



Research article

Short-term impacts of soil nutrient management on maize (*Zea mays* L.) productivity and weed dynamics along a toposequence in Eastern ZimbabweJustin Chipomho^{a,b,*}, Joyful T. Rugare^b, Stanford Mabasa^b, Shamie Zingore^c, Arnold Bray Mashigaidze^d, Regis Chikowo^{b,e}^a Marondera University of Agricultural Sciences and Technology, P.O. Box 35, Marondera, Zimbabwe^b University of Zimbabwe, Crop Science Department, P.O. Box MP 167 Mt Pleasant Harare, Zimbabwe^c African Plant Nutrition Institute, Lot 660 Hay Moulay Rachid, 43150, Benguérir, Morocco^d Chinhoyi University of Technology, P. Bag 7724, Chinhoyi, Zimbabwe^e Plant, Soil and Microbial Sciences Department, Michigan State University, East Lansing, MI 48824, USA

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ABSTRACT

Poor soil fertility and weed infestation are among major constraints to maize production in southern Africa. Nutrient and weed management strategies that are products of empirical research, are needed to improve efficiencies on farms. A field experiment was carried out in Eastern Zimbabwe on three smallholder farms positioned on upper, middle and lower catena. The farms differed in soil organic carbon (SOC) content, 3.9, 6.4 and 8.9 g kg⁻¹ (hereafter referred to as low, medium and high), respectively, and are located within one km distance. The objective of the study was to investigate short-term (6 years) repeated application of soil nutrient amendments on maize productivity and weed dynamics across a soil fertility gradient. Treatments included strategic combinations of NPK fertiliser, cattle manure, and lime. On each farm, a randomised complete block design with three replicates was used. Multivariate, Principal Component Analysis, was used to establish the relationship between season, SOC content, nutrient management, and weed density. Maize yield was strongly linked to SOC content, with six-year mean maize grain yields of 1.31, 2.47, and 2.75 Mg ha⁻¹ for low, medium, and high SOC content, respectively. Maize grain yields with cattle manure (CM) or NPK application were only 0.25 and 0.60 Mg ha⁻¹, respectively for the poorest SOC content field. However, when manure was combined with NPK fertiliser, yields at the site substantially increased to 1.5 Mg ha⁻¹ while in medium and high SOC recorded 2.47 and 2.75 Mg ha⁻¹ respectively. Weed density, and biomass were larger in the medium, and high SOC content. *Richardia scabra*, *Melinis repens*, and *Cyperus* sp. were associated with low SOC. *Luercus martinicensis*, *Bidens pilosa*, and *Galinsoga parviflora* were linked to medium and high SOC content. Results from this study suggest site-specific weed management approach. On soils critically poor in SOC content, maize yield gains are only achieved when organic and mineral fertilisers are combined. Our results also suggest that farmers must increase vigilance and intensity of weed management in soils with medium and high SOC content, particularly after application of CM.

1. Introduction

Maize (*Zea mays*) is the staple food in the Southern African region, and 90% of smallholder farmers in Zimbabwe grow maize under rain-fed conditions across ecological regions (Tibugari et al., 2019). Despite widespread cultivation of maize by smallholder farmers, yields are low, averaging 1.5 Mg ha⁻¹, which is far below the 8 Mg ha⁻¹ average yields obtained by commercial farmers (Rugare, 2018). The major constraints in rain-fed maize production include high rainfall variability-induced

drought (Chikowo et al., 2004), declining soil fertility (Vanlauwe et al., 2015), and weeds infestation (Mashingaidze et al., 2009).

Weed interference during the early stages of maize development in the subtropical region results in a yield decline of between 34 and 90% depending on weed seed bank status (Schwartz-Lazaro and Copes, 2019). Despite being slow, and labour demanding, hand hoeing is the most commonly used method for weed management by smallholder farmers because of their predominant reliance on family labour, which is not directly paid (Mashingaidze et al., 2009). However, labour bottlenecks commonly experienced early in the season result in delayed weeding for

* Corresponding author.

E-mail address: jusychipomho@gmail.com (J. Chipomho).

a large proportion of the fields and consequently maize yield losses (Chikowo et al., 2008).

Smallholder farms are known to be spatially heterogeneous in terms of soil fertility, mainly due to inherent properties of the soil arising from different parent material, catena position or differential management of fields within and across farms (Kurwakumire et al., 2014; Masvaya et al., 2010). Generally, smallholder farmers continuously grow crops without external fertiliser inputs mainly due to lack of purchasing power and scarcity of mineral fertilisers (Chikowo et al., 2008). Over time, nutrient mining results in poor soil fertility degradation and soil organic matter depletion (Nezomba et al., 2015). Integrating organic and inorganic fertilisers has shown the potential to rehabilitate nutrient-depleted soils and improve maize yields in SSA (El-Naggar et al., 2019; Rusinamhodzi et al., 2013). Long term experiments in Africa have provided evidence on the benefits of integrating organic and inorganic fertilisers to replenish nutrient and carbon reserves in poor soils (Munera-Echeverri et al., 2020; Oldfield et al., 2019). Although the synergistic benefits of integrating inorganic fertiliser (NPK) and cattle manure (CM) are well documented (Mtangadura et al., 2017; Rusinamhodzi et al., 2013), the effect of such soil nutrient amendments on weed infestation and maize yield across catenal landscapes require further investigation.

Catena position influences physical and chemical properties of soils through water movement and soil-forming processes (Dessalegn et al., 2014). Sedimentation on lower catena position often results in clay, iron oxides, pH, and organic matter content increase creating a fertility gradient from coarser soil texture on the crest and increasingly finer texture downslope (Nezomba et al., 2015; Touré et al., 2014). A survey by Koné et al. (2013) provided evidence of a strong association between catena position, organic carbon, and *Cyperus sp.* distribution in rice fields when diverse weed species were present. However, the influence of SOC status, and soil nutrient amendment on maize productivity, and weed dynamics along a catena has not been investigated. It was hypothesized that farm position on catena, and initial SOC levels affect maize productivity and weed dynamics. The objective of the study was to investigate the short-term effects of SOC status and repeated application of soil nutrient amendment on maize productivity, weed biodiversity, density, and biomass across the catena.

2. Materials and methods

2.1. Study site selection

The study was carried out on three smallholder farms in Wedza district, (18° 43' S, 31° 42' E) Eastern Zimbabwe (Figure 1) for six years (2011–2016). The research site lies at an altitude of 1150 m with mean annual precipitation of about 800 mm received between November and March. Wedza is known to have high inter-annual rainfall variability with a coefficient of variation of between 23 - 40 % (Mazvimavi, 2010).

Monthly rainfall distribution and cumulative rainfall from planting to harvesting period for each cropping season (2011–2016) were recorded from rain gauges placed at each experimental field (Figure 2). The predominant soil type on all three fields is sandy textured soils derived from granitic parent material with SOC ranging between 3.9–8.9 g kg⁻¹ (Table 1). The soils are classified as Alfisol (USDA soil taxonomy) or Lixisol (FAO soil classification).

An exploratory survey was carried out in 2011 by sampling soils (0–20 cm depth) from 60 farm fields from within a catena, with sandy soils on the upper catena and vertic soils at the lower catena. Physical and chemical analysis of soils revealed that 70% of the sampled farms had SOC ranging from 3.9 to 8.9 g kg⁻¹ from the upper to the lower catena and that SOC was correlated to clay content ($R^2 = 0.85$; Kurwakumire et al., 2014). Three smallholder farms situated within one-kilometre radius, on upper, middle, and lower catena positions were then selected for the study (Table 1).

In September 2011, soil samples were collected from 0–20 cm depth on ten randomly selected positions from each of the three experimental farms and one composite sample per field was made for detailed characterization. Total nitrogen (N) and available phosphorus (P) were analysed using the micro-Kjeldahl method and the modified Olsen method, respectively (Anderson and Ingram, 1993; Okalebo et al., 2002). Exchangeable bases (K, Mg, and Ca) were extracted using ammonium acetate, and Ca and Mg concentrations were determined by atomic absorption spectrophotometry while K was determined by flame photometry (Okalebo et al., 2002). Soil pH was determined in water using a ratio of 1:10 and soil texture was determined by the hydrometer method (Gee and Bauder, 1986) (Table 1).

2.2. Experimental design, treatments and field management

Beginning the 2011/12 cropping season, soil nutrient amendments treatments shown in Table 2 were repeatedly applied on the same plots for six consecutive seasons. Determination of weed data commenced in the fourth year providing a short-term assessment on the effects of soil nutrient amendments on weed density, and biomass along a catena. Land was ploughed to 20 cm depth using an ox-drawn plough after the first effective rainfall in mid-November for all the seasons. The experiment was laid in a randomised complete block design with each treatment replicated three times. The gross plot size was 4.5 × 5 m. Fertilisers and cattle manure were repeatedly applied to the same plots for the six cropping seasons from 2011 to 2016 and lime was applied at a rate of 1.5 Mg ha⁻¹ biennially in 2011, 2013, and 2015 to plots that were designated to be limed. Cattle manure used each season was obtained from the same source and analysed each cropping season before being applied (Table 3). Manure moisture content was determined using Delmhorst G.7 moisture meter (Delmhorst Instrument Company, Towaco, New Jersey, USA) and manure quantity applied was based on dry matter.



Figure 1. Wedza experimental site in Eastern Zimbabwe.

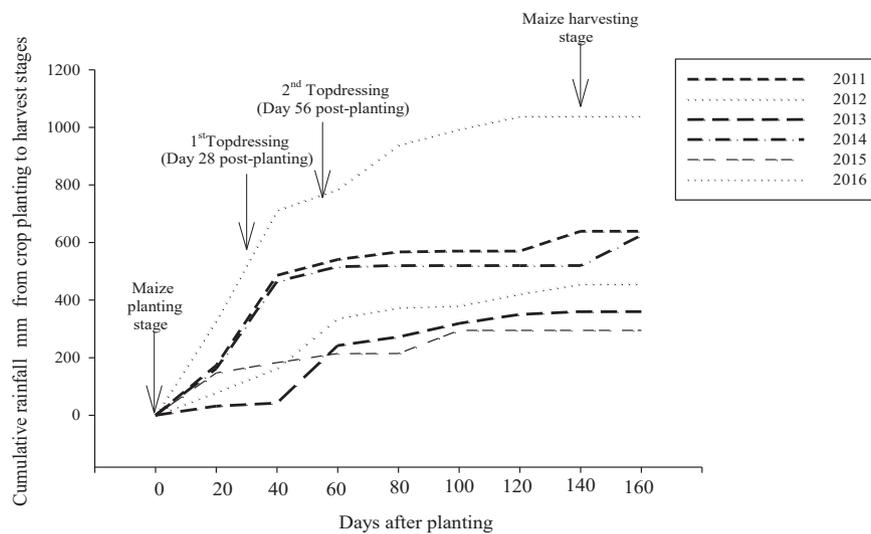


Figure 2. Mean of three rain gauge readings each placed near the experimental site and cumulative rainfall recorded over six cropping seasons (2011–2017) from planting to harvesting period for three smallholder farms with varying SOC and situated on a catena in Wedza, Eastern Zimbabwe.

Table 1. Soil physical and chemical characteristics (0–20 cm) of three smallholder experimental fields situated on soils varying in organic carbon along a catena prior to the trial establishment in 2011.

Soil organic carbon	Sand	Clay	Organic carbon	Total N	available P	pH	Ca	Mg	K
SOC	(g kg ⁻¹)				(mg kg ⁻¹)	1:10 (H ₂ O)	cmol (c) kg ⁻¹		
Low 3.9 g C kg ⁻¹ soil	840	100	3.9	0.3	3.3	4.4	6.2	5.1	0.15
Medium 6.4 g C kg ⁻¹ soil	750	150	6.4	0.4	7.3	4.9	7.3	4.4	0.43
High 8.9 g C kg ⁻¹ soil	650	190	8.9	0.6	10.5	5.2	7.5	5.3	0.48

General fertility range interpretation: Adapted from Tanner and Grant (1963). (a). Available–P (resign-extracted): <7=very low; 7-15=low; 15-30=high. (b).Exchangeable–K; <0.15=very low; 0.15-0.3=low; 0.3-0.5=medium; >0.5=high. (c) Exchangeable–Ca; <5= very low; 5-10= low to medium; > 10= high (d) Exchangeable– Mg; <0.1= very low; 0.1-0.2=low to medium; >0.2=high.

Table 2. The experimental setup used for the Short-term soil nutrient management trial 2011–2016 on three smallholder farms situated along a catena in Eastern Zimbabwe.

Treatments	abbreviation used	Nutrient application rates in kg ha ⁻¹ and cattle manure (Mg ha ⁻¹)
1. Control (unfertilized)	Control	nil
2. Cattle manure only	CM	5 Mg ha ⁻¹ each season
3. Inorganic fertilisers only	NPK	120 N + 30 P + 60 K + 30 S
4. Inorganic fertilisers + micro nutrient mix	NPK + MN	120 N + 30 P + 60 K + 30 S + 8 Zn + micronutrient mix
5. Inorganic fertiliser + cattle manure	NPK + CM	120 N + 30 P + 60 K + 30 S + 5 Mg ha ⁻¹ CM
6. Inorganic fertiliser + lime	NPK + LM	120 N + 30 P + 60 K + 30 S + 1.5 Mg ha ⁻¹ Dolomitic lime
7. Inorganic fertiliser + CM + micro-nutrient mix	NPK + CM + MN	120 N + 30 P + 60 K + 30 S + 5 Mg ha ⁻¹ CM + 8 Zn + micronutrient mix

†Under normal rainfall of 120 kg, N. ha⁻¹ would be applied. In this study due to dry spell in some seasons, 70 kg N ha⁻¹ was applied while the second application of 50 kg N ha⁻¹ was withheld.

‡Dolomitic lime with 84% relative neutralizing value was applied at 1.5 Mg ha⁻¹ at the inception of project 2011 and repeated in 2013 and 2016.

§Zn-micro nutrient mix combination applied at planting as Zinc sulphate and foliar application at anthesis of commercial foliar fertiliser applied at 0.001, 0.015 and 0.003 L ha⁻¹ of Cu, Bo and Mn respectively.

A medium maturing (135 days) maize hybrid variety SC 513® (Seed-Co, Zimbabwe) was planted between the 2nd and 12th of December each cropping season. Plant spacing was 0.9 m × 0.25 m with a target population of 44 444 plants ha⁻¹. Two seeds were planted per hill and the crop thinned to one plant per hill two weeks after crop emergence (WACE).

The experiment was designed with a target nutrient application rate (kg ha⁻¹) of 120 N, 20 P, and 30 K. High nutrient application rates for P and K were used, compared with prevalent rates commonly used by farmers, to enable determination of water-limited attainable yields for the three soil fertility domains when all P and K are non-limiting. At

planting stage, P, K, and 20 kg N ha⁻¹ was applied as basal compound (7% N, 14% P₂O₅, 7% K₂O) fertiliser while additional K was applied as MOP (61% K). Nitrogen balance (100 kg) was split applied, 50 kg N ha⁻¹ (ammonium nitrate 34.5% N) at 4 and 8 WACE, respectively. The full 120 kg/ha N topdressing target was only met in seasons with normal rainfall distribution i.e. 2011/12, 2014/15, and 2016/17. Due to poor rainfall distribution and dry spells coinciding with N topdressing, the second N topdressing was withheld in three cropping seasons viz. 2012/13, 2013/14, and 2015/16 to avoid osmotic stress exacerbating the moisture stress suffered by the crop.

Table 3. Nutrient contents of Cattle manure 2011–2016 cropping seasons and used on three smallholder farms with varying SOC status situated on a catena, Eastern Zimbabwe.

Cropping season	Total N	Total P	Total C	C/N ratio	Total Zn	Ca	Mg	K	Total N and P (kg ha ⁻¹) added through 5 000 kg cattle manure ha ⁻¹	
	g kg ⁻¹					g kg ⁻¹			N	P
2011–12	9.0	2.2	233	26	36	8.5	0.7	5.6	45.0	11.0
2012–13	8.3	2.1	221	27	29	7.0	0.5	4.2	41.5	10.5
2013–14	9.8	2.3	230	24	35	8.0	0.65	5.3	49.0	11.5
2014–15	7.2	2.0	233	32	35	8.5	0.7	5.7	36.0	10.0
2015–16	8.5	2.4	224	26	28	7.4	0.6	4.4	42.5	12.0
2016–17	10.5	2.7	235	22	35	8.5	0.65	5.7	52.5	13.5

2.3. Determination of weed diversity, density, and biomass

Before weeding at 3 and 6 WACE, weed density (number m⁻²) and biomass (g m⁻²) were measured and recorded. Five quadrates measuring 30 cm × 30 cm were randomly thrown in each plot, weeds counted by species, cut at ground level, packed in brown paper bags, oven-dried at 70 °C for 48 h, and weighed. Weed species diversity was established using species richness, evenness, and Shannon Weiner index using the formula;

$$\text{Shannon Weiner index (H)} = - \sum_{i=1}^S p_i \ln (p_i)$$

where H' is Shannon Weiner diversity index, S is the number of individual species in the community (richness), p_i will be the proportion of S made up of the i -th species that is $p_i = N_i/N_{total}$, where N_i is the individuals of species i (plants per m²) and N_{total} is the total number of individuals (plants per m²). Evenness: (J) was calculated as $J = H'/\ln(S)$ where S is the species richness calculated as the total number of species per plot.

2.4. Determination of maize grain yield

Maize grain yield was determined after the maize crop attained physiological maturity and dry down in the field in May each season. Dried maize plants were hand-harvested from the net plot (3.6 m²) consisting of two central rows and 2 m long. Maize cobs were sun-dried in perforated harvesting bags over 15 days, hand shelled and grain weight was measured using a digital scale. A Delmhorst G.7 moisture meter was used to measure grain moisture content and maize grain yield was adjusted to 12.5% moisture content.

2.5. Data analysis

Maize grain yield was tested for normality and homogeneity of variance using Ryne-Joiner and Bartlett's test respectively. Maize yield data were normally distributed and homogenous so the combined analysis was done using linear mixed-effects model analysis (Restricted Maximum Likelihood (REML)) using GenStat Discovery 14 (VSN-International, 2011). The fixed analysis model used was, constant + Blocking (B) + soil organic carbon (SOC) + soil nutrient amendment + SOC x soil nutrient amendment, and the random/(covariate) in the model was the season (S).

Principal component analysis (PCA) was used to establish the relationship between season, SOC, soil nutrient amendment, and weed density using CANOCO 5 (ter Braak, 2013). The PCA was used because weed density had a linear relationship (gradient 2.9 SD units) with environmental variables (Smilauer and Lepš, 2014). Weed density data was examined using Principal Response Curve (PRC) a multivariate technique suitable for repeated measures designed to test the effects of treatments and their changes with time (Whitehouse et al., 2014). Monte Carlo method was performed on the first principal component axis (SOC) of the PCA to test if the PRC generated by the analysis had a significant

variance. Results were presented only for PRCs that were significant at $P \leq 0.05$ effects of SOC and soil nutrient amendment on weed species density. Weed species densities between -0.5 and 0.5 on the PRC were excluded for further statistical analysis as they had little effect on the PRC (Whitehouse et al., 2014).

The density of weed species with an absolute score above 0.5 was analysed using linear mixed-effects model analysis, REML and means were separated using \pm standard error of the difference when the F test had significant treatment effect at $P \leq 0.05$. Weed density data were not normally distributed and were transformed using $\sqrt{(X + 0.5)}$ before analysis (Steel et al., 1997). Weeds diversity indices that is richness, Shannon Wiener (H), and evenness eH/S data were calculated using Paleontological Statistics (PAST) package version 3.14 (Hammer et al., 2001) and was also analysed using linear mixed-effects model analysis, REML.

3. Results

3.1. Effects of SOC content and nutrient management on maize grain yield

Maize grain yield was significantly influenced by SOC status ($P \leq 0.001$), soil nutrient amendment ($P < 0.001$), and the interaction of the two factors ($P \leq 0.052$). The overall maize grain yield means for high SOC status (lower catena) was 2.75 ± 0.16 Mg ha⁻¹ compared to medium SOC (middle catena) 2.47 ± 0.16 Mg ha⁻¹ and least maize grain yield was from low SOC on (upper catena) 1.31 ± 0.16 Mg ha⁻¹ with approximately half of what was harvested from high and medium SOC status.

Mean grain yield of maize over six cropping seasons was lowest from unfertilized control 0.77 ± 0.24 Mg ha⁻¹ followed by cattle manure (CM) 1.23 ± 0.24 Mg ha⁻¹. Moderately higher maize grain yield was recorded from NPK 2.28 ± 0.24 , NPK + MN 2.39 ± 0.24 Mg ha⁻¹ while the highest grain yields of maize were recorded from NPK + CM 3.04 ± 0.24 , NPK + LM 2.76 ± 0.24 and NPK + CM + MN 2.77 ± 0.24 Mg ha⁻¹.

Maize grain yield response to CM, NPK, and NPK + MN was low on upper catena, with low SOC, despite the application of these soil nutrient amendments over six seasons (Figure 3a). In contrast, maize grain yield significantly increased on upper catena when NPK + CM and NPK + LM were used as nutrient amendments. Besides, on medium to high SOC status fields maize grain yield significantly responded to the application of NPK fertiliser and recorded yield similar to NPK + CM or lime (Figure 3a).

Short-term soil nutrient amendment had a significant effect on cumulative maize grain yield over a six-year period. Cumulative maize grain yields were low in the sole CM treatment 7.39 ± 0.32 and were 1.6 times higher than unfertilized control 4.63 ± 0.32 Mg ha⁻¹. The moderately performing treatments were NPK 13.66 ± 0.32 , and NPK + MN 14.33 ± 0.32 Mg ha⁻¹ which yielded 2.95 and 3.10 times higher than the unfertilized control. The best three performing soil nutrient amendment treatments were NPK + CM + MN 16.25 ± 0.32 , NPK + LM 16.36 ± 0.32 , and NPK + CM 17.21 ± 0.32 Mg ha⁻¹ which yielded 3.51, 3.53-

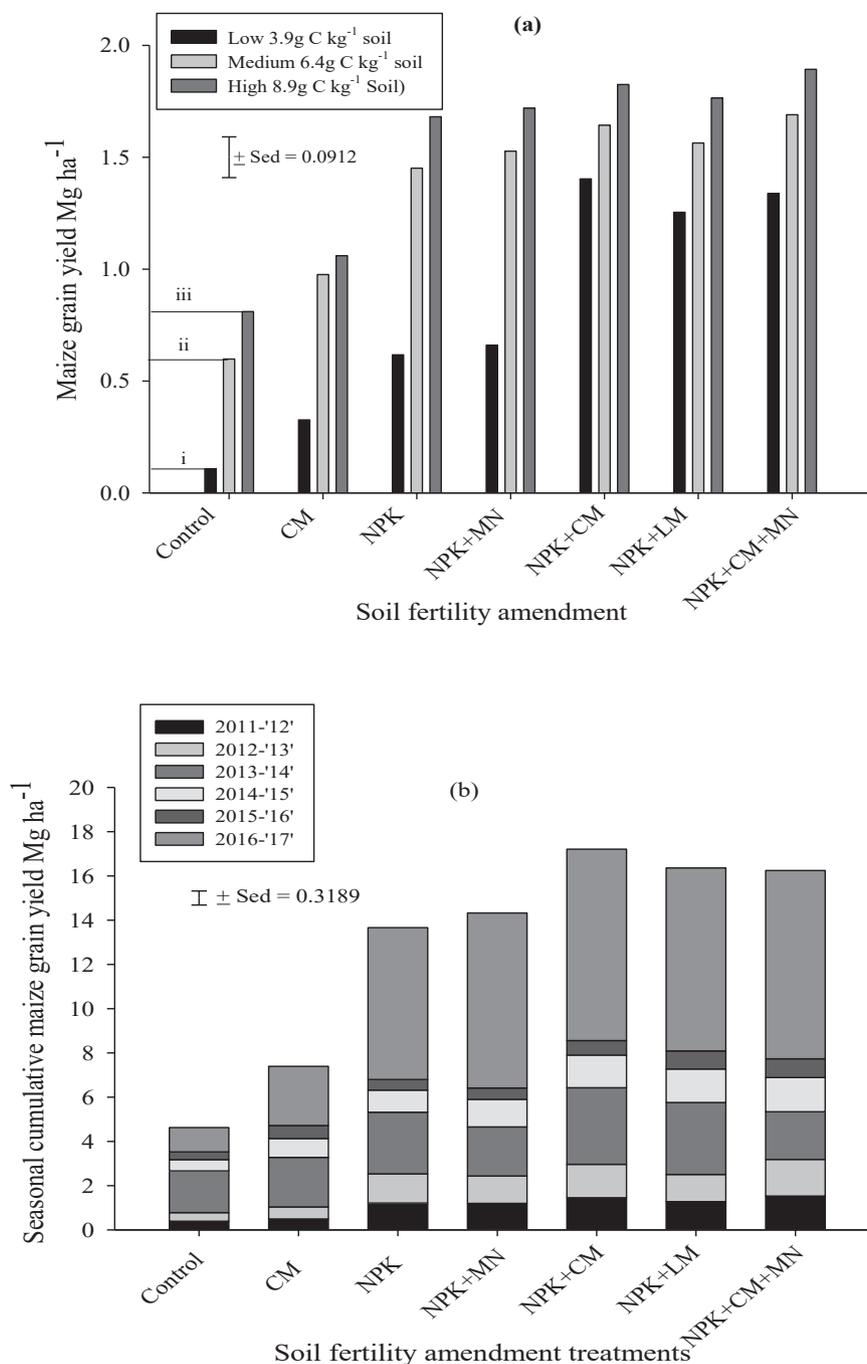


Figure 3. The effect of SOC status and soil nutrient amendment on maize productivity (2011–2017 cropping seasons) on three smallholder farms varying SOC status situated on a catena in Wedza, Eastern Zimbabwe. (i, ii, iii indicate the influence of SOC on maize grain yield from the control treatment).

and 3.72-times higher maize grain yield than unfertilized control, respectively (Figure 3b).

3.2. Weed diversity, density, and biomass along the catena

Twenty-three weed species were identified and recorded across three smallholder farms situated along the catena with varying SOC status. Seventy-eight percent of the weed species were broadleaf, 17 and 0.04 percent being grasses and sedges, respectively (Figure 4).

The principal component analysis (PCA) provided evidence of the strong association between SOC status, season, and weed composition (Figure 4). The PCA bi-plot accounted for 46.0 % of total variance in weed composition with Axis 1 accounting for 23.79 % (eigenvalue of

0.2370) whilst Axis 2 accounted for 16.49 % (eigenvalue = 0.1649). SOC status had a strong influence on weed composition while soil nutrient amendment was not significant at $P \leq 0.05$. Weeds strongly associated with the low SOC status (upper catena) were *Cyperus sp.*, *M. repens*, *C. monophylla*, *C. benghalensis*, and *R. scabra*. whilst weed species associated with medium SOC status (middle catena) were *C. datylon*, *O. latifolia*, *L. martinicensis*, *A. hispidum*, and *S. alba*. Weeds strongly associated with high SOC status (lower catena) were *G. parviflora*, *E. indica*, and *B. pilosa* (Figure 4).

There were distinct differences in weed species diversity among the three smallholder farms (Figure 5a). Greater weed species diversity was associated with high SOC status compared to medium and low SOC statuses at all weed sampling periods, in particular when sampling was

Table 4. The density of major weeds influenced by SOC status and soil nutrient amendments as depicted by Principal Response Curve scale viz *Biden pilosa*, *Cyperus sp.*, *Galinsoga parviflora* *Luacus martinicensis*, *Melenis repens* and *Richardia scabra* on three smallholder farms with varying SOC status and situated on the upper, middle and lower catena positions in Wedza, Eastern Zimbabwe.

SOC status kg -1 soil	Weed density (3 WACE)					
	<i>Biden pilosa</i>	<i>Cyperus sp.</i>	<i>Galinsoga parviflora</i>	<i>Luacus martinicensis</i>	<i>Melenis repens</i>	<i>Richardia scabra</i>
High 8.9 g C	2.8 ^c (14)	4.2 ^b (27)	8.0 ^b (78)	4.4 ^c (20)	1.1 ^a (1)	4.0 ^a (17)
Medium 6.4 g C	2.4 ^b (9)	2.5 ^a (12)	0.8 ^a (0)	4.0 ^b (19)	1.6 ^b (4)	5.4 ^b (32)
Low 3.9 g C	1.0 ^a (1)	5.0 ^c (26)	0.8 ^a (0)	2.0 ^a (6)	2.5 ^c (9)	8.0 ^c (76)
F pr	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Sed	0.32	0.44	0.43	0.35	0.24	0.44
Soil nutrient amendments						
Control	1.1 ^a (4)	3.0 ^a (12)	2.7 (16)	3.1 (14)	1.6 ^b (4)	5.2 (30)
CM	2.5 ^c (13)	4.4 ^c (27)	4.0 (42)	3.5 (16)	1.9 ^b (6)	5.4 (38)
NPK	1.9 ^b (7)	4.7 ^c (28)	3.2 (27)	3.1 (13)	2.3 ^c (8)	6.1 (49)
NPK + CM	2.0 ^b (6)	3.6 ^b (20)	3.1 (23)	3.6 (16)	1.6 ^a (3)	6.1 (45)
NPK + LM	1.8 ^b (5)	3.9 ^b (20)	3.1 (23)	3.6 (16)	1.4 ^d (2)	6.1 (48)
F pr	<0.001	<0.001	ns	ns	0.022	ns
Sed	0.41	0.57	0.55	0.45	0.31	0.57
SOC × soil nutrient amendment interaction						
P	ns	ns	ns	ns	0.052	ns
Sed	0.71	0.98	0.96	0.78	0.54	1.72

*Means followed by the same letter superscript in a column are no significantly different at P < 0.05.

†Number in brackets are back-transformed (actual) weed numbers m⁻².

Table 5. The density of major weeds influenced by SOC status and soil nutrient amendments as depicted by Principal Response Curve scale viz *Biden pilosa*, *Cyperus sp.*, *Galinsoga parviflora* *Luacus martinicensis*, *Melenis repens* and *Richardia scabra* on three smallholder farms with varying SOC status and situated on the upper, middle and lower catena positions in Wedza, Eastern Zimbabwe.

SOC status kg ⁻¹ soil	Weed density (6 WACE)					
	<i>B. pilosa</i>	<i>Cyperus sp.</i>	<i>G. parviflora</i>	<i>L. martinicensis</i>	<i>M. repens</i>	<i>R. scabra</i>
High 8.9 g C	0.9 ^b (1)	1.7 ^b (4)	3.1 ^b (14)	2.6 ^b (8)	0.7 ^a (0)	2.1 ^a (5)
Medium 6.4 g C	1.3 ^c (2)	0.8 ^a (0)	0.8 ^a (0)	3.0 ^c (12)	0.7 ^a (0)	2.0 ^a (5)
Low 3.9 g C	0.8 ^a (1)	2.1 ^c (5)	0.7 ^a (0)	0.9 ^a (0)	1.3 ^b (1.6)	3.0 ^b (12)
F pr	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Sed	0.09	0.19	0.23	0.19	0.07	0.16
Soil nutrient amendments						
Control	0.8 ^b (0)	1.1 ^a (1)	1.2 (1)	1.6 ^a (3)	0.9 ^{bc} (1)	1.9 ^a (4)
CM	1.3 ^c (1)	1.7 ^d (5)	7.0 (2)	2.5 ^c (10)	1.0 ^{bc} (1)	2.6 ^b (8)
NPK	1.0 ^c (1)	1.9 ^c (4)	4.8 (2)	2.1 ^b (6)	1.0 ^c (1)	2.4 ^b (7)
NPK + CM	1.1 ^d (1)	1.5 ^c (3)	5.6 (2)	2.3 ^{bc} (8)	0.9 ^b (0)	2.9 ^c (11)
NPK + LM	0.7 ^a (0.07)	1.2 ^b (2)	5.0 (2)	2.1 ^b (7)	0.7 ^a (0)	2.2 ^b (7)
F pr	<0.001	0.007	ns	0.006	<0.010	<0.001
Sed	0.12	0.25	2.15	0.25	0.09	0.44
SOC × soil nutrient amendment interaction						
P	ns	0.001	ns	0.003	0.001	ns
Sed	0.64	0.43	0.51	0.43	0.16	0.35

*Means followed by the same letter superscript in a column are no significantly different at P < 0.05.

†Number in brackets are back-transformed (actual) weed numbers m⁻².

3.3. Weed diversity

Generally, small weed species diversity values were observed from low SOC status compared to medium and high SOC status in conformity with results from PRC analysis (Figure 5a). Higher richness, Shannon, and evenness index values were found in medium and high SOC statuses compared to low SOC status (Table 6).

Significantly higher richness indices were found in NPK + CM (10.0 ± 0.33), CM (9.8 ± 0.33) soil nutrient amendment treatments compared to NPK and NPK + LM (7.4 and 7.3 ± 0.33 respectively) while unfertilized control recorded the lowest richness index value (6.7 ± 0.33) in Table 6. Higher Shannon index value (1.6 ± 0.04) was recorded in NPK + CM

compared to 1.34 ± 0.04 in unfertilised control. Evenness index values were higher (0.53 ± 0.02) in both NPK and NPK + LM treatments compared to unfertilised control (0.47 ± 0.02) treatment (Table 6).

3.4. Weed density and biomass at 3 and 6 WACE

Weed density increased by between 1.1-1.2 and 1.2-1.3 times in medium and high SOC status respectively compared to low SOC status (Table 6). According to the PRC scale there were higher densities of *B. pilosa* L, *G. parviflora*, and *L. martinicensis* in medium and high SOC compared to low SOC. In contrast, *R. scabra* and *M. repens* densities were higher in low SOC status than medium and high SOC status (Table 4).

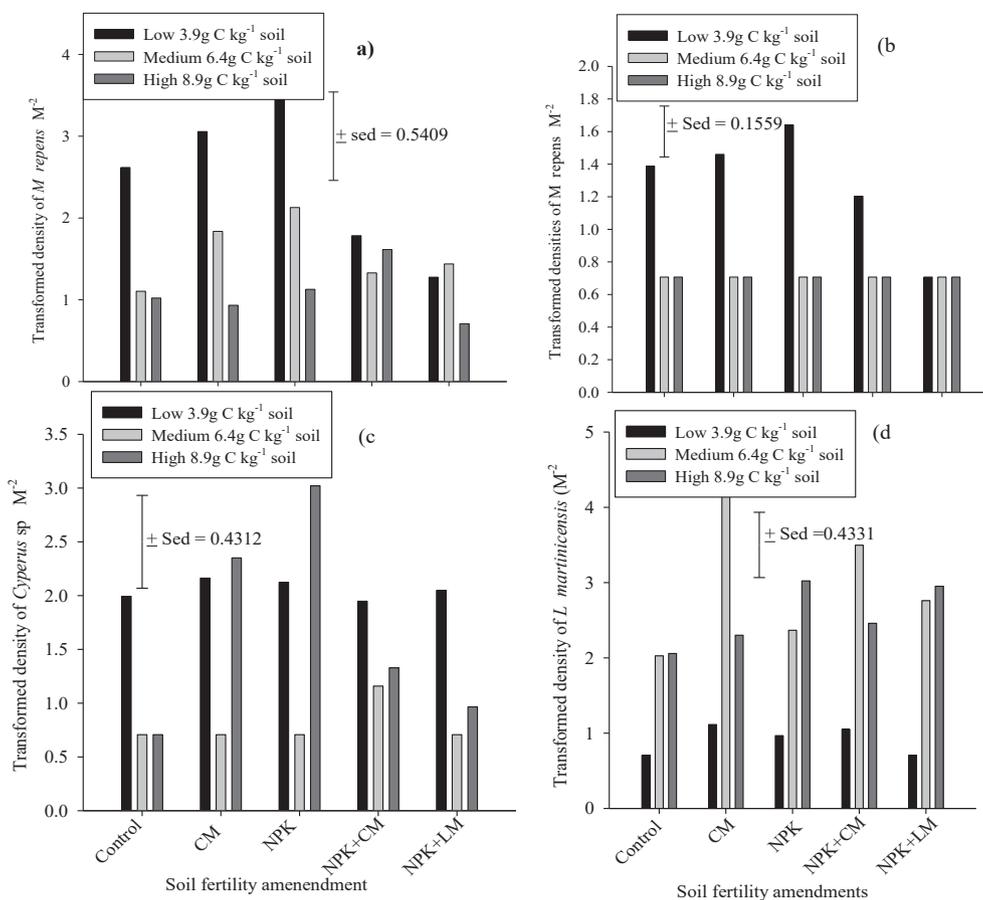


Figure 6. The influence of SOC × soil nutrient amendment interactions on (a) *M. repens* at 3 WACE, (b) *M. repens* at 6 WACE (c) *Cyperus sp.* and (d) *L. martinicensis* weed densities on three smallholder farms with varying SOC status along a catena in Wedza, Eastern Zimbabwe.

Table 6. The influence of SOC status and soil nutrient amendment on weed density, biomass, and diversity indices for three smallholder farms with varying SOC and situated on a catena in Wedza, Eastern Zimbabwe.

Treatments	Density numbers m ⁻²		Biomass g m ⁻²		Diversity indices		
	3 WACE	6 WACE	3 WACE	6 WACE	Richness	Shannon	Evenness
Soil organic carbon (SOC) kg ⁻¹ soil							
High 8.9 g C.	108.4 ^c (438)	72.1 ^b (130)	200.8 ^c	127.7 ^c	10.0 ^b	1.52 ^b	0.51 ^b
Medium 6.4 g C	101.0 ^b (311)	70.5 ^b (134)	83.0 ^b	61.7 ^b	9.1 ^b	1.59 ^c	0.55 ^c
Low 3.9 g C	88.0 ^a (320)	57.0 ^a (51)	44.4 ^a	39.3 ^a	6.6 ^a	1.25 ^a	0.52 ^a
F pr	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.048
Sed	2.52	2.10	18.04	14.71	0.26	0.03	0.01
Soil nutrient amendment							
Control	86.8 ^a (251)	54.42 ^a (43)	32.8 ^a	27.2 ^a	6.7 ^a	1.34 ^a	0.47 ^a
CM	107.3 ^c (429)	75.21 ^d (148)	120.0 ^b	84.7 ^b	9.8 ^c	1.57 ^c	0.50 ^b
NPK	99.2 ^b (384)	64.63 ^c (96)	116.4 ^b	74.0 ^b	7.4 ^b	1.39 ^b	0.53 ^c
NPK + CM	105.3 ^c (372)	76.78 ^d (153)	135.3 ^b	116.4 ^c	10.0 ^c	1.62 ^d	0.51 ^b
NPK + LM	97.2 ^b (344)	61.54 ^b (85)	122.4 ^b	78.9 ^b	7.3 ^b	1.36 ^{ab}	0.53 ^c
F pr	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.005
Sed	3.25	2.70	23.28	18.99	0.33	0.04	0.02
SOC x soil nutrient amendment interaction							
F pr	ns	ns	ns	ns	ns	ns	ns
Sed	5.63	4.68	1.72	1.12	0.58	0.58	0.03

†Treatments that share the same letter in each section are not significantly different at P > 0.05. ns = not significant, soil nutrient amendment.

‡Biomass grams m⁻² and weed density numbers in brackets are back-transformed (actual) weed numbers m⁻².

Significantly higher weed densities were recorded from CM and NPK + CM treatments compared to NPK, NPK + LM, and unfertilized control which had the lowest densities. Correspondingly, soil nutrient

amendment significantly affected densities of major weeds namely *B. pilosa*, (P ≤ 0.001) *Cyperus sp.* (P ≤ 0.007) *L. martinicensis* (P ≤ 0.006) *M. repens* (P ≤ 0.01) and *R. scabra* (Table 4).

Generally, high weed densities were observed in response to NPK, CM and NPK + CM applied treatments. However, *M. repens* densities increased in CM and NPK applied treatments and declined in NPK + lime and NPK + CM treatments (Figure 6a) and at 6 WACE, *M. repens* density was higher on low SOC status and in unfertilized control, CM and NPK treatments (Figure 6b).

SOC × soil nutrient amendment interaction recorded high *Cyperus sp.* densities associating with low SOC for all soil nutrient amendment treatments and the control. However, when CM and NPK were applied, high *Cyperus sp.* densities were also observed. *Cyperus sp.* density was lowest in the medium SOC treatment and did not vary across all soil nutrient amendment and the control (Figure 6c).

Lupeolus martinicensis densities were high in medium and high SOC status compared to low SOC status. In medium SOC status, *L. martinicensis* densities increased in CM and NPK + CM applied treatments compared to other treatments (Figure 6d).

Weed biomass increased by 86.9 and 141.9 % when SOC status change from low SOC status on upper catena to medium and high SOC status on middle lower catena respectively. Weed biomass was also influenced by soil nutrient amendment with an increase in weed biomass over unfertilized control of all nutrient amended treatments in (Table 6).

At 6 WACE weed biomass increased from 39.3 ± 0.33 , 61.7 ± 0.33 and 127.7 ± 0.33 g m⁻² in low, medium and high SOC status respectively. High weed biomass was recorded in NPK + CM (116.4 ± 0.33) followed by CM, NPK, NPK + LM with 9.8 ± 0.33 , 7.4 ± 0.33 , 7.3 ± 0.33 and unfertilised control had the lowest weed biomass 6.65 ± 0.33 (Table 6).

4. Discussion

4.1. Short-term maize productivity on three farms across the catena

This study focused on the short-term impacts of SOC and soil nutrient management on maize productivity and weed dynamics across the catena. Varying SOC status on catena strongly affected weed density, weed biomass, and maize productivity. Mean maize grain yield over six years increased by 89% and 110% in medium and high SOC status, respectively compared to low SOC, whilst a marginal 12% difference in grain yield was observed between medium and high SOC status. These results are similar to earlier findings by Kone et al. (2013), Touré et al. (2014), and Kurwakumire et al. (2015), who observed that soil fertility gradient, catena position, and farmer management influenced rice and maize grain yield across the catena.

The coarse-textured, inherently low fertility, and acidic soils on the upper slope had a low response to the sole application of CM and NPK fertilisers. Our results confirm findings by Touré et al. (2014) who found out lower rice yield on the upper catena due to low nutrient response. The low response of maize grain yield to the application of CM in the upper catena (low SOC) could be attributed to low protection of added CM, poor cattle manure quality, loss of nutrients through leaching and inherently low nutrient status on sandy soils (Chivenge et al., 2011). The low response of maize grain yield to application NPK fertilisers in the upper catena could be due to low pH (acidic soils) resulting in unavailability of elements such as P which is essential for root development causing limited water and nutrient uptake (Gwenzi et al., 2016). Whereas in medium to high SOC status fields the high clay content, high cation exchange capacity (CEC), water holding capacity, and inherently fertile soils with moderate pH, resulted in high response to applied soil nutrient amendment and water uptake by plants. However, the marginal difference in maize yield between medium and high SOC could be attributed to low additional fertiliser uptake by maize under low fertile soils and fluctuation of maize grain yields on lower catena when yields decline due to effect of flooding in wet seasons. The results are in agreement with findings by (Koné et al., 2013; Kurwakumire et al., 2015) who reported that soil fertility and hydrological gradients were the main drivers of differences in rice and maize grain yields on a catena.

Our results, suggest that smallholder farmers situated in low fertile sandy soils have to repeatedly apply cattle manure in their fields to make up for the unprotected losses of SOC (Chivenge et al., 2011). Although with limitations, options available to farmers subject to resource capacity include green manures technology (Barthès et al., 2004) mulch tillage (Mtambanengwe et al., 2015), livestock manure application (Nyamangara and Giller, 2008) which is only applicable to cattle owners while resource-constrained farmers rely on nutrient-rich termitaria soil or pit composts (Mtambanengwe et al., 2012).

Sandy soils are widespread in SSA and are characterised by inherently poor stocks of mineral nutrients, organic matter and are highly susceptible to degradation. In Zimbabwe, more than 65% of smallholder farmers are located on these granitic and acidic sandy soils (Chaumba et al., 2003). Low pH could be one of the causes maize yields decline in inorganic fertiliser applied treatments. Low pH (acidic) soils affected the availability of nutrient elements like phosphorus and increase the availability of some microelements such as Fe, Mn, and Al which may reach a toxic concentration in the soil. Farmers can, therefore, increase maize yields by liming fields once in two to three seasons where NPK fertilisers are used or integrating NPK fertilisers with CM (Rusinamhodzi et al., 2013). Smallholder farmers in Zimbabwe rarely lime their farms yet their fields are generally acidic.

Maize yield was lower in sole cattle manure treatment compared to the NPK + CM treatment. This is attributed to low nutrient release from organic manures, which could have failed to meet the mineral nutrient demand by the maize crop. The increase in maize grain yield from NPK + CM treatments has been reported in earlier studies (Chivenge et al., 2011; Kafesu et al., 2018; Kurwakumire et al., 2014). The synergistic effect of integrating NPK + CM influences both the physical and chemical properties of the soil. Organic manures improve soil physical properties such as aggregation, aeration, infiltration, water retention capacity, and soil chemical properties such as cation exchange capacity, amelioration of soil pH, and increase crop nutrients supply (Wuta, and Nyamugafata, 2012; Zingore et al., 2011). Manure that is available and used by most smallholder has a similar nutrient composition with manure used in this study Kurwakumire et al. (2015), suggesting that our findings are broadly applicable in the region under similar climatic conditions.

4.2. Weed abundance

Weed species had a strong link with SOC across catena (Figure 4). The effects of catena on weeds were also explained in other studies (Koné et al., 2013; Touré et al., 2014). Weeds found to be strongly associated with low SOC content were *Cyperus sp.*, *M. repens*, and *R. scabra*. The weeds are well adapted in infertile, acidic, and degraded soils. Mavunganidze et al. (2016) described such weeds as 'scavenger' weeds and can be used as bio-indicator species of soils of increasing acidity and declining fertility. In medium and high SOC soils, *O. latifolia*, *S. alba*, *C. dactylon*, and *L. martinicensis* were found in the middle catena while *G. parviflora*, *E. indica*, and *B. pilosa* were found in the lower catena. The weed species are generally associated with fertile soils or highly fertilized fields while *Cyperus sp.* is also associated with vlei areas. The influence of soil properties and catena position on weeds was also observed by Touré et al. (2014) while the dominance of *R. scabra*, and *M repens* in degraded and acidic soils was also reported by (Nezomba et al., 2015). Likewise, a survey and studies by Mavunganidze et al. (2016) in Midlands and Kafesu et al. (2018) in Murewa Eastern Zimbabwe confirms that farmers associate the presence of *R. scabra*, and *M. repens* with poor soils.

Experienced smallholder farmers are cognisant of weed species compositional changes in their fields and integration of this indigenous knowledge with laboratory backed scientific explanation will help farmers make correct crop management decisions. In this study maize grain yield under low SOC conditions dominated by *R. scabra* and *M. repens* was significantly increased when NPK + CM and NPK + LM treatments were applied suggesting that the amendments ameliorated soil pH and improved soil nutrient uptake response confirming findings

by (Zingore et al., 2011). However, in fields medium to high SOC contents crop production could be sustained through the addition of NPK, NPK + CM, and NPK + LM. Our findings address the proposal by Nezomba et al. (2015) who highlighted the need for further studies to explore the relationship between weed species and soil properties in space and time as diagnostic bio-indicators. Understanding how weed species can be used as bio-indicators has the potential to help smallholder farmers in Zimbabwe who face challenges in accessing seed, fertiliser, and labour resources make important management decisions on resource allocation and their site-specific deployment (Zingore et al., 2011).

4.3. Weed diversity

A total of twenty-three weed species were identified in three smallholder farms along the catena indicating a diverse weed species. Shannon Wiener and richness index values increased by 27 and 38 % respectively as SOC status change from low to high. The change is an indication of a weed compositional shift due to changes in SOC, catena, and soil nutrient amendments influence. Moreover, treatments applied with cattle manure (CM) and NPK + CM had the highest weed species richness and Shannon Wiener index values. The results were in line with finding by (Baker et al., 2018) who reported an increase in weed diversity from organic amendment treatments.

This information is vital for practicing farmers in ensuring that manure treated fields should be kept weed-free in the early part of the season before full ground cover by the maize canopy (emergence to 6 WACE) to avert yield losses. The majority of smallholder farmers in Zimbabwe rely on family labour for hand hoe weed control and at the start of rain season family, labour is usually engaged in ploughing, planting and other house-hold duties resulting in delayed weeding of first planted crops causing maize yield decline (Mavunganidze et al., 2016).

4.4. Weed density and biomass

Weed density and biomass had a strong association with both SOC status along the catena (Table 6). The differences in weed species composition, density, and biomass have earlier been explained by the catena position, hydrological gradient, soil fertility gradient, and management by the farmer (Touré et al., 2014). Our results reveal an increase in both weed density and biomass as SOC change from low on upper catena, to medium and high on middle, lower catena, respectively. The middle and lower catena influence both the physical and chemical properties of the soils, nutrient, and water uptake by the crop and weeds hence the increase weed density and biomass down the slope (Touré et al., 2014). Major et al. (2005) also observed an increase in weed biomass as SOC status and soil fertility improved. Weeds tend to benefit more owing to their greater ability to efficiently extract nutrients from such soils and increase weed density and biomass. Our findings were, however, contrary to observations Boling et al. (2008) who reported that rice yield and weeds composition was not different across the catena.

Cattle manure and NPK + CM amended treatments increased weed density and biomass compared to unfertilized control. Results confirm previous findings that the application of manure in cropping systems increases weeds density and biomass (Kaur et al., 2018). Weeds are efficient users of nutrient elements with high neutrophils and phosphophilous weeds benefiting from the application of both nitrogen and phosphorus fertilisers respectively (Blackshaw et al., 2010). The use of both organic and inorganic fertiliser application fertilisers in agro-systems does not only benefit the crop but to a greater extent weeds whose nutrient uptake system is more efficient than crop plants (Hunková et al., 2011).

High weed density and biomass in CM, NPK + CM applied treatments can be attributed to the effects of cattle manure as a weed seed source or possible stimulant of weed seed germination. Similar findings were recorded by Efthimiadou et al. (2012) and Hassan et al. (2012). Livestock manure is known to influence physical (aggregation, aeration, infiltration

and water retention capacity) and chemical properties (cation exchange capacity, amelioration of soil pH) of the soil which benefit established crops and also un-intentionally benefit weeds (Materechera and Modiakgotla, 2013). Moreover, cattle manure is known to can carry high numbers of germinable weed seeds and is associated with high density and biomass in field crops especially when it has not been cured or incubated for less than five months (Materechera and Modiakgotla, 2006). Chipomho et al. (2018) also reported the presence of *Amaranthus hybridus*, *Eleusine indica*, and *Nicandra physaloides* in cattle manure treated plots, suggesting that manure use in agro-systems have potential increase density, and biomass of these species.

5. Conclusions

Results from the study demonstrated that maize productivity, weed, density, and biomass were strongly linked to SOC content along the catena. An increase in grain yield of maize, weed density, and weed biomass was recorded as SOC content change from low in the upper catena position to high SOC in the lower catena. Results from this study suggest site-specific management of soils according to position on the catena and SOC status. Little or no grain yield responses are likely for farmers who apply sole CM or NPK fertiliser on poor soils of low SOC in the upper catena and application NPK + CM or lime is recommended. In the middle and lower catena with medium and high SOC, respectively, CM or NPK fertilisers were effective in increasing maize grain yield. Our results also suggest that farmers increase the vigilance and intensity of weed management in medium and high SOC positions and after application of soil nutrient amendment, particularly CM, as weed density, diversity and biomass significantly increased. Further research is also required to generate robust information on site-based weed management for sustainable maize production as weed density, diversity and biomass depend on SOC status, and application of soil nutrient amendment.

Declarations

Author contribution statement

Justin Chipomho: Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Joyful T. Rugare, Stanford Mabasa, Arnold Bray Mashingaidze: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Shamie Zingore: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Regis Chikowo: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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