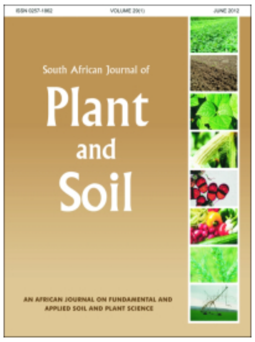

South African Journal of Plant and Soil

ISSN: 0257-1862 (Print) 2167-034X (Online) Journal homepage: www.tandfonline.com/journals/tjps20

Influence of soil organic carbon, fertiliser management, and weeding regime on weed dynamics and maize productivity on sandy soils in eastern Zimbabwe

Justin Chipomho, Cosmas Parwada, Joyful T Rugare, Stanford Mabasa, Regis Chikowo & Arnold B Mashingaidze

To cite this article: Justin Chipomho, Cosmas Parwada, Joyful T Rugare, Stanford Mabasa, Regis Chikowo & Arnold B Mashingaidze (2021) Influence of soil organic carbon, fertiliser management, and weeding regime on weed dynamics and maize productivity on sandy soils in eastern Zimbabwe, South African Journal of Plant and Soil, 38:2, 81-92, DOI: 10.1080/02571862.2020.1845831

To link to this article: https://doi.org/10.1080/02571862.2020.1845831

Published online: 17 Jun 2021.

South African Journal of Plant and Soil 2021, 38(2): 81–92
Printed in South Africa — All rights reserved

SOUTH AFRICAN JOURNAL OF PLANT AND SOIL
ISSN 0257-1862 EISSN 2167-034X
https://doi.org/10.1080/02571862.2020.1845831

Influence of soil organic carbon, fertiliser management, and weeding regime on weed dynamics and maize productivity on sandy soils in eastern Zimbabwe

Justin Chipomho[1,2]*, Cosmas Parwada[1], Joyful T Rugare[2], Stanford Mabasa[2], Regis Chikowo[2] and Arnold B Mashingaidze[3]

[1] *Crop Science Department, Marondera University of Agricultural Sciences and Technology, Marondera, Zimbabwe*
[2] *Department of Crop Science, University of Zimbabwe, Harare, Zimbabwe*
[3] *Department of Crop Science and Post-Harvest Technology, Chinhoyi University of Technology, Chinhoyi, Zimbabwe*
* *Correspondence: jusychipomho@gmail.com*

Labour bottlenecks and multiple operations at the start of a cropping season often result in inadequate early weed control and subsequent poor crop performance. Therefore, there is a need to establish management practices that provide the best opportunities for the gains associated with weeding and nutrient management across farms. We investigated the influence of soil organic carbon (SOC), fertiliser management, and weeding regimes on weed dynamics and maize productivity on smallholder farms with contrasting SOC in eastern Zimbabwe. On each site, and for two seasons, a 2 × 5 factorial experiment laid in a randomised complete block design was used. Fertiliser management was NPK or NPK + cattle manure (CM); weeding regimes were herbicide + hoe weeding, hoe weeding thrice/twice/once, or weedy check. Principal component analysis was used to evaluate weed density. The grain yield of maize increased by 13% on the sites with higher SOC. Integrating NPK + CM increased weed density and maize grain yield by 1.32 and 1.46-times, respectively, compared with NPK application only. The increased maize yield from fertiliser-managed treatments occurred only in early frequently weeded treatments. However, fertiliser application had little effect when weeding was delayed, as maize yield instead declined by 40–80%. We concluded that higher SOC increased weed density and weed biomass. Smallholder farmers are encouraged to combine herbicide application combined with hoe-weeding options for sustainable maize production.

Keywords: cost–benefit analysis, Lixisols, maize yield, partial budget analysis, sub-Saharan Africa, weed density, weeding frequency

Introduction

Weed infestation is among the major causes of low maize (*Zea mays* L.) grain yield in sub-Saharan Africa (Rodenburg and Johnson 2013). Weeds directly compete with crops for growth resources (Kaur et al. 2018). Besides competition, weeds directly affect crops negatively through parasitism (Sibhatu 2016) and allelopathy (Bhadoria 2011; Rugare 2018).

Biotic stress caused by weeds during the early development stages of maize impedes growth and consequently reduces the final grain yield (Mashingaidze 2004; Tibugari et al. 2019). Indirectly, weeds act as alternative hosts for disease pathogens (Handiseni et al. 2008), insect pests (Capinera 2005) and nematodes (Sikora et al. 2019), which negatively affect crop yield. Timely and efficient weed management is therefore vital for sustainable, increased crop yields and food security.

Smallholder farms in Zimbabwe are spatially heterogeneous in terms of soil fertility mainly due to the inherent geopedological conditions (Masvaya et al. 2010). The predominant parent materials in Zimbabwe are mafic, which give rise to high clay content soils and sandy soils from granite. The latter covers more than 66% of the soils in Zimbabwe (Nyamapfene 1991). Kurwakumire et al. (2014) revealed a strong correlation between soil texture and soil organic carbon (SOC) content for Zimbabwean soil (R^2 = 85%). The level of organic carbon determines the physicochemical and biological properties of the soil (Davis 2007). Management practices by farmers should, therefore, aim to maintain or increase the SOC level to sustain crop production (Shibabaw and Alemeyehu 2015). Although the influence of SOC on crop productivity was researched by Munera-Echeverri et al. (2020), its effects on weed density and weed biomass in maize-based cropping systems still require investigation.

Maize is the main cereal crop consumed in Zimbabwe, and 42% of the national grain supply is from small-scale commercial (model A2 scheme) farms. More than 58% of maize production is from resettled (model A1) and communal (smallholder) farmers (Bonsu and Esterhuizen 2018). The majority (65%) of smallholder farms are located on granite-derived sandy soils (Chaumba et al. 2003). The soils are inherently infertile with low concentrations of organic carbon (C) and crop nutrients to support plant growth (Nyamangara et al. 2000; Ncube et al. 2007). Crop yields are also depressed owing to the extractive and low external input management practices common in the smallholder sector (Zingore et al. 2011). The use of inorganic fertilisers and available organic resources is therefore inevitable for increased crop productivity. Mineral fertiliser use in Zimbabwe is, however, limited because of the lack of purchasing power by smallholder farmers and scarcity of the product (Mtangadura et al. 2017). Moreover, repeated inorganic fertiliser use without lime application increases soil acidity (Nardi et al. 2002). Owing to high inorganic fertiliser costs, smallholder farmers usually apply suboptimal rates of sole inorganic (NPK) fertiliser or these in combination with available local resources like leaf litter or livestock manure (Chikowo et al. 2004).

Co-applying cattle manure (CM) and NPK fertiliser is one such option that has the potential to rehabilitate poor soils, build upon carbon reserves, and improve maize yields (Rusinamhodzi et al. 2013). Cattle manure supply is readily available to more than 70% of the smallholder farmers in Zimbabwe, as most of these farmers rely on an integrated crop–livestock system for their livelihood (Mugwira and Murwira 1997; Matarauka and Samaz 2014). However, the use of CM in fields may come with increased weed infestation which impacts negatively on crop productivity.

Studies by Chivinge and Mariga (1998) and Mavunganidze et al. (2016) revealed that the benefits of fertiliser application depended on effective weed removal to avert yield loss. Smallholder farmers in Zimbabwe, like in many other sub-Saharan African countries, rely on family labour which is not directly paid to carry out farming operations (Mashingaidze et al. 2009). Family labour usually comprises the elderly and school-going children because the active, youthful age groups often migrate to urban centres in search of employment (Tibugari et al. 2019). Labour shortages coupled with the slow, inefficient and laborious hoe-weeding method normally result in delayed first weeding in farmers' fields (Mashingaidze 2004). Some planted fields may be abandoned if the farmers fail to cope with the weed infestation (Mavunganidze et al. 2016). Inputs that were previously committed to failed or abandoned crops are invariably lost when such crops produce little or no economic yield (Mashingaidze 2004). Consequently, efficient weed management options should be explored to improve crop yields especially on smallholder homefields.

Homefields are more secure and more fertile than outer fields (Nyamangara et al. 2011), and farmers often allocate more production resources, such as labour, seed and fertilisers, to such fields compared with the outer fields (Zingore et al. 2007). Despite being more fertile, the majority (>60%) of smallholder farmers still attain low yields (<1 t ha^{-1}) from homefields owing to delayed weeding, among other reasons (Mavunganidze et al. 2016). The objectives of this study were to (1) investigate the effects of fertiliser management and weeding frequency on weed density, weed biomass, and grain yield of maize on fields with contrasting SOC content, and (2) determine the cost–benefit of weeding options.

Materials and methods

Site description

The experiment was carried out in Marondera district (18°22′ S, 31°45′ E), eastern Zimbabwe, in the 2015/16 and 2016/17 cropping seasons. Two adjacent smallholder farms within 1-km distance from each other and with 4.0 and 6.4 g kg^{-1} SOC, respectively, were selected for the experiment. The area has a subtropical climate, with average summer temperatures of 25 °C and annual precipitation of approximately ±800 mm year^{-1}. Rainfall follows a unimodal pattern, received between November and April. Monthly rainfall distribution and cumulative rainfall from planting to the harvesting period for each cropping season were recorded from rain gauges placed close to the experimental fields (Figure 1). The predominant soil type in both experimental fields is sandy textured soils derived from granitic parent material, classified as a Lixisol (FAO soil classification).

Soil sampling and analysis

Before establishing the experiments in November 2015, a composite soil sample collected from the 0–20 cm depth at 10 randomly selected points within each experimental field was collected for detailed soil characterisation. Soil texture, SOC, total nitrogen (N), available phosphorus (P), exchangeable bases (K, Mg and Ca) and soil pH were determined using standard laboratory procedures (Anderson and Ingram 1993; Okalebo et al. 2002) (Table 1).

Experimental treatments and field management

Land preparation was done by tilling the soil using an ox-drawn plough to a depth of 20 cm after a cumulative 30 mm of rainfall was received within two days during November for both cropping seasons. In each field, and in years 1 and 2, the same treatments were repeatedly applied to the same plots. Aerobically composted cattle manure obtained from the cattle pen of one of the host farmers was used on both fields each season. For each season, manure samples were analysed (Table 1) and moisture content was determined for subsequent moisture correction to apply 5 t ha^{-1} dry-matter equivalent in manure treatments. Cattle manure was broadcasted before marking planting furrows, and inorganic fertiliser was band applied in planting furrows.

On each site, which had contrasting SOC, namely low (4.0 g kg^{-1} soil) and high (6.4 g kg^{-1} soil), and for two cropping seasons, a 2 x 5 factorial experiment was laid in a randomised complete block design. Fertiliser management was either NPK or NPK + cattle manure (CM). Total

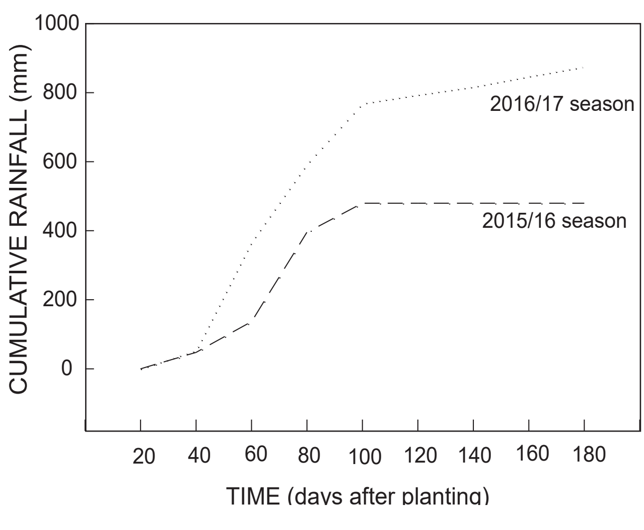

Figure 1: Cumulative rainfall recorded from the period of planting to harvesting, during the 2015/16 and 2016/17 cropping seasons, at the experimental sites in eastern Zimbabwe

Table 1: Soil physicochemical characteristics (sampled at 0–20 cm depth) at two smallholder experimental farms with varying soil organic carbon (SOC) contents in eastern Zimbabwe. Soil samples were collected before trial establishment in 2015; cattle manure characterisation was made for each cropping season

Soil and manure chemical properties	Sand	Clay	Organic carbon	Total N	Available P	pH 1:10 (H_2O)	Ca	Mg	K
	($g\ kg^{-1}$)				($mg\ kg^{-1}$)		($cmol_c\ kg^{-1}$)		
Low SOC, 4.0 g C kg^{-1} soil*	830	100	4.0	0.09	2.5	5.2	6.2	5.1	0.15
High SOC, 6.4 g C kg^{-1} soil*	560	150	6.4	0.4	7.3	5.5	7.3	4.4	0.43
Cattle manure in 2015/16	–	–	233	9.0	2.2**	6.4	8.5	0.7	5.6
Cattle manure in 2016/17	–	–	221	8.9	2.1**	5.7	7.0	0.5	4.2

*General soil fertility range interpretation adapted from Tanner and Grant (1963). (a) Available-P (resin-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 = 6.4; >0.5 = high. (c) Exchangeable-Ca: <5 = very low; 5–10 = low to 6.4%; >10 = high. (d) Exchangeable-Mg: <0.1 = very low; 0.1–0.2 = low to 6.4%; >0.2 = high
** Total P measurement

nutrients applied were 120 kg N, 30 kg P, and 28 kg K ha^{-1}. There were five weeding regimes: herbicide + hoe (clean weeding); early frequent (three times); late and less frequent (twice); very late (once); and weedy check. The gross plot size was 4.5 × 5 m.

At planting, 25 kg ha^{-1} P, 28 kg ha^{-1} N and K were applied through compound fertilisers (7% N, 14% P_2O_5, 7% K_2O). A further 92 N kg ha^{-1} was split-applied as ammonium nitrate (34.5% N) at 4 and 7 weeks after crop emergence (WACE). A medium-maturing (138–145 days) maize hybrid variety SC 637 (Seed Co. Zimbabwe) was planted on each field on the same date in the two cropping seasons (i.e. on 19 and 21 November, respectively). Plant spacing was 0.9 × 0.25 m, with a target population of 44 444 plants ha^{-1}. Two seeds were planted per station and the crop thinned to one plant per station at 2 WACE.

Determination of weed density and biomass

At 3, 6 and 9 weeks after crop emergence (WACE) and before each weeding, weed density (number m^{-2}) and biomass (g m^{-2}) were measured. Five quadrats measuring 30 × 30 cm were randomly placed in each plot. Weeds in the quadrat were identified and counted by species using the weed identification book developed by Makanganise and Mabasa (1999). The number of horizontal stems shoots within a quadrat were counted for grass weeds with stoloniferous growth habit. The counted weed species were cut at ground level and packed in brown paper bags. Harvested weeds were oven-dried at 70 °C for 48 h (Reeb and Milota 1999) and then weighed for biomass using a digital scale.

Determination of maize height and grain yield

Maize harvesting was done in May for each cropping season. The crop was harvested after attaining physiological maturity and dryness (±16% moisture content). Before maize harvesting, plant and ear height were measured with a tape measure. Maize plants were hand-harvested from the net plot (1.8 × 2 m, 3.6 m^2) consisting of two central rows. 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 Digital Moisture Meter was used to measure grain moisture content, and yield was adjusted to 12.5% moisture content. Maize yield parameters measured and recorded at the shelling stage were ear length and the number of rows cob^{-1}.

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) with GenStat Discovery 14 (VSN International 2011) to determine the effects of SOC, fertiliser management, and weeding regime on weed density, weed biomass and grain yield of maize. The fixed and random model used to analyse weed density, weed biomass, and maize yield was:

$$Y_d = a + BL + SOC + FM + WF + S_j$$

where Y_d = is crop yield or weed density or biomass; a = fixed effects model constant term; BL = block; SOC = soil organic carbon; FM = fertiliser management; WF = weeding frequency; S_j = season (random model).

Principal component analysis (PCA) was used to establish the relationship between season, SOC, FM and WR using CANOCO 5 (Ter Braak and Simlauer 2012). The PCA was the most appropriate technique because weed density had a linear relationship with environmental variables with a gradient of 3.9 SD units (Smilauer and Lepš 2014). Weed density data was further examined using the principal response curves (PRC) technique to establish the effect of the sampling period (weeding regime) on weed density, with SOC and fertiliser management as variables. PRC are suitable for repeated measures and designed to test the effects of treatments and their changes with time (Whitehouse et al. 2014). The Monte Carlo method was performed on the first principal component axis (i.e. SOC content) of the PCA to test whether the PRC generated by the analysis had significant variance. Results are presented only for PRC when SOC and fertiliser management significantly ($p \leq 0.05$) affected weed density. Species densities between −0.5 and 0.5 on the PRC scale were excluded for further statistical analysis as they had little effect (Whitehouse et al. 2014). The weed species with an absolute density score above 0.5 were *Nichandria physaloides*, *Eleusine indica*, *Cyperus* sp. and *Richardia scabra.* These weed species were analysed using linear mixed-effects model analysis (REML), and mean values were separated using standard error of the difference when the *F*-test had a significant treatment effect at $p \leq 0.05$.

Partial budget analysis

The partial budget and net benefit were calculated with the partial budget method of CIMMYT (1988). Variable costs associated with weeding, specifically herbicide and labour, were compared, and those costs that varied compared only with the unweeded controls. The costs that varied were the price of herbicide S-Metolachlor (960 g a.i., US$12 litre^{-1}) and the labour charge (rate US$3.00 per 8-hour day). The maize grain producer price used was US$390 tonne^{-1} (2016/17 producer price). The costs of tillage, fertilisers, insecticides, harvesting and transport did not vary among the treatments and thus were not included in the cost analysis. Maize grain yield was adjusted down by 15% based on the assumption of variation in crop management and post-harvest loss in farmer fields when compared with experiments managed by researchers (Odendo et al. 2006). The net benefit ratio (NBR) was calculated by dividing the expected total benefit hectare^{-1} by total weeding costs that varied.

Results

Weed density, weed biomass, maize plant height and maize grain yield were significantly (p = 0.05) affected by SOC status, fertiliser management (FM), weeding regime (WR) and some two-way interactions, as outlined in Table 2.

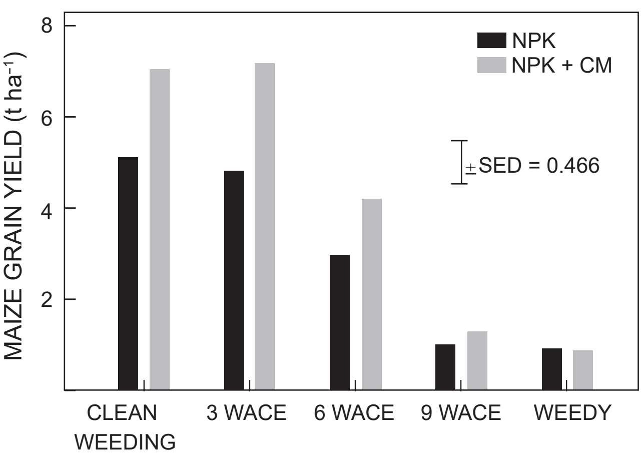

Figure 2: Interaction of fertiliser management and weeding regime (FM × WR) on maize grain yield on two smallholder farms with varying SOC in eastern Zimbabwe

Maize grain yield

Maize grain yield was significantly ($p \leq 0.05$) affected by SOC, FM, WR (Table 3) and the interaction of FM × WR (Figure 2). The FM × WR interaction significantly ($p \leq 0.001$) affected maize grain yield, as depicted in Figure 2. In early frequently weeded treatments, significantly higher maize grain yield was recorded with application of NPK + CM compared with sole use of NPK. In contrast, late and reduced weeding intensity (twice) at 6 and 9 WACE, and once at 9 WACE, reduced maize yields by 40% and 88%, respectively. Late-weeded treatments recorded no significant difference between FM treatments on maize grain yield. The interaction revealed that delayed weeding nullifies any yield gains that might accrue as an outcome of fertiliser management (Figure 2).

Mean grain yield for the two seasons significantly

Table 3: The effects of soil organic carbon (SOC) content, fertiliser management (NPK alone or NPK + cattle manure) and weeding regime on maize yield parameters, as tested on two smallholder farms in eastern Zimbabwe. Treatments that share the same letter in each section are not significantly different at $p > 0.05$; ns = not significant. LSD = least significant difference; WACE = weeks after crop emergence. SED = standard error of difference

	Mean plant height (m)	Mean cob length (cm)	Mean no. grain rows cob^{-1}	Maize grain yield (t ha^{-1})
SOC				
Low SOC, 4.0 g kg^{-1} soil	1.51^{a}	9.50^{a}	13.64	2.83^{a}
High SOC, 6.5 g C kg^{-1} soil	2.34^{b}	14.60^{b}	13.64	4.26^{b}
p-value	<0.001	<0.001	ns	<0.001
SED	0.03	0.33	0.22	0.21
LSD	0.06	0.65	0.44	0.41
Fertiliser management				
NPK	1.91	11.33^{a}	13.68	2.97^{a}
NPK + cattle manure	1.94	12.74^{b}	13.6	4.12^{b}
p-value	ns	<0.001	ns	<0.001
SED	0.03	0.33	0.22	0.21
LSD	0.06	0.65	0.44	0.41
Weeding regime				
Clean weeding	2.05^{c}	14.25^{c}	14.69^{d}	6.07^{c}
3 WACE (weeding thrice)	1.94^{bc}	14.10^{c}	13.65^{cd}	5.99^{c}
6 WACE (weeding twice)	1.92^{bc}	12.80^{b}	13.50^{bc}	3.59^{b}
9 WACE (weeding once)	1.91^{b}	9.74^{a}	13.30^{ab}	1.17^{a}
Weedy check	1.83^{a}	9.30^{a}	13.05^{a}	0.90^{a}
p-value	<0.001	<0.001	<0.001	<0.001
SED	0.05	0.52	0.35	0.33
LSD	0.09	1.03	0.69	0.66

Table 2: Summary of ANOVA for the linear mixed-effects model (REML) output explaining the variability of weed density, weed biomass, and maize grain yield. Pr > *F* is probability of a greater *F* value or *p*-value

Source of variation	df	Weed density		Weed biomass		Maize grain yield	
		F-value	Pr. > *F*	*F*-value	Pr. > *F*	*F*-value	Pr. > *F*
Blocking	2	0.23	0.791	0.02	0.984	1.13	0.347
Soil organic carbon (SOC)	1	17.44	<0.001	6.85	0.009	47.26	<0.001
Fertiliser management (FM)	1	7.87	0.005	1.59	0.208	30.51	<0.001
Weeding regime (WR)	4	52.25	<0.001	28.00	<0.001	115.01	<0.001
SOC × FM	1	0.42	0.517	0.20	0.659	0.00	0.952
SOC × WR	4	2.83	0.025	1.02	0.397	0.55	0.702
FM × WR	4	0.75	0.558	0.46	0.767	4.96	<0.001
SOC × FM × WR	4	0.07	0.990	0.06	0.994	0.43	0.789

increased to 4.3 ± 0.21 t ha^{-1} from high SOC (6.4 g kg^{-1}) as compared with 2.8 ± 0.21 t ha^{-1} from low SOC (4.0 g kg^{-1}) (Table 3). Co-applying NPK + CM significantly increased the maize grain yield by 1.36-times compared with NPK only (Table 3). WR significantly ($p \leq 0.001$) affected maize grain yield. Higher (6 t ha^{-1}) maize grain yield was obtained from early frequently weeded treatments. However, late and less-frequent (twice) weeding at 6 and 9 WACE and very-late weeding (once) at 9 WACE decreased maize grain yield. Weeding once at 9 WACE was similar to the unweeded control treatment, with yield decline (Table 3).

Maize plant height

Maize height at the harvesting stage was significantly ($p \leq 0.001$) affected by SOC content and WR (Table 3). No significant interaction was recorded. Maize plants from the field with the highest SOC content (6.4 g kg^{-1}) were 1.5-times taller compared with plants in the field with low SOC (4.0 g kg^{-1}). Taller maize plants were observed from treatments that were early and frequently weeded. Very-late and less-frequent weeding (that is, once at 9 WACE) and the unweeded control treatment reduced maize height by 6% and 10%, respectively (Table 3). However, FM did not significantly affect maize height.

Maize cob/ear length and mean number of grain rows cob^{-1}

Soil organic carbon, fertiliser management, and weeding regime significantly affected mean cob/ear length ($p \leq 0.001$) although no significant interactions were observed. Maize cob/ear length significantly increased by 1.54-times in soil with high SOC (6.4 g kg^{-1}) as compared with low SOC (4.0 g kg^{-1}) (Table 4). Treatments co-applied with NPK + CM increased cob length by 12% compared with sole NPK (Table 4). Compared with early and frequent weeding, late to very-late, less-frequent weeding and the unweeded control treatment significantly reduced cob length by 9%, 31% and 34%, respectively. Weeding once at 9 WACE was significantly different from the unweeded control (Table 3).

Early and frequent weeding increased the number of rows cob^{-1} by 8% compared with the unweeded control. However, SOC and FM did not affect the mean number of rows cob^{-1} (Table 3).

Effects of SOC, fertiliser management and weeding frequency on weeds

Twenty weed species were identified and recorded from the two smallholder experimental farms with contrasting SOC. Broadleaf weeds constituted 80% of the weed species, whereas 15% and 5% of the species were grasses and sedges, respectively (Figure 3).

Principal component analysis (PCA) ordination on environmental factors and weeds

The unconstrained PCA provided evidence of the association between SOC content, FM and WR on weed composition (Figure 3). The PCA biplot accounted for 73.3% of the total variance in weed composition. The horizontal Axis 1 accounted for 63.3% (eigenvalue of 0.6) while the Axis 2 accounted for 10.0% (eigenvalue = 0.1) of the cumulative fitted variation. Soil organic carbon content and weeding frequency had a strong influence on weed composition, whereas FM was not significant ($p \leq 0.05$). The weeds associated with low SOC

Table 4: The effects of soil organic carbon (SOC) content, fertiliser management, and weeding regime on total weed density and biomass, and the advanced densities (results of principal response curves [PRC] technique) of *Nichandria physaloides*, *Eleusine indica*, *Cyperus* sp. and *Richardia scabra*, at the two smallholder farms in eastern Zimbabwe. Treatments that that share the same letter in each section of the column are not significantly different at $p > 0.05$. ns = not significant; LSD = least significant difference; SED = standard error of difference; WACE = weeks after crop emergence

Parameter	Total weed density (no. m^{-2})	Total weed biomass (g m^{-2})	PRC weed densities			
			N. physaloides	*E. indica*	*Cyperus* sp.	*R. scabra*
SOC						
Low SOC, 4.0 g C kg^{-1} soil	100.2^{a}	48.6^{a}	7.2^{a}	4.9^{a}	5.2^{a}	15.8
High SOC, 6.5 g C kg^{-1} soil	152.0^{b}	77.7^{b}	20.9^{b}	7.8^{b}	7.5^{b}	18.7
p-value	<0.001	0.009	<0.001	<0.001	0.002	ns
SED	12.42	11.13	2.45	0.81	0.71	2.9
LSD	24.42	21.90	4.80	1.60	1.40	5.60
Fertiliser management						
NPK	108.7^{a}	56.1	8.8^{a}	5.1^{a}	5.7	18.8
NPK + cattle manure	143.5^{b}	70.2	19.2^{b}	7.6^{b}	7.0	15.7
p-value	0.005	ns	<0.001	0.002	ns	ns
SED	12.42	11.13	2.45	0.81	0.71	2.86
LSD	24.42	21.90	4.80	1.60	1.40	5.60
Weed regime						
Clean weeding	0^{a}	0^{a}	0.0^{a}	0.0^{a}	0.0^{a}	0.0^{a}
3 WACE (weeding thrice)	56.7^{b}	10.0^{b}	9.2^{b}	2.7^{b}	2.5^{b}	5.8^{b}
6 WACE (weeding twice)	127.3^{c}	38.5^{c}	13.1^{c}	6.8^{c}	7.7^{c}	15.9^{c}
9 WACE (weeding once)	241.5^{d}	132.7^{d}	24.7^{d}	10.5^{d}	11.9^{d}	41.2^{d}
Weedy check	235.0^{d}	134.5^{d}	22.9^{d}	11.8^{d}	9.8^{d}	43.5^{d}
p-value	<0.001	0.001	<0.001	<0.001	<0.001	<0.001
SED	19.63	17.60	3.87	1.28	1.12	4.52
LSD	38.62	34.63	7.60	2.50	2.20	8.90

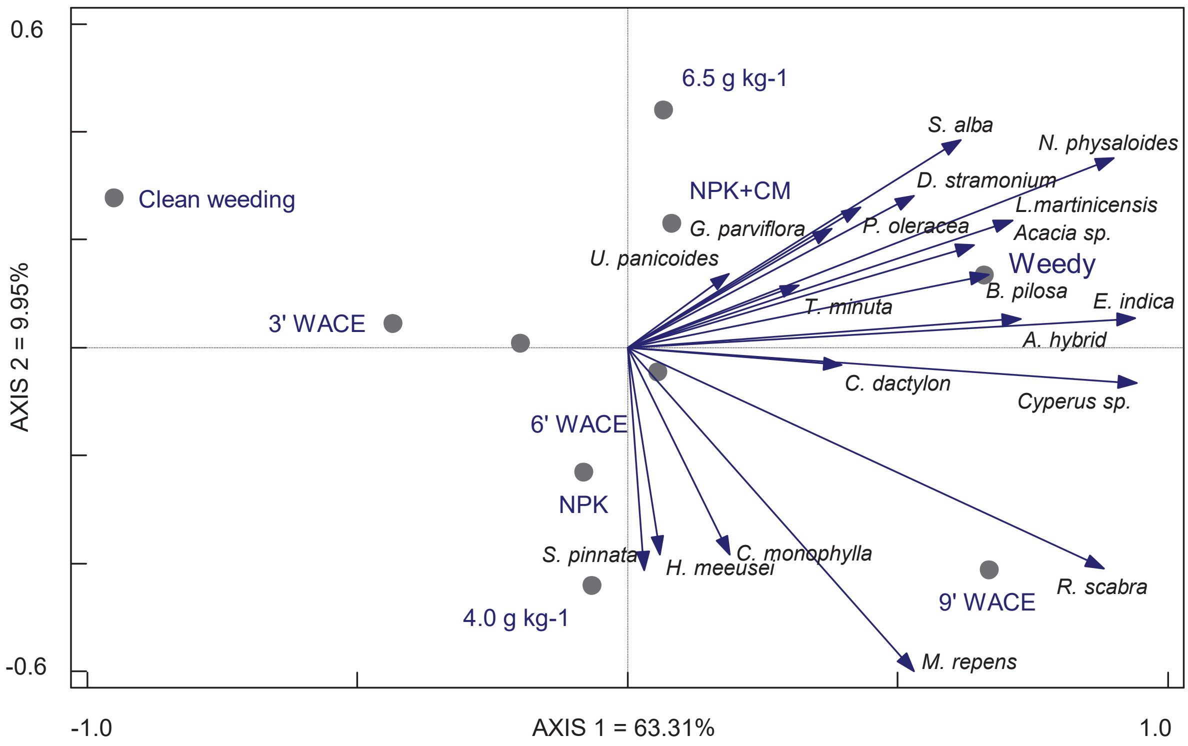

Figure 3: Principal component analysis (PCA) projecting weed species data as influenced by environmental factors, for two smallholder farms in eastern Zimbabwe. Biplot of SOC content, fertiliser management (FM), and weeding regime (WR) in relation to weed species

(4.0 g kg^{-1}) were *Cleome monophylla*, *Cynodon dactylon*, *Cyperus* species, *Hibiscus meeusei*, *Melenis repens*, *Richardia scabra* and *Schkuhria pinnata*. Weeds strongly associated with high SOC (6.4 g kg^{-1}) were *Acacia* sp., *Amaranthus hybridus*, *Bidens pilosa*, *Eleusine indica*, *Datura stramonium*, *Nicandra physaloides*, *Sida alba* and *Luecus martinicensis* (Figure 3).

The principal response curves (PRC) of weeds to sampling periods

Weed species density was strongly linked to high SOC (6.4 g kg^{-1}) compared with low SOC (4.0 g kg^{-1}) at 3 WACE, when weeds were counted before the first weeding operation (Figure 4a). The PRC Monte Carlo permutation tests revealed significant effects of SOC (F = 18.2, p = 0.018) and WR (F = 84.6, p = 0.002) on weed density (Figure 4a,d); however, FM had no significant effect.

According to the PRC Monte Carlo permutation tests, the densities of *Cyperus* sp., *E. indica*, *R. scabra* and *N. physaloides* were significantly ($p \leq 0.05$) affected by SOC content and WR (Figure 4b,e). *Nicandra physaloides* recorded the highest negative species weight on the PRC scale. The weed species were further analysed using REML (Table 4); however, 80% of the weed species whose PRC scale fell in between −0.5 and 0.5 were not influenced by SOC status, and were therefore excluded for further statistical analysis (Figure 4c).

Weed density and weed biomass

Total weed density was significantly ($p \leq 0.05$) affected by SOC content, WR, and the interaction of the SOC × WR ($p \leq 0.03$). However, FM only influenced weed density but did not affect total weed biomass.

The change in SOC content from low to high significantly increased total weed density and weed biomass by 52% and 60%, respectively (Table 4). Treatments co-applied with NPK + CM increased total weed density by 32% compared with sole NPK. However, total weed biomass was not affected by FM (Table 4).

The interaction of SOC × WR significantly affected total weed density ($p \leq 0.03$). Weed density in the first 3 WACE was not significantly different between the SOC and FM treatments. However, as weed removal was delayed, a sharp increase in weed density was observed from high SOC content and with NPK + CM fertiliser treatment compared with weed density from low SOC content (Figure 5a).

Compared with early and frequent weeding (thrice), late and less-frequent weeding (twice), and very-late weeding (once) at 9 WACE increased total weed density by 2.25 and 4.26 times, respectively. Weeding once at 9 WACE was not significantly different from the unweeded control treatment. Total weed biomass also increased by 3.9- and 13.4-times in late, less-frequent weeding (twice), and very-late weeding (once) compared with early and frequent (thrice) weeding (Table 4).

The PRC scale revealed significantly higher densities of *N. physaloides*, *E. indica* and *Cyperus* sp. from high SOC (6.4 g kg^{-1}) compared with low SOC (4.0 g kg^{-1}), while *R. scabra* density was not affected (Table 5). Co-applying NPK + CM significantly increased densities of *N. physaloides* and *E. indica*, while *Cyperus* sp. and *R. scabra* were not affected by FM (Table 4).

The weeding regime significantly affected the density of the main weed species as depicted by the PRC scale in Figure 4b. Late, less-frequent weeding increased densities of *N. physaloides* (by 1.4-times), *E. indica*, (2.5-times), *R. scabra* (2.7-times) and *Cyperus* sp. (3.8-times) compared with early frequent weeding. Very-late and single weeding at 9 WACE further increased the densities of *N. physaloides, E. indica*, *Cyperus* sp. and *R. scabra* by 2.7-, 3.9-, 4.8- and 7.1-times, respectively, compared with early frequently weeded treatments (Table 4).

Nichandria physaloides densities were significantly ($p \leq 0.02$) affected by the SOC × WR interaction (Figure 5b). Lower *N. physaloides* densities were recorded from low SOC (4.0 g kg^{-1}) compared with from high SOC (6.4 g kg^{-1}). In both fields, *N. physaloides* densities were low when early and frequent weeding was done. In contrast, a sharp increase in *N. physaloides* was observed from high SOC (6.4 g kg^{-1}) when late and infrequent weeding was done (Figure 5b).

Eleusine indica densities were significantly affected by SOC × FM (Figure 5c). Higher *E. indica* density was recorded from high (6.4 g kg^{-1}) compared with low (4.0 g kg^{-1}) SOC. A sharp increase in *E. indica* densities was recorded from NPK + CM under low SOC content. In contrast, under high SOC content (6.4 g kg^{-1}), *E. indica* densities were not significantly different between NPK + CM and sole NPK treatments (Figure 5c).

The interaction FM × WR significantly affected the density of *N. physaloides* (Figure 6a). Significantly higher *N. physaloides* density was observed in NPK + CM compared with the NPK treatment. Clean weeding (herbicide + hoe) and early frequent weeding (three times) reduced *N. physaloides* densities under both fertiliser regimes. However, in late and less-frequent weeding, a sharp increase of *N. physaloides* density was observed with NPK + CM compared with NPK treatment (Figure 6a).

The interaction FM × WR also significantly affected *E indica* density (Figure 6b). Higher densities of *E indica* were found with NPK + CM as compared with NPK. In both fertiliser treatments, *E indica* density was lower with clean weeding (herbicide + hoe) and early frequent weeding. On the contrary, there was a significant sharp increase in *E. indica* NPK + CM compared with the NPK fertiliser treatment in late, less frequently weeded treatments (Figure 6b).

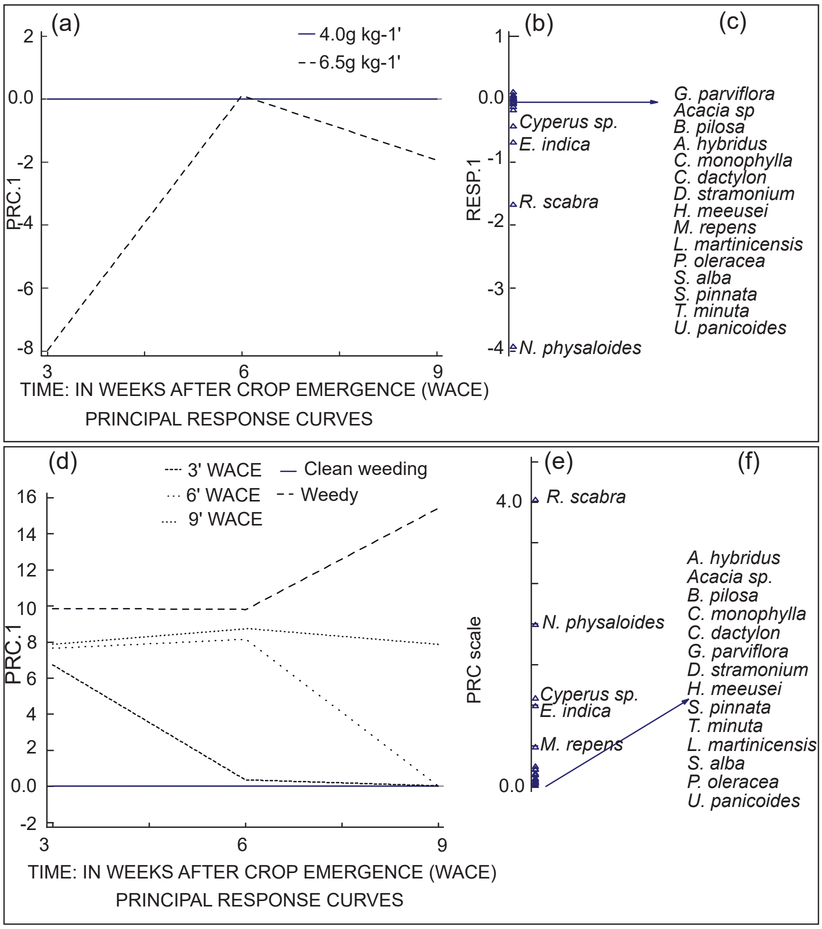

Figure 4: Principal response curves (PRC) showing (a) the response of weeds to high (6.4 g kg^{-1}) soil organic carbon (SOC) content relative to a more-standard low (4.0 g kg^{-1}) SOC content, over sampling periods at 3, 6 and 9 weeks after crop emergence (WACE). (b) PRC showing weed species are strongly influenced by SOC content. (c and f) Weed species with scores between −0.5 and 0.5 on the PRC scale were not considered for further analysis. (d) PRC of weeds to weeding regime relative to standard clean weeding over sampling periods at 3, 6 and 9 WACE. (e) PRC showing weed species strongly influenced by the weeding regime on two smallholder farms in eastern Zimbabwe, 2015–2017

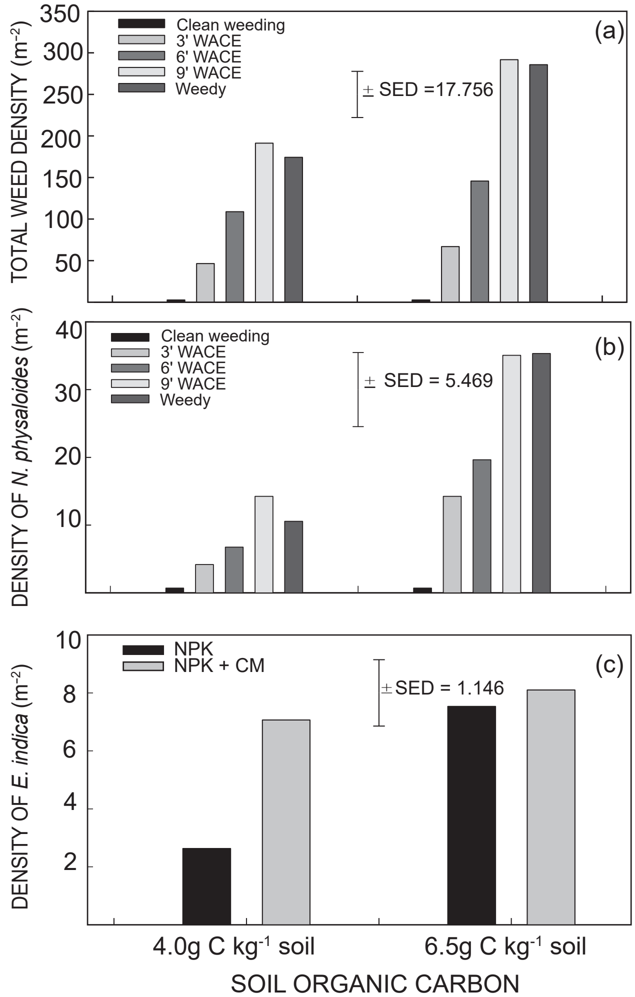

Figure 5: Influence of the soil organic carbon and weeding regime interaction (SOC × WR) on (a) total weed density, (b) density of *Nicandra physaloides*; and (c) the interaction of SOC × fertiliser management (FM) on the density of *Eleusine indica*, at two smallholder farms with varying SOC in eastern Zimbabwe

Partial budget and net benefit ratio (NBR) analysis

High maize grain yield (>4.5 t ha^{-1}) recorded from 6.4 g kg^{-1} SOC content gave a higher (>6.8) net benefit ratio compared with 4.0 g kg^{-1} SOC content (Table 5). Clean weeding (herbicide + hoe) gave the highest net benefit ratio on both SOC levels depending on the FM treatment. NPK + CM recorded higher NBR compared with NPK on each farm. This was followed by an early frequent (thrice) weeding at 3, 6 and 9 WACE. However, late less-frequent weeding, that is twice at 6 and 9 WACE, and very-late single weeding at 9 WACE recorded a negative NBR in 4.0 g kg^{-1} SOC and low NBR in 6.4 g kg^{-1} SOC (Table 5).

Discussion

Grain yield of maize

The study focused on the influence of SOC, fertiliser management, and weeding regime on grain yield of maize. There was a positive link between SOC and maize grain yield. Maize grain yield increased by 13% as the SOC content changed from low (4.0 g kg^{-1}) to high (6.4 g kg^{-1}). The results are in line with the findings of Boling et al. (2008) and Ogwuike et al. (2014) who reported an increase in rice (*Oryza sativa*) yield by 17% and 27%, respectively, on lower catena position with high SOC content compared with on upper catena. The increase in maize grain yield in high SOC content (6.4 g kg^{-1}) can be attributed to the inherent nutrient supply associated with increased SOC levels. Soil organic carbon improves the physicochemical properties, biological activities and crop productivity (Davis 2007; Shibabaw and Alemeyehu 2015).

The combined application of NPK + CM increased the grain yield of maize by 1.46-times compared with using NPK only. This result confirms earlier research findings by Zingore et al. (2007), Rusinamhodzi et al. (2013), Kurwakumire et al. (2015) and Kafesu et al. (2018), who reported an increase in maize productivity when organic manures are co-applied with NPK fertiliser treatments. An increase in maize grain yield from the NPK + CM treatment may be in part due to increased nutrient uptake by the maize crop. Combining NPK + CM ensures a steady nutrient supply during the crop growth cycle. Nutrients from inorganic fertilisers are unusually readily available for crop uptake, while the slow-nutrient-release nature of organic manures ensures a steady nitrogen supply during the crop development stages (Blackshaw 2005). Besides, Nikoli (2011) reported that the integration of organic manures and inorganic fertilisers improved micronutrient uptake by the crop, thereby increasing maize productivity.

Organic manures ameliorate soil pH (Nyamangara et al. 2000), enhance the build-up of organic carbon (Kihanda et al. 2006), improve soil physicochemical properties (Nyamangara et al. 2011), increase soil biological activities (Nezomba et al. 2015) and increase crop productivity. A long-term experiment (>8 years) Kihanda et al. (2006) revealed a build-up of SOC with repeated organic manure applications, which enhanced uptake of N and P by the maize crop in low-fertilised soils.

Our results partly explain a lower maize-yield response to inorganic fertiliser in low (4.0 g kg^{-1}) SOC content. Less fertile soils require the use of organic amendments to rehabilitate them before any meaningful crop returns can be realised from inorganic fertiliser application (Chikowo et al. 2004). More so, continuous use of chemical inorganic fertilisers without lime use increases soil acidity, pollution of water bodies, and affects soil physical properties (Mariaselvam et al. 2015). Cattle manure becomes a cheap and alternative option for the management of soil pH under the smallholder farming sector.

The grain yield of maize significantly increased by more than 6 t ha^{-1} in clean weeding (herbicide + hoe), early and frequently (thrice) weeded treatments. Our results are in line with findings by Chivinge and Mariga (1998), Doğan et al. (2004) and Mavunganidze et al. (2016), who reported an increase in grain yield of maize in early (4 WACE) weeded plots. Maize is sensitive to weed competition during the first 6 weeks of crop development in the subtropical region (Mashingaidze et al. 2009). Depending on weed seed-bank status, weed infestation during the early stages of maize development, both directly and indirectly, hindered crop

Table 5: Partial budget analysis: Adjusted maize grain yield is 15% of the yield attained by research at the two smallholder farmers; Total gross income = Adjusted maize grain yield × Producer price tonne^{-1} (US $390); Total variable costs = total weeding costs that varied were herbicide S-Metolachlor 1.5 l ha^{-1} and hoe weeding ha^{-1}; Net benefit = Total gross income – Total weeding cost that varied; Net benefit = Net benefit divided by Total weeding cost that varied. SOC = soil organic carbon; WACE = weeks after crop emergence

Weeding treatments	4.0 g kg^{-1} SOC		6.4 g kg^{-1} SOC	
	NPK	NPK + cattle manure	NPK	NPK + cattle manure
	Adjusted maize grain yield (tonne ha^{-1}) (15%)			
Clean weeding	3.421	5.290	5.242	6.695
At 3 WACE (weeding thrice)	3.678	5.239	4.501	6.957
At 6 WACE (weeding twice)	1.793	2.983	3.273	4.154
At 9 WACE (weeding once)	0.364	0.586	1.406	1.638
	Total gross income			
Clean weeding	$1 334.29	$2 062.92	$2 044.36	$2 610.89
At 3 WACE (weeding thrice)	$1 434.40	$2 043.03	$1 755.29	$2 713.33
At 6 WACE (weeding twice)	$699.13	$1 163.23	$1 276.61	$1 620.04
At 9 WACE (weeding once)	$141.88	$228.40	$548.30	$638.80
	Total variable costs			
Clean weeding	$138.00	$138.00	$138.00	$138.00
At 3 WACE (weeding thrice)	$225.00	$225.00	$225.00	$225.00
At 6 WACE (weeding twice)	$240.00	$240.00	$240.00	$240.00
At 9 WACE (weeding once)	$180.00	$180.00	$180.00	$180.00
	Net benefit			
Clean weeding	1 196.29	1 924.92	1 906.36	2 472.89
At 3 WACE (weeding thrice)	1 209.40	1 818.03	1 530.29	2 488.33
At 6 WACE (weeding twice)	459.13	923.23	1 036.61	1 380.04
At 9 WACE (weeding once)	−38.12	48.40	368.30	458.80
	Net benefit ratio			
Clean weeding	8.67	13.95	13.81	17.92
At 3 WACE (weeding thrice)	5.38	8.08	6.80	11.06
At 6 WACE (weeding twice)	1.91	3.85	4.32	5.75
At 9 WACE (weeding once)	−0.21	0.27	2.05	2.55

performance, causing yield declines by 34–90% (Deen et al. 2003). Apart from competition for growth resources, weeds can directly affect crops by parasitising the maize crop, releasing toxic allelochemicals into the environment which suppress growth and development of the crop (Bhadoria 2011; Rugare 2018).

Late and infrequent weeding reduced grain yield of maize by 40–88%. Late (6 WACE), and very-late (9 WACE) weed removal nullified the benefits accrued from organic manures alongside NPK fertiliser use. These results were in line with finding by Chivinge and Mariga (1998) and Workayehu, (2011) who observed that the benefits of inorganic fertiliser applications depended on effective weed removal during the critical stages of crop growth for weed competition. The decrease in maize grain yield presumably was caused by weed–crop competition for growth resources during the critical maize development stages.

Weed density and weed biomass

Fertiliser management and weeding regime strongly influenced weed density and weed biomass on the two smallholder farms with varying SOC content. Our results reveal an increase in total weed density and weed biomass, by 52% and 60%, respectively, in high (6.4 g kg^{-1}) SOC. The effect of fertiliser on weed density and biomass was earlier reported by Johnson and Kent (2002), Dvorsky et al. (2011) and Touré et al. (2014). Increased weed density and weed biomass in 6.4 g kg^{-1} SOC content can be attributed to improved moisture and nutrient uptake. Touré et al. (2014) and Jiang et al. (2014) revealed that weeds tend to benefit more from improved soil fertility and moisture because of greater and more-efficient nutrient extraction from the soil. Contrary to our findings, Boiling et al. (2008) found no significant differences in weed composition across fertility domains in a rice crop across the toposequence.

Combined application of NPK + CM increased total weed density by 32%, and the weed species whose density increased according to the PRC scale were *N. physaloides* and *E. indica*. These results were similar to earlier findings by Efthimiadou et al. (2012) who reported an increase in weed density and weed biomass from organic amendment treatments in baby corn. Similarly, Blackshaw and Brandt (2009) recorded an increase in *Malva pusilla* and *Avena fatua* with luxurious P (phosphophilous) uptake, and the N (nitrophilous) weed species were *Chenopodium album*, *Amaranthus retroflexus* (L.) and *Kochia scoparia* (L.). These weeds were found to be highly competitive in well-fertilised fields.

Our study, therefore, confirmed earlier findings that the use of organic and inorganic fertilisers in agro-systems not only increases grain yield of maize but increases the competitive nature of weeds whose nutrient uptake is more efficient when compared with the crops (Chikuvire et al. 2013). Fertilisers applied in cropping systems also break weed-seed dormancy and initiate weed seedling emergence (Karimmojeni et al. 2011), promote weed growth and competitiveness

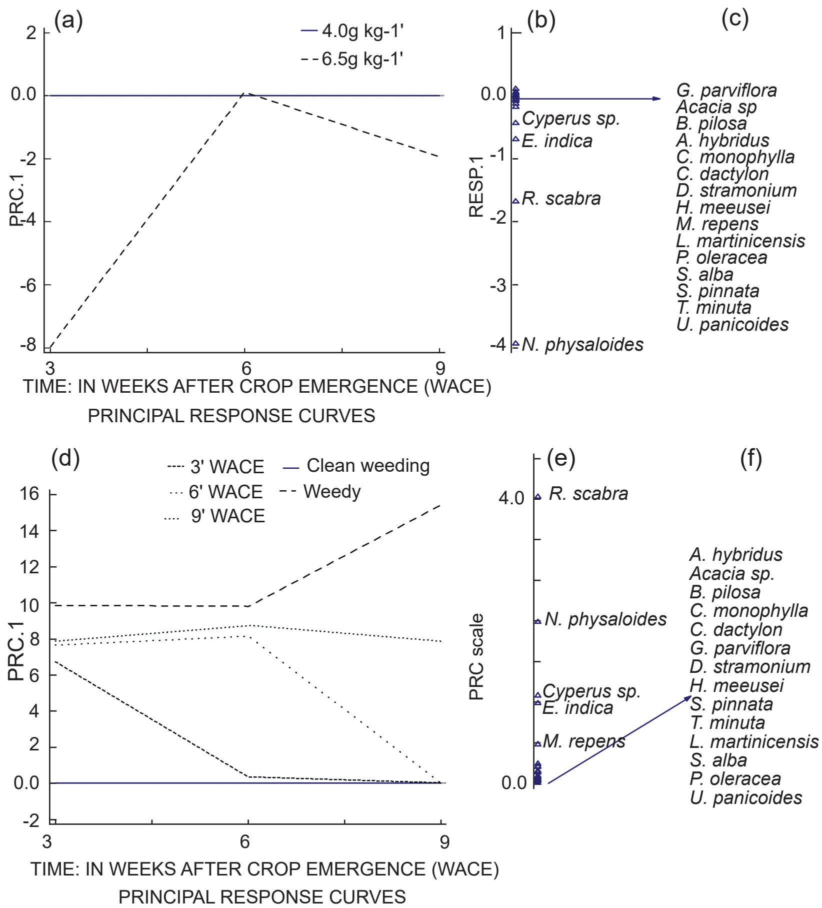

Figure 6: Influence of fertiliser management and weeding regime interaction (FM × WR) on (a) *Nicandra physaloides* and (b) *Eleusine indica* at two smallholder farms with varying SOC in eastern Zimbabwe

(Mohammadi 2012), increase weed biomass accumulation (Blackshaw et al. 2002), and cause prolific weed seed production (Blackshaw and Brandt 2009).

The gradual and slow release of nutrients such as nitrogen by organic matter benefited weeds, mainly owing to their efficient nutrient uptake compared with the crops (Blackshaw 2005). More so, organic manure improves the soil's physical and chemical properties, and such conditions were found to be favourable for weed growth and competitiveness (Mohammadi 2012). Otinga et al. (2013) observed vigorous weed growth in organic manure applied treatments.

Furthermore, previous research revealed that cattle manure contains a considerable number of potentially germinable weed seeds (Materechera and Modiakgotla 2013). For instance, Cook et al. (2007) found that 25% of weed seeds were intact in cattle manure. Our findings also concur with earlier work by Rupende et al. (1998) and Mtambanengwe et al. (2015) who recorded *A. hybridus*, *E. indica*, *C. dactylon*, *N. physaloides* and *A. hispidium* as the most dominant weeds in cattle manure treatments.

Economic analysis

Early and frequently weeded treatments increased the net benefit ratio (NBR) while late weed removal resulted in a negative NBR. Our findings are in-line with Shumba et al. (1989) who reported that weeding of maize 30 days after crop emergence in the high-potential area of Mangwende communal (Murehwa District, eastern Zimbabwe) resulted in a 28% decline in maize grain yield. Our results also confirm findings by Workayehu, (2011) who reported a decrease in broadleaf density in herbicide + hand-weeding treatments, while this translated to high wheat-grain yield.

Early and frequent weeding reduce weed–crop competition and, here, increased maize grain yield to >5 t ha^{-1}. The increase in grain yield also increased gross income and offset the production variable costs, thereby increasing the crop gross margin. In contrast, late weeding increase weed–crop competition and reduced maize grain yield to <1 t ha^{-1} and gave negative gross-margin values in fields with low SOC status. Weed infestations during early stages (3–6 WACE) of maize development, directly and indirectly, impede crop performance (Mashingaidze et al. 2009). In some cases, severe yield declines of up to 100% have been reported in some communal area fields in Zimbabwe (Mandumbu et al. 2017), and this impact is more severe in soils with low fertility. Our results suggest that the clean weeding (herbicide + hoe) practice can ease the labour shortage often experienced by smallholder farmers during the early part of the season, when demand for family labour is high. This weed-management option showed an increase in the grain yield of maize and in the NBR.

Conclusions

This study revealed that weed density, weed biomass, and the grain yield of maize were each strongly linked to the initial SOC content. The combined use of NPK + CM increased maize grain yield and weed density compared with sole NPK treatment. However, weed biomass was not affected by fertiliser management. The benefits of integrating NPK + CM and initial high SOC were realised only under the early and frequent weeding regime. Late and infrequent weeding and very late weeding reduced maize grain yield and nullified the yield benefits accrued from improved fertiliser management.

The results also revealed an increase in weed density and weed biomass as SOC changed from low (4.0 g kg^{-1}) to high (6.4 g kg^{-1}). In both fields, early and frequent weeding reduced weed density and weed biomass and increased maize grain yield as well as the NBR. Furthermore, it is recommended that smallholder farmers combine herbicide + hoe weeding during the early stages of maize development to avert labour bottlenecks, a situation that often results in inadequate early weed control and, subsequently, poor crop performance and reduced yields.

Acknowledgments — We would like to acknowledge the facilities and assistance rendered by the University of Zimbabwe through IPNI, Marondera University of Agricultural Sciences and Technology for processing and analysing samples, and the Regional Universities Forum for capacity-building (RUFORUM) for proving financial assistance to buy reagents for the sample analysis (grant no. RU/2018/Post Doc/11).

ORCID iDs

Justin Chipomho – https://orcid.org/0000-0001-7733-7646
Cosmas Parwada – https://orcid.org/0000-0002-7960-4303
Joyful T Rugare – https://orcid.org/0000-0001-9573-3394
Stanford Mabasa – https://orcid.org/0000-0002-7115-271X
Arnold B Mashingaidze – https://orcid.org/0000-0001-9148-2858

References

Anderson JM, Ingram JS. 1993. *Tropical soil biology and fertility: a handbook of methods* (2nd edn). Wallingford, UK: CAB International.

Bhadoria PBS. 2011. Allelopathy: a natural way towards weed management. *American Journal of Experimental Agriculture* 1: 7–20.

Blackshaw RE. 2005. Nitrogen fertilizer, manure, and compost effects on weed growth and competition with spring wheat. *Agronomy Journal* 97: 1612–1621.

Blackshaw RE, Brandt RN. 2009. Phosphorus fertilizer effects on the competition between wheat and several weed species. *Weed Biology and Management* 9: 46–53.

Blackshaw RE, Brandt RN, Janzen HH. 2002. Weeds dine out on nitrogen and phosphorus. *Better Crops with Plant Food* 86: 20–22.

Boling AA, Tuong TP, Suganda H, Konboon Y, Harnpichitvitaya D, Bouman BAM, Franco DT. 2008. The effect of toposequence position on soil properties, hydrology, and yield of rainfed lowland rice in Southeast Asia. *Field Crops Research* 106: 22–33.

Bonsu K, Esterhuizen D. 2018. Zimbabwe: Grain and Feed Annual. The supply and demand for corn in Zimbabwe. GAIN Report No. 6/15/2018, USDA Foreign Agricultural Service.

Capinera JL. 2005. Relationships between insect pests and weeds: an evolutionary perspective. *Weed Science* 53: 892–901.

Chaumba J, Scoones I, Wolmer W. 2003. From *jambanja* to planning: the reassertion of technocracy in land reform in south-eastern Zimbabwe? *The Journal of Modern African Studies* 41: 533–554.

Chikowo R, Mapfumo P, Nyamugafata P, Giller KE. 2004. Maize productivity and mineral n dynamics following different soil fertility management practices on a depleted sandy soil in Zimbabwe. *Agriculture, Ecosystems, and Environment* 102: 119–131.

Chikuvire TJ, Karavina C, Parwada C, Maphosa BT. 2013. *Lantana camara* and *Tithonia diversifolia* leaf teas improve the growth and yield of *Brassica napus*. *African Journal of Agricultural Research* 8: 6220–6225.

CIMMYT (The International Wheat and Maize Improvement Center) (1988) From agronomic data to farmer recommendations: an economics training manual (completely revised Edn). Mexico D.F. Available at http://www.cimmyt.org/english/docs/manual/agronomic/manual/part_one.pdf.

Cook AR, JL Posner, JO Baldock. 2007. Effects of dairy manure and weed management on weed communities in corn on Wisconsin cash-grain farms. *Weed Technology* 21: 389–395.

Davis AS. 2007. Nitrogen fertilizer and crop residue effects on seed mortality and germination of eight annual weed species. *Weed Science* 55: 123–128.

Deen W, Cousins R, Warringa J, Bastiaans L, Carberry P, Rebel K et al. 2003. An evaluation of four crop:weed competition models using a common dataset. *Weed Research (Oxford)* 43: 116–129.

Doğan MN, ÜnayA, Boz Ö, Albay F. 2004. Determination of optimum weed-control timing in maize (*Zea mays* L.). *Turkish Journal of Agriculture and Forestry* 28: 349–354.

Efthimiadou A, Froud-Williams RJ, Eleftherohorinos I, Karkanis A, Bilalis DJ. 2012. Effects of organic and inorganic amendments on weed management in sweet maize. *International Journal of Plant Production* 6: 291–307.

Handiseni M, Sibiya J, Ogunlela V, Koomen I. 2008. Comparative study of the effect of different weed management strategies on disease severity and marketable yield of paprika (*Capsicum annuum* L.) in the smallholder farming sector of Zimbabwe. *Journal of Plant Protection Research* 48: 107–117.

Jiang M, Shen XP, Gao W, Shen MX, Dai QG. 2014. Weed seed-bank responses to long-term fertilization in a rice–wheat rotation system. *Plant, Soil and Environment* 60: 344–350.

Johnson DE, Kent RJ. 2002. The impact of cropping on weed species composition in rice after fallow across a hydrological gradient in West Africa. *Weed Research* 42: 89–99.

Kafesu NRC, Mazarura U, Gwenzi W, Snapp S, Zingore S. 2018. Comparative fertilization effects on maize productivity under conservation and conventional tillage on sandy soils in a smallholder cropping system in Zimbabwe. *Field Crops Research* 218: 106–114.

Karimmojeni H, Rashidi B, Behrozi D. 2011. Effect of different treatments on dormancy-breaking and germination of perennial pepperweed (*Lepidium latifolium*) (Brassicaceae). *Agriculture* 2: 50–55.

Kaur S, Kaur R, Chauhan BS. 2018. Understanding crop–weed–fertilizer–water interactions and their implications for weed management in agricultural systems. *Crop Protection* 103: 65–72.

Kurwakumire N, Chikowo R, Mtambanengwe F, Mapfumo P, Snapp S, Johnston A, Zingore S. 2014. Maize productivity and nutrient and water-use efficiencies across soil-fertility domains on smallholder farms in Zimbabwe. *Field Crops Research* 164: 136–147.

Kurwakumire N, Chikowo R, Zingore S, Mtambanengwe F, Mapfumo P, Snapp S, Johnston A. 2015. Nutrient management strategies on heterogeneously fertile granitic-derived soils in sub-humid Zimbabwe. *Agronomy Journal* 107: 1068–1076.

Makanganise A, Mabasa S. 1999. *A field guide to the identification of important weeds of arable lands in Zimbabwe*. Harare, Zimbabwe: Department of Research and Specialist Services.

Mandumbu R, Mutengwa C, Mabasa S, Mwenje E, Gotosa J, Munyati VT. 2017. The parasitic weeds scourge in northern Zimbabwe: effects of soil degradation, hosts and food-security implications to rural farmers. *Scientia Agriculturae* 20: 86–91.

Mariaselvam AA, Dandeniya WS, Indraratne SP, Dharmakeerthi RS. 2015. High C/N materials mixed with cattle manure as organic amendments to improve soil productivity and nutrient availability. *Tropical Agricultural Research* 25: 201.

Mashingaidze AB. 2004. Improving weed management and crop productivity in maize systems in Zimbabwe. PhD thesis, Wageningen University, The Netherlands.

Mashingaidze AB, Van Der Werf W, Lotz LAP, Chipomho J, Kropff MJ. 2009. Narrow rows reduce biomass and seed production of weeds and increase maize yield. *Annals of Applied Biology* 155: 207–218.

Masvaya EN, Nyamangara J, Nyawasha RW, Zingore S, Delve RJ, Giller KE. 2010. Effect of farmer management strategies on spatial variability of soil fertility and crop nutrient uptake in contrasting agro-ecological zones in Zimbabwe. *Nutrient Cycling in Agroecosystems* 88: 111–120.

Matarauka D, Samaz M. 2014. Organization of manure from Ruminant (cattle and goat) in Wedza smallholder farming area, Zimbabwe. *International Journal of Manures and Fertilizers* 3: 489–494.

Materechera SA, Modiakgotla LN. 2013. Cattle manure increases soil weed population and species diversity in a semi-arid environment. *Soth African Journal of Plant and Soil* 23: 21–28.

Mavunganidze Z, Madakadze IC, Nyamangara J, Mafongoya P. 2016. Influence of selected soil properties, soil management practices, and socio-economic variables on relative weed density in a hand hoe-based conservation agriculture system. *Soil Use and Management* 32: 433–445.

Mohammadi GR. 2012. Living mulch as a tool to control weeds in agroecosystems: a review. In: Price A (ed.), *Weed Control*. InTech. pp. 75–100.

Mtambanengwe F, Nezomba H, Tauro T, Chagumaira C, Manzeke M, Mapfumo P. 2015. Mulching and fertilization effects on weed dynamics under conservation agriculture-based maize cropping in Zimbabwe. *Environments* 2: 399–414.

Mtangadura TJ, Mtambanengwe F, Nezomba H, Rurinda J, Mapfumo P. 2017. Why organic resources and current fertilizer formulations in southern Africa cannot sustain maize productivity: evidence from a long-term experiment in Zimbabwe. *PLoS ONE* 12: 1–23.

Mugwira LM, Murwira HK. 1997. Use of cattle manure to improve soil fertility in Zimbabwe: past and current research and future research needs. Network Working Paper No. 2, Soil Fertility Network for Maized-based Cropping Systems in Zimbabwe and Malawi. Harare, Zimbabwe: CIYMMYT.

Munera-Echeverri JL, Martinsen V, Strand LT, Cornelissen G, Mulder J. 2020. Effect of conservation farming and biochar addition on soil organic carbon quality, nitrogen mineralization, and crop productivity in a light textured Acrisol in the sub-humid tropics. *PLoS One* 15: e0228717.

Nezomba H, Mtambanengwe F, Tittonell P, Mapfumo P. 2015. Point of no return? Rehabilitating degraded soils for increased crop productivity on smallholder farms in eastern Zimbabwe. *Geoderma* 239: 143–155.

Nyamangara J, Makarimayi E, Masvaya EN, Zingore S, Delve RJ. 2011. Effect of soil fertility management strategies and resource-endowment on spatial soil fertility gradients, plant nutrient uptake, and maize growth at two smallholder areas, north-western Zimbabwe. *South African Journal of Plant and Soil* 28: 1–10.

Nyamangara J, Mugwira LM, Mpofu SE. 2000. Soil fertility status in the communal areas of Zimbabwe in relation to sustainable crop production. *Journal of Sustainable Agriculture* 16: 15–29.

Nyamapfene K. 1991. A geographical overview of the soils of Zimbabwe and their agricultural potential. *Geographical Education University of Zimbabwe* 15: 63–73.

Odendo M, Ojiem J, Bationo A, Mudeheri M. 2006. On-farm evaluation and scaling-up of soil fertility management technologies in western Kenya. *Nutrient Cyclying in Agroecosystems* 76: 369–381.

Ogwuike P, Rodenburg J, Diagne A, Agboh-Noameshie AR, Amovin-Assagba E. 2014. Weed management in upland rice in sub-Saharan Africa: impact on labor and crop productivity. *Food Security* 6: 327–337.

Otinga AN, Pypers P, Okalebo JR, Njoroge R, Emong M, Six L et al. 2013. Field crops research partial substitution of phosphorus fertiliser by farmyard manure and its localised application increases agronomic efficiency and profitability of maize production. *Field Crops Research* 140: 32–43.

Reeb JE, Milota MR. 1999. Moisture content by the oven-dry method for industrial testing. In: Western Dry Kiln Association (ed), *Proceedings Western Dry Kiln Association 50th Meeting, Portland, Oregon, 1999*. pp 66–74. Available at https://ir.library.oregonstate.edu/concern/conference_proceedings_or_journals/fq977v782.

Rodenburg J, Johnson DE. 2013. Managing weeds of rice in Africa. In: Wopereis MCS, Johnson DE, Ahmadi N, Tollens E, Jalloh A. (eds), *Realizing Africa's rice promise*. pp 204–212.

Rugare JT. 2018. Allelopathic effects of green manure cover crops on the germination and growth of blackjack (*Bidens pilosa* L.) and goosegrass grass (*Eleusine indica* [L.] Gaertn). PhD thesis, Stellenbosch University, South Africa.

Rusinamhodzi L, Corbeels M, Zingore S, Nyamangara J, Giller KE. 2013. Pushing the envelope? Maize production intensification and the role of cattle manure in recovery of degraded soils in smallholder farming areas of Zimbabwe. *Field Crops Research* 147: 40–53.

Shibabaw A, Alemeyehu M. 2015. Council for Innovative Research. *Journal of Advances in Chemistry* 3: 267–274.

Sibhatu B. 2016. Review on *Striga* weed management. *International Journal of Life-Sciences Scientific Research* 2: 110–120.

Sikora E, Kemble J, Hagan A, Gazaway W. 2019. 'Nematode control in the home vegetable garden.' Alabama Cooperative Extension, Alabama A&M University, and Auburn University. Available at https://www.aces.edu/blog/topics/fruits-lawn-garden/nematode-control-in-the-home-vegetable-garden.

Tanner PD, Grant PM. 1963. *Soil fertility nutrient elements range for Zimbabwean soils: a laboratory guide*. Harare, Zimbabwe: Ministry of Agriculture.

Tibugari H, Chikasha T, Manyeruke N, Mathema N, Musara JP, Dlamini D et al. 2019. Poor maize productivity in Zimbabwe: can collusion in pricing by seed houses be the cause? *Cogent Food and Agriculture* 5: 1–13.

Touré A, Rodenburg J, Marnotte P, Dieng I, Huat J. 2014. Identifying the problem weeds of rice-based systems along the inland-valley catena in the southern Guinea Savanna, Africa. *Weed Biology and Management* 14: 121–132.

Zingore S, Murwira HK, Delve RJ, Giller KE. 2007. Influence of nutrient management strategies on variability of soil fertility, crop yields and nutrient balances on smallholder farms in Zimbabwe. *Agriculture, Ecosystems and Environment* 119: 112–126.

Zingore S, Tittonell P, Corbeels M, van Wijk MT, Giller KE. 2011. Managing soil fertility diversity to enhance resource use efficiencies in smallholder farming systems: a case from Murewa District, Zimbabwe. *Nutrient Cycling in Agroecosystems* 90: 87–103.

Received 28 July 2020, revised 08 October 2020, accepted 23 October 2020
Associate Editor: Christopher Preston