weed suppression in farming systems when they are not associated with strong management or temporal changes across growing seasons, as in smallholder systems in Zimbabwe.

Cropping systems containing the slower-growing yet larger and longer-lived pigeon pea were also observed to be more weed suppressive than those containing cowpea. Overall, maize-pigeon pea strip cropping was the most effective of the tested systems at reducing weed numbers and biomass while promoting evenness in the weed community. Adopting this system could improve weed management for smallholders on clay-rich soils in Zimbabwe without further increasing the use of environmentally risky herbicides and/or tillage. However, future research is needed to investigate effective options for sandy soils.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The dataset underpinning this study is available on the CIMMYT Dataverse: https://doi.org/10.71682/10549381.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Figure S1:** Mean weed species richness across all sampling events in each treatment in each site and season, indicated by the large dark points, with error bars showing 95% confidence intervals. The small pale points indicate observations from each plot. Means and pairwise comparisons for each combination of cropping system (*x*-axis) by fertiliser (colour and shape) treatment are shown for each site and season, given significant interactions among cropping system, fertiliser, site and season (Table 1). Lowercase letters indicate significant differences between treatments within sites and seasons: means that do not share a letter are significantly different. Note the different *y*-axis scales between sites and seasons. See Figure 1 for treatment abbreviations. **Figure S2:** Mean weed species evenness (Pielou index) observed in each site, season and treatment, indicated by the large dark points, with error bars showing 95% confidence intervals. The small pale points indicate observations from each plot in each season. In the left panels, overall means for each cropping system are shown, and in the right panels, overall means for each fertiliser treatment are shown. Means are shown for each site and season given the significant interactions between each treatment factor and site and season, but no significant interaction between the cropping system and fertiliser treatments (Table 1). Lowercase letters indicate significant differences between treatments within sites and seasons; treatments that do not share a letter are significantly different. Note the different *y*-axis scales. See Figure 1 for treatment abbreviations. **Figure S3:** The distribution of cropping system biomass within each cropping system by fertiliser treatment at each site. The points show data collected in each plot in each year, while the boxes show the medians (thick bar) and interquartile range (box limits) of all data collected for each cropping system × fertiliser treatment in each site. The whiskers extending from the boxes indicate the largest value no more than 1.5 times the interquartile range away from the box limits. The point in the fertilised MZCP2 treatment at UZ with a value over 25 000 kg ha^{-1} is the outlier that was removed from the models of the effects of cropping system biomass on weed responses. **Figure S4:** Weed Pielou evenness in relation to cropping system biomass. The lines show the estimated relationship between the Pielou evenness index for weeds and crop biomass for each site and season (significant biomass by site and season interactions; Table 2). Ribbons show 95% confidence intervals. The equations give the intercept and regression coefficients (slope) for cropping system biomass (*x*). The points are measurements from each plot, with colours indicating the seasons and shapes indicating the sites.