Weed growth and crop yield responses to tillage and mulching under different crop rotation sequences in semi-arid conditions

N. MASHINGAIDZE[1, 2*], S. TWOMLOW[1, 3], I.C. MADAKADZE[2], W. MUPANGWA[1, 4], Z. MAVUNGANIDZE[2]

[1]ICRISAT, P.O. Box 776, Bulawayo, Zimbabwe.
[2]Department of Plant Production and Soil Science, Faculty of Natural and Agricultural Sciences, University of Pretoria, P. Bag X20 Hatfield, Pretoria, 0028, South Africa.
[3]IFAD Via di Paolo di Dono 44, 00142 Rome, Italy.
[4]CIMMYT, Southern Africa Regional Office, P.O. Box MP 63, Harare, Zimbabwe.

Weed crop conservation agriculture

[*]Correspondence: Nester Mashingaidze, Midlands State University, P. Bag 9055, Gweru, Zimbabwe.
E-mail: nestermash@yahoo.com, telephone: +263 772 484 338

Abstract

Conservation agriculture (CA) is thought to reduce weed pressure from the third year of adoption, when recommended practices are followed. Weed growth and crop yield were assessed during the third and fourth year of maize-cowpea-sorghum rotation, second and third year maize-cowpea rotation and first and second year maize **monocropping** on a clay loam soil at Matopos Research Station (annual rainfall, 573mm) following recommended CA management practices. Each experiment **had** a split-plot randomized complete block design with mouldboard plough (CONV), minimum tillage (MT) **with** ripper tine and planting basins as main-plot factor and **a** maize residue mulch rate (0, 2 and 4 t/ha) as sub-plot factor, **with threefold replication**. All sub-plots **were surface mulched and weeded by hoe** at the same time We hypothesised **under MT weed growth would be considerable with maize monocropping but from year 3 of CA, weed growth would decrease and crop yield increase** relative **to values from** un- mulched CONV. **Minimum tillage increased weed growth** in 2nd year of maize monocropping. Under the maize-cowpea rotation, the **considerable** weed growth in planting basins was likely due to the large intra-row spacing and poor light competiveness of the cowpea variety. **Mulch contributed to weed growth being suppressed** by up to 36% under CA in the maize-cowpea- sorghum rotation relative to un-mulched CONV. When planted on the same date, crop yield did not differ between CA and un-mulched CONV. Maize-cowpea-sorghum rotation grain yield (3143 kg/ha) was double that **under monocropping,** probably due to improvements in soil physical and chemical conditions.

Keywords: Conservation agriculture, tillage, maize residue mulch, crop rotation, weeds, crop yield

Introduction

Conservation agriculture (CA) is **considered** by many development organisations **to be** a promising intervention **for increasing** crop yields **and** conserving soil and water in smallholder agriculture in sub-Saharan Africa. According to Ekboir, (2002), CA results in long term improvements in weed management that may reduce the weeding burden faced by smallholder farmers. Promoters of CA believe that **adopting** minimum tillage (MT), soil cover and crop rotation decreases weed pressure within three to five years of CA adoption (FAO, 2016). Although in the first years of MT, newly shed weed seeds on the soil surface layer can result in **large** weed infestations (Mashingaidze, 2013; Mavunganidze *et al*., 2014), this is expected to decline with time **if** recommended CA practices are followed (Muoni *et al*., 2014). This is because in CA systems, weed seeds previously buried by inversion tillage are not brought to the soil surface and eventually die while weed seeds remaining on the soil surface layer are exposed to predators and harsh environmental conditions (Dekker, 1999). Furthermore, the other CA practices of crop residue mulching and crop rotation aid weed management. Mulching suppresses weeds through reduction in light transmittance and soil temperature oscillations, and changes in soil moisture. Decreased weed growth was observed in plant residue mulched MT systems in Zambia (Gill *et al*., 1999) and Zimbabwe (Vogel, 1994). Rotating crops with varied growth patterns and management practises can lead to better weed control through decreases in weed population density, biomass production and weed seed density (Liebman & Dyck, 1993; Chauhan *et al*., 2012). These practices in tandem with optimal weed management throughout the year are hypothesised to result in a rapid decline in the viable seed bank leading to decreased weed pressure in CA over time.

Empirical evidence to support the argument that over time CA systems see an improvement in weed management is highly debated (Andersson & Giller, 2012). In southern Africa, most available research suggests increased weeding frequency under CA (Mashingaidze, 2013) often translating into increased labour requirements for hoe weeding particularly under hand hoe-based CA systems (Baudron *et al*., 2007; Nyamangara *et al*., 2014). Although Muoni *et al.* (2014) report that herbicide usage is a viable strategy in CA, Mafongoya *et al*. (2016) found out that herbicide use in CA was not profitable for smallholder farmers in Zimbabwe at the current yields. Consequently, weed management is still one of the main deterrents to widespread CA adoption.

Yet, proponents of CA argue that weeds are only a problem in the first years of adoption, with the weed population declining with time, unless the CA package is poorly implemented (Wall *et al*., 2013). The partial adoption of the three CA principles in South America and southern Africa (Pittelkow *et al*., 2014) may, thus, be the reason for reported weed problems under CA. In 2003, a taskforce led by the Food and Agriculture Organization of the United Nations (FAO), comprising government research and extension officers, researchers and developmental specialists was established to coordinate CA approaches in Zimbabwe. The Zimbabwe Conservation Agriculture Taskforce (ZCATF) promotes the simultaneous application of MT, crop residue mulching and crop rotation as central CA tenets with frequent manual weeding to minimize weed seed return (ZCATF, 2009). The recommended crop rotation for semi-arid areas is a rotation of maize (*Zea mays* L.) followed by a drought tolerant legume and cereal crop over a three-year period. Evidence is limited, but it appears that with time smallholder farmers in Zimbabwe (Pedzisa *et al*., 2015) and Zambia (Baudron *et al*., 2007) may eventually adopt the full complement of CA practices.

The challenges of weed management under MT for monocropped maize are well documented in Zimbabwe. Although Vogel (1994) reported on the potential of maize residue mulching to reduce weed growth under MT, no information was provided on the maize mulch rates used. **Due to other studies being limited**, little is known about the **thresholds for** mulch rates that **suppress weeds**. We used a series of experiments (Mupangwa *et al*. 2012) to i) determine tillage and maize residue mulch rates effects on weed growth and crop yield **-** in the first two years of maize **monocropping**, 2nd and 3rd year of a maize-cowpea rotation and 3rd and 4th year of a maize-cowpea-sorghum rotation and ii) test the hypothesis that CA decreased weed growth and increased crop yield relative to the farmers' practice of un-mulched mouldboard ploughing.

Materials and methods

Experimental site

The study was conducted at Matopos Research Station, Zimbabwe (28^{0} 30.92`E, 20$^{0}$ 23.32`S; 1 344 m above sea level). The climate is semi-arid with an average annual rainfall of 573 mm occurring between November and April. The mean maximum temperature is 26 ºC and an evapo-transpiration > 900 mm. The soil is a **Chromic-Leptic Cambisol** with 45% clay, 19% silt and 36% sand in the top 0.5 m (Moyo, 2001), a pH (water) of 6, a soil organic carbon content of 1.2% and bulk density of 1.4 t/m^{3} (Mupangwa *et al*., 2012).

Experimental design

The experiment started in the 2004/05 cropping season with additional experiments established in adjacent fields in subsequent years. Prior to the 2004/05 season, all three fields were disc ploughed and used for production of breeder's sorghum seed with similar management practices. The crop sequences in the fields (Table 1) represented the ZCATF three-year rotation in CA, a two-year cereal/legume rotation and the current smallholder farmer's practice of maize monocropping. Weeds were not controlled in fields 2 and 3 during the fallow. Each experiment **had** a split-plot Randomised Complete Block design. To facilitate animal-drawn operations, tillage was the main plot (63 m × 6 m) factor at three levels; mouldboard ploughing (conventional tillage, CONV), non-inversion MT systems of ripper tine (RT) and planting basin (PB). Maize residue rate (0, 0.5, 1, 2, 4, 8 and 10 t/ha) was randomly assigned to 8 m × 6 m sub- plots within each tillage system and replicated three times.

Hoeing was carried out on all plots in July of each year **to kill weeds**, followed by maize residue applications in August. The PB and RT plots were then prepared following ZCATF, (2009) guidelines (Table 2). Planting basins, 0.15 m × 0.15 m × 0.15 m, were dug using hand hoes. Rip lines were opened using a ZimPlow® ripper tine attached to the beam of a donkey-drawn mouldboard plough to achieve an average ripping depth of 0.16 m. Planting basins and rip line positions were maintained across seasons and 3 t/ha of cattle manure (40% C, 0.43% N, 0.21% P), from the Matopos' cattle kraals was applied within basins and banded along ripped furrows each September. At the first effective seasonal rains (30 - 50 mm), maize residue was removed from CONV sub-plots prior to ploughing to prevent residue incorporation into the soil. Plots were ploughed to 0.15 m depth using a donkey-drawn ZimPlow® VS200 mouldboard plough. Then, planting furrows were opened with hoes at the recommended inter-row spacing for crops (Table 2) and maize residue re-applied. Cattle manure was banded along the planting furrows at a rate of 3 t/ha. No weed seedlings emerged over 16 weeks during weed seedling germination tests on the manure used, in contrast to the weed loading found in manure from smallholder farms (Mashingaidze, 2013)

Table 1. Sequence of crops grown on experimental fields at Matopos Research Station between 2004 and 2008

Field	Crop grown			
	2004/05	2005/06	2006/07‡	2007/08‡
1	Maize	Cowpea	Sorghum	Maize
2	Fallow	Maize	Cowpea	Maize
3	Fallow	Fallow	Maize	Maize

‡ Study seasons

Table 2. Crop characteristics and agronomic practices of experimental crops at Matopos Research Station

Crop	Sorghum			Cowpea			Maize		
	Mouldboard plough	Ripper tine	Planting basin	Mouldboard plough	Ripper tine	Planting basin	Mouldboard plough	Ripper tine	Planting basin
‡Variety	Macia			IT86D-719			SC403		
Source	ICRISAT			IITA			SeedCo.		
Duration, days	115			70			120		
Growth habit	Erect			Semi-erect			Erect		
Plant height, m	1.4			0.7			2.6		
∞Yield, t/ha	3			2.5			5		
Spacing, m	0.75 × 0.2	0.9 × 0.2	0.9 × 0.6	0.6 × 0.2	0.9 × 0.2	0.9 × 0.6	0.9 × 0.3	0.9 × 0.3	0.9 × 0.6
Plants /station	1	1	4	1	1	4	1	1	2
†Plants / m^2	6.7	5.6	7.4	8.3	5.6	7.4	3.7	3.7	3.7

‡ Same crop variety grown in all tillage systems, ∞ Yield potential, †Target crop density

Early maturing crop varieties (Table 2) were grown to take advantage of the short growing period at Matopos. In 2007/08 season, planting and all other management operations were carried out at the same time in all fields. **At 6 weeks after planting** (WAP) 20 kg N/ha ammonium nitrate (34.5% N) was applied to cereals. Hand hoeing was carried out as required during the wet and dry seasons as recommended by ZCATF (2009) to reduce **weed seed addition** to the soil seed bank.

Weeding was done at the same time in all sub-plots. Thiodan 35EC (80 ml in 20L water) was sprayed on cowpea at 4 WAP and flowering to control aphids (*Aphis craccivora* L.). Crops were harvested at physiological maturity. Further details on experimental management are provided in Mupangwa *et al*. (2012).

Data collection

Weed growth and crop yield data were collected during the 2006/07 and 2007/08 cropping seasons from the tillage × mulch sub-plots that received residue rates of 0, 2 and 4 t/ha. These rates reflected the rates observed on farmers' fields when mulching was practised (Mashingaidze, 2013). In both seasons prior to weeding, a quadrat of **0.5 m^2** was placed at two random positions within a sub-plot to determine weed growth. The quadrat was placed centred on the inter-row so as to include four basins or two rip/planting furrows. In the 2006/07 season, weeds were counted to determine weed density at 3, 5, 9 and 19 WAP after which the weeds were cut at ground level and oven-dried at 60 ^{0}C to constant weight and the dry weight determined. In the following season, weed density data was collected at 1 week before planting, 3, 9 and 13 WAP. Crop density per sub-plot was determined at 3 WAP. At harvesting, sorghum, cowpea and maize grain, and residue yields were estimated from a net plot of five central rows each of 6 m long. Grain yield was standardized to 12.5% moisture content.

Statistical analysis

All data was assessed for normality using GenStat Release 10.3DE (Lawes Agricultural Trust, 2011). A $\sqrt{(x+0.5)}$ transformation of weed data improved the variance homogeneity. Weed (transformed) and crop data were subjected to split-plot analysis of variance done separately for each crop. A one-way ANOVA with 3 × 3 levels was performed with contrasts to test if the weed and crop yield means of (i) the un-mulched CONV differed from that of two mulched MT practices and (ii) the two mulched MT types differed. Treatments means were separated by least significant difference (LSD) at 5% level of significance. Untransformed weed data means are presented and separated based on ANOVA results. Relationships among variables were determined by regression analysis.

Results and discussion

Seasonal rainfall

Although 2006/07 was characterized by poor rainfall distribution it was 25% wetter than 2007/08. Yet both seasonal totals were less than the long-term average rainfall for Matopos Research Station (Fig. 1). **R**ainfall on 22 November 2006 resulted in waterlogging of the clay loam soil. Consequently, ploughing and planting of cowpea was delayed by two weeks in CONV compared to MT (Fig. 1b). Lengthy dry spells between 29 December 2006 and 6 February 2007 result in late application of N fertilizer to the cereal crops. These dry periods coincided with maize and sorghum anthesis and grain set. Although the first half of the 2007/08 cropping season had better rainfall distribution than the 2006/07 season, the season ended abruptly on 15 January 2008 (Fig. 1d) during maize tasselling. This cessation resulted in **small** weed infestations in maize fields such that only three post-planting weeding's were carried out compared to four in the previous season (Fig. 1 c and d). These two seasons highlight the production challenges of erratic rainfall and mid-seasonal dry spells faced by smallholder farmers in semi-arid areas.

Weed growth

First two years of maize monocrop

There was no significant tillage × maize residue mulch rate interaction effect on weed density and biomass during the two years (Table 3). In the first year of the experiment, there was no difference in weed growth between MT and CONV (Table 4). Without soil inversion in MT, the majority of weed seeds are maintained at the soil surface. Predation of these accessible seeds may have reduced the seed bank size under MT in the season following a fallow (Table 2). Blubaugh & Kaplan, (2016) observed reduced weed emergence due to seed predation in fallow

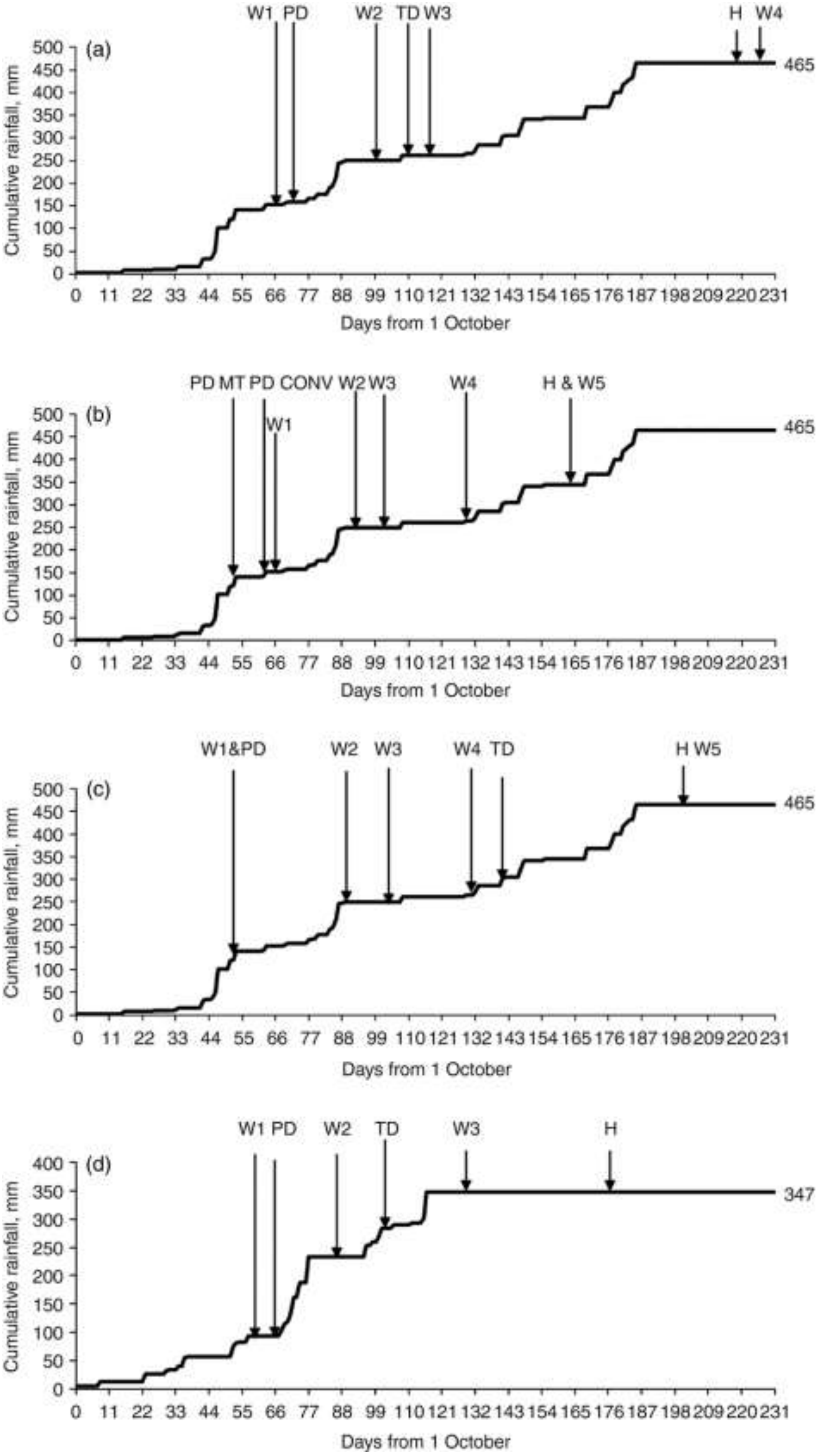

Fig 1. Cumulative daily rainfall received and the timing of crop management practices (a) sorghum, (b) cowpea (c) maize crops grown during the 2006/2007 season and (d) maize in 2007/2008 season at Matopos Research Station. W1 to W5: hoe weeding operations; PD, planting date; MT, minimum tillage; CONV, conventional tillage; TD, N top dressing and H, harvesting.

Table 3. *P*-value and significance of treatment effects from ANOVA for weed density, weed biomass and crop yield during 2006–2008

Rotation	Crop (season)	Source of variation	DF	P-value of treatments										
				Weed density at WAP				Weed biomass at WAP				Crop yield		
				3	5	9	19	3	5	9	19	Density	Grain	Residue
Maize-maize	**Maize (2006/07)**	Tillage	2	0.156	0.819	0.809	0.061	0.536	0.654	0.456	0.365	0.152	0.252	0.072
		Mulch	2	0.062	0.156	0.014	0.022	0.106	0.004	0.016	<0.0001	0.015	0.006	0.874
		Tillage × Mulch	4	0.996	0.501	0.205	0.697	0.962	0.437	0.618	0.699	0.005	0.052	0.039
	Contrasts													
	CONVO vs (mulched PB and mulched RT)/4		1	0.005^{∞}	0.954	0.428	0.112	0.039^{∞}	0.623	0.135	<0.0001	0.036	0.009	0.002
	Average mulched PB vs average mulched RT		1	0.325	0.819	0.31	0.005	0.074	0.58	0.324	0.066	0.809	0.075	0.028
				Weed density at WAP								Crop yield		
				-1	3	9	13					Density	Grain	Residue
	Maize (2007/08)	Tillage	2	0.009	0.372	0.022	0.89					0.833	0.694	0.711
		Mulch	2	0.816	0.126	0.993	0.088					0.286	0.776	0.858
		Tillage × Mulch	4	0.185	0.166	0.071	0.363					0.942	0.268	0.219
	Contrasts													
	CONVO vs (mulched PB and mulched RT)/4		1	<0.0001	0.592	<0.0001	0.629					0.885	0.248	0.263
	Average mulched PB vs average mulched RT		1	0.71	0.404	0.168	0.635					0.771	0.864	0.903
				Weed density at WAP				Weed biomass at WAP				Crop yield		
				3	5	9	19	3	5	9	19	Density	Grain	Residue
Maize-cowpea	**Cowpea (2006/07)**	Tillage	2	0.071	0.538	0.002	0.332	0.042	0.806	0.026	0.111	0.178	0.047	<0.001
		Mulch	2	0.191	0.412	0.258	0.315	0.002	0.01	0.288	<0.0001	0.197	0.667	0.793
		Tillage × Mulch	4	0.774	0.916	0.209	0.725	0.852	0.54	0.845	0.55	0.328	0.235	0.878
	Contrasts													
	CONVO vs (mulched PB and mulched RT)/4		1	0.145	0.666	0.234	0.286	0.142	0.297	0.698	0.018	0.217	0.005	<0.0001
	Average mulched PB vs average mulched RT		1	0.384	0.394	<0.001	0.251	0.01	0.623	<0.0001	0.002	0.489	0.809	0.863
				Weed density at WAP								Crop yield		
				-1	3	9	13					Density	Grain	Residue
	Maize (2007/08)	Tillage	2	0.017	0.011	0.156	0.021					0.703	0.551	0.736
		Mulch	2	0.217	0.6	0.959	0.284					0.003	0.155	0.063
		Tillage × Mulch	4	0.006	0.613	0.09	0.811					0.05	0.417	0.168
	Contrasts													
	CONVO vs (mulched		1	<0.0001	0.262	0.019^{∞}	0.005					054	0.162	0.34

	PB and mulched RT)/4												
	Average mulched PB vs average mulched RT		1	0.823	0.608	0.037	0.77					0.868	0.749	0.642
				Weed density at WAP				Weed biomass at WAP				Crop yield		
				3	5	9	19	3	5	9	19	Density	Grain	Residue
Maize-cowpea-sorghum	**Sorghum (2006/07)**	Tillage	2	0.588	0.943	0.434	0.91	0.288	0.967	0.004	0.323	0.007	0.027	0.06
		Mulch	2	0.045	0.002	0.034	0.031	0.005	<0.0001	<0.0001	<0.0001	0.769	0.515	0.337
		Tillage × Mulch	4	0.556	0.225	0.75	0.405	0.765	0.599	0.895	0.343	0.298	0.502	0.602
	Contrasts													
	CONVO vs (mulched PB and mulched RT)/4		1	0.271	0.034	0.274	0.501	0.873	0.029	0.027	0.02	0.001	0.647	0.5
	Average mulched PB vs average mulched RT		1	0.104	0.715	0.679	0.846	0.387	0.808	0.053	0.597	<0.0001	<0.0001	0.005
				Weed density at WAP								Crop yield		
				-1	3	9	13					Density	Grain	Residue
	Maize (2007/08)	Tillage	2	0.022	0.064	0.218	0.534					0.009	0.457	0.907
		Mulch	2	0.048	0.134	0.223	0.568					0.125	0.345	0.034
		Tillage × Mulch	4	0.948	0.092	0.271	0.945					0.45	0.163	0.096
	Contrasts													
	CONVO vs (mulched PB and mulched RT)/4		1	0.481	0.715	0.202	0.823					0.003	0.819	0.204
	Average mulched PB vs average mulched RT		1	0.408	0.678	0.575	0.251					0.165	0.772	0.216

WAP, weeks after planting, -1[†], 1 week before planting, , [∞], contrast tests ignored as overall P > 0.05 for one-way ANOVA , CONV0- un-mulched mouldboard plough, PB- planting basin, RT – ripper tine

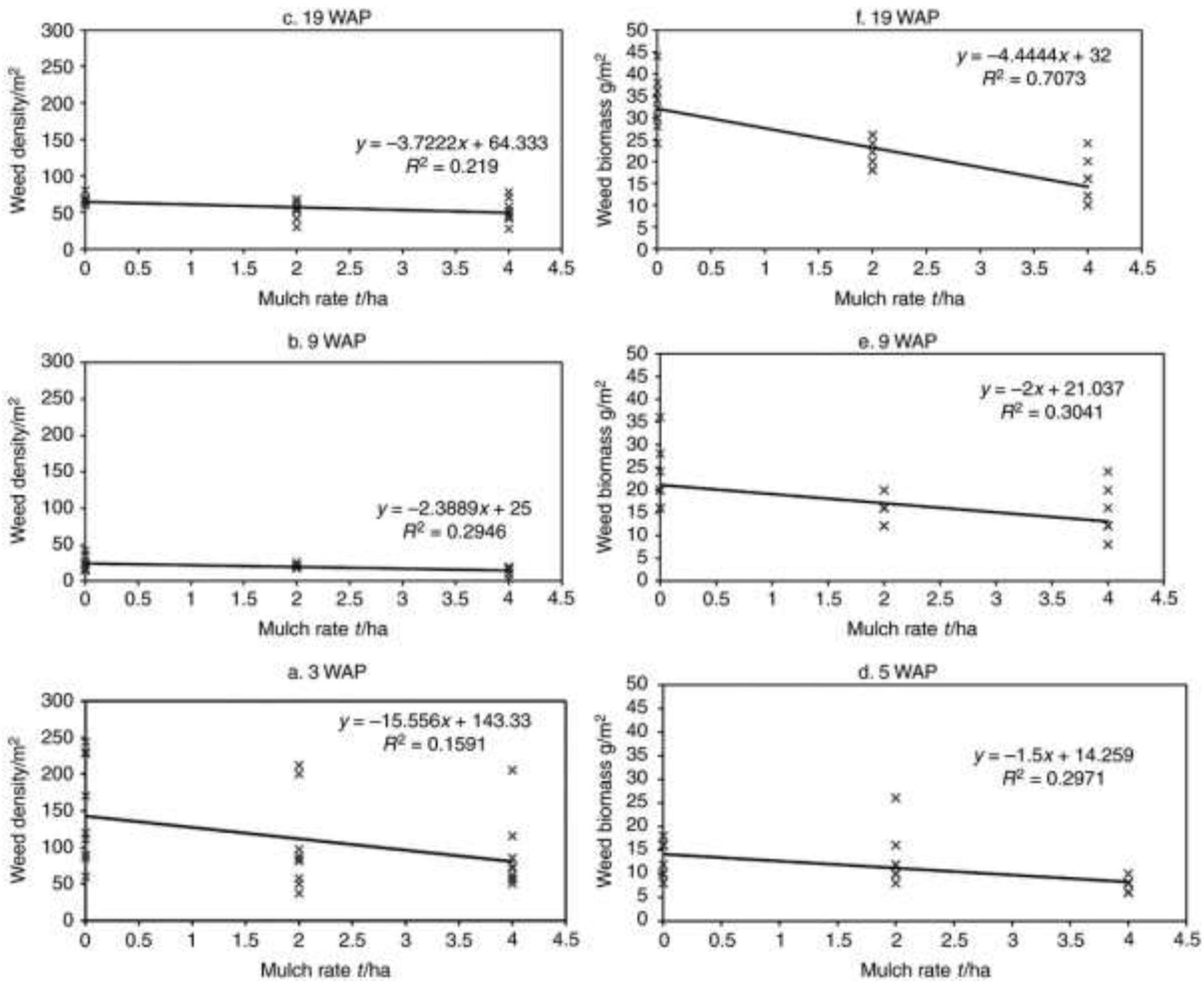

Fig 2. Responses of weed density (a, b, c) and weed biomass (d, e, f) to maize residue mulch rate in the first year of maize monocropping during the 2006/2007 season.

plots. Weed suppression increased with maize residue mulch rate for most of this season (Fig. 2). Residue mulching inhibits weed germination through shading of the soil surface and reducing the soil temperature amplitude that is used as a germination cue by many weeds (Teasdale & Mohler, 1993). The moderately strong relationship between weed biomass and mulching at 19 WAP (Fig. 2f) probably contributed to the lower weed biomass in mulched MT relative to un-mulched CONV (Table 4). This highlights the importance of mulching in MT for within cropping season weed management. In addition, the decrease in weed growth may result in reduced weed seed return under MT as fecundity of annual weeds is linearly related to biomass.

In the second season, MT had greater weed density at a week before planting and 9 WAP than CONV (Table 4). Both PB and RT had at least twice the weed density in CONV before planting. Ploughing buries weed seeds to soil depths from where emergence is difficult and clears standing vegetation. The conducive conditions in the upper soil layer probably contributed to increased germination of the fresh weed seeds maintained in these layers in MT. Higher weed growth in PB relative to CONV has been observed on smallholder farms in Zimbabwe early (Mashingaidze, 2013) and late in the cropping season (Nyamangara *et al*., 2014). Increased field activities may have reduced predator populations and level of predation during the second year. With no weed suppression on maize residue mulching (Table 3), weed density under mulched PB and RT still remained higher than un-mulched CONV at planting time and 9 WAP (Table 4).

Second and third year of maize-cowpea rotation

At 3 and 9 WAP, PB had almost double the weed growth in CONV and RT (Table 5). A combination of the wide intra-row spacing in PB, the semi-erect, short stature and early maturity of IT86D-719 (Table 2) exacerbated by poor cowpea establishment probably led to a more open cowpea canopy early in the season and at leaf senescence. This likely resulted in high light transmittance to the soil surface leading to increased weed growth in planting basins. Early maturing cowpea genotypes have a narrower canopy spread than medium and late maturing genotypes (Mohammed *et al*., 2008). Poor cowpea weed competitiveness is further supported by the higher post-planting weeding operations in cowpea than in other crops (Fig. 1). A medium maturing, prostrate cowpea variety may have been better at suppressing weeds than IT86D-719. Mulching reduced weed biomass at all sampling times except at 9 WAP (Fig. 3). As observed in

Table 4. Tillage effects at different maize residue mulch rates on weed density and biomass under the first- and second-year maize crop in maize monocropping during the 2006/2007 and 2007/2008 cropping seasons at Matopos Research Station

Crop (Season)	Tillage / Mulch rate	Weed density /m^2															
		3 WAP				5 WAP				9 WAP				19 WAP			
		0 t/ha	2 t/ha	4 t/ha	*Mean*	0 t/ha	2 t/ha	4 t/ha	*Mean*	0 t/ha	2 t/ha	4 t/ha	*Mean*	0 t/ha	2 t/ha	4 t/ha	*Mean*
Maize (2006/07)	CONV	195	133	121	*150*	37	39	37	*38*	20	21	19	*20*	65	51	47	*54*
	RT	105	63	60	*76*	43	43	33	*43*	26	22	15	*21*	65	42	45	*51*
	PB	146	107	79	*111*	54	43	31	*40*	27	21	10	*20*	71	63	64	*66*
CONVO vs MT + mulch		ns				ns				ns				ns			
Mulched PB vs mulched RT		ns				ns				ns				*			
		Weed biomass g/m^2															
Maize (2006/07)		3 WAP				5 WAP				9 WAP				19 WAP			
		0 t/ha	2 t/ha	4 t/ha	*Mean*	0 t/ha	2 t/ha	4 t/ha	*Mean*	0 t/ha	2 t/ha	4 t/ha	*Mean*	0 t/ha	2 t/ha	4 t/ha	*Mean*
	CONV	29	20	18	*22*	11	11	8	*10*	20	13	16	*16*	32	23	15	*23*
	RT	23	19	15	*19*	15	16	7	*12*	20	16	11	*16*	29	19	13	*20*
	PB	26	16	18	*20*	15	11	8	*11*	25	17	15	*19*	37	23	17	*26*
CONVO vs MT + mulch		ns				ns				ns				*			
Mulched PB vs mulched RT		ns				ns				ns				ns			
		Weed density/ m^2															
Maize (2007/08)		-1^{∞} WAP				3 WAP				9 WAP				13 WAP			
		0 t/ha	2 t/ha	4 t/ha	*Mean*	0 t/ha	2 t/ha	4 t/ha	*Mean*	0 t/ha	2 t/ha	4 t/ha	*Mean*	0 t/ha	2 t/ha	4 t/ha	*Mean*
	CONV	9	39	18	22b	36	69	38	*47*	16	30	23	*23b*	32	37	32	*33*
	RT	91	58	60	73a	39	38	50	*42*	44	42	39	*42a*	22	31	36	*30*
	PB	72	52	58	60a	23	35	36	*35*	43	27	38	*36a*	33	36	39	*36*
CONVO vs MT + mulch		*				ns					*			ns			
Mulched PB vs mulched RT		ns				ns					ns			ns			

CONV- mouldboard plough, RT- ripper tine, PB- planting basins, CONV0- un-mulched mouldboard plough, MT + mulch – average of mulched PB and mulched RT, WAP, weeks after planting, $^{\infty}$-1, one week before planting. Within columns, means followed by the same letter are not significantly different according to $LSD_{0.05}$, ns – not significantly different at $P < 0.05$, * Denotes when the contrast is significant at the 0.05 level

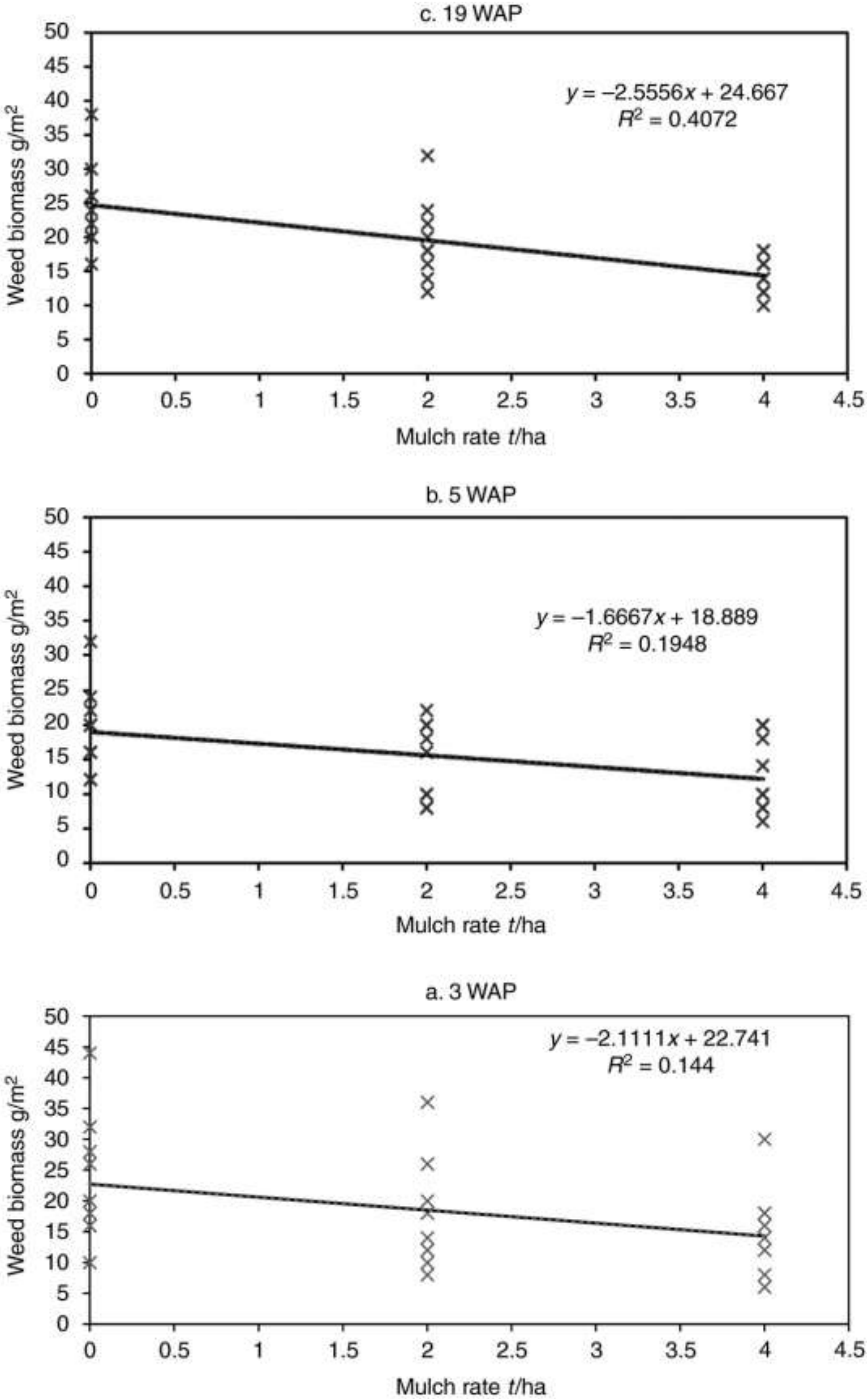

Fig 3. Responses of weed biomass to maize residue mulch rate in the second year of maize–cowpea rotation during the 2006/2007 season.

Table 5. Tillage effects at different maize residue mulch rates on weed density and biomass under the second-year cowpea and third-year maize crop in maize–cowpea rotation during the 2006/2007 and 2007/2008 cropping seasons at Matopos Research Station

Crop	Tillage /	Weed density /m^2															
(Season)	Mulch rate	3 WAP				5 WAP				9 WAP				19 WAP			
		0 t/ha	2 t/ha	4 t/ha	*Mean*	0 t/ha	2 t/ha	4 t/ha	*Mean*	0 t/ha	2 t/ha	4 t/ha	*Mean*	0 t/ha	2 t/ha	4 t/ha	*Mean*
Cowpea	CONV	41	36	29	*36*	36	32	34	*34*	23	16	21	*20b*	45	37	32	*38*
(2006/07)	RT	109	81	52	*81*	43	35	43	*40*	21	20	19	*20b*	41	35	*38*	*38*
	PB	116	76	95	*96*	62	41	66	*56*	27	30	46	*34a*	45	39	45	*43*
CONVO vs MT + mulch		ns				ns				ns				ns			
Mulched PB vs mulched RT		ns				ns				*				ns			
		Weed biomass g/m^2															
Cowpea		3 WAP				5 WAP				9 WAP				19 WAP			
(2006/07)		0 t/ha	2 t/ha	4 t/ha	*Mean*	0 t/ha	2 t/ha	4 t/ha	*Mean*	0 t/ha	2 t/ha	4 t/ha	*Mean*	0 t/ha	2 t/ha	4 t/ha	*Mean*
	CONV	14	10	9	*11b*	18	15	12	*15*	11	10	8	*10b*	23	18	15	*19*
	RT	24	15	14	*18b*	16	12	13	*14*	11	9	8	*10b*	21	15	12	*16*
	PB	32	27	22	*27a*	24	17	13	*18*	17	16	17	*17a*	30	25	17	*24*
CONVO vs MT + mulch		ns				ns				ns				*			
Mulched PB vs mulched RT		*				ns				*				*			
		Weed density/ m^2															
Maize		-1^{∞} WAP				3 WAP				9 WAP				13 WAP			
(2007/08)		0 t/ha	2 t/ha	4 t/ha	*Mean*	0 t/ha	2 t/ha	4 t/ha	*Mean*	0 t/ha	2 t/ha	4 t/ha	*Mean*	0 t/ha	2 t/ha	4 t/ha	*Mean*
	CONV	1	2	10	*4b*	52	49	68	*56c*	42	28	20	*30*	12	13	14	*13b*
	RT	24	29	8	*21a*	73	99	53	*75b*	19	32	26	*26*	21	20	30	*26a*
	PB	48	27	19	*31a*	115	97	74	*95a*	13	12	19	*15*	20	25	24	*23a*
CONVO vs MT + mulch		*				ns				ns				*			
Mulched PB vs mulched RT		ns				ns				ns				ns			

CONV- mouldboard plough, RT- ripper tine, PB- planting basins, CONV0- un-mulched mouldboard plough, MT + mulch – average of mulched PB and mulched RT, WAP, weeks after planting; $^{\infty}$-1, one week before planting. Within columns, means followed by the same letter are not significantly different according to $LSD_{0.05}$, ns – not significantly different at $P< 0.05$, * Denotes when the contrast is significant at the 0.05 level first year maize, the strongest relationship between weed suppression and mulching was at 19 WAP (Fig. 3c) **when weed biomass was significantly reduced** in mulched MT relative to un-mulched CONV (Table 5). Mulched PB, however, had greater weed biomass than mulched RT for most of the season.

In the maize following cowpea, PB and RT had a higher weed density than CONV at 1 week before planting and 13 WAP, but followed the ranking PB > RT> CONV at 3 WAP (Table 5). Although mulching suppressed weeds in MT, mulched MT on average had a greater weed density than un-mulched CONV at a week before planting and at 13 WAP (Table 5). However, at a week before planting, maize residue retention at a rate of 4 t/ha decreased weed density to the level in un-mulched CONV showing a positive correlation between weed suppression and mulch rate. The high incidence of a tillage effect on weeds under maize have been due to the preceding cowpea crop having allowed some weeds to escape and set seeds. Dorado *et al*. (1999) observed higher weed density in a barley-vetch rotation than barley **monocropping** and attributed this to the less competitive vetch crop that allowed weeds to establish during the season it was planted. These findings suggest that crops in rotation can influence weed growth in subsequent crops. Selection of crops should also consider weed competitiveness of varieties.

Third and fourth year of maize-cowpea-sorghum rotation

There was no tillage effect on weed density under sorghum (Table 6). However, at 9 WAP PB had 20% higher weed biomass than CONV, with RT weed biomass intermediate. Maize residue mulching suppressed weed growth throughout the season (Fig. 4), contributing to 36% lower weed density at 5 WAP and between 18 – 26% reduction in weed biomass from 5 WAP in mulched MT relative to un-mulched CONV (Table 6). This supports reports by CA proponents that CA reduces weed pressure compared to un-mulched mouldboard ploughing. In maize after sorghum, PB had the **smallest** weed density at 1 week before planting (Table 6). The greater level of soil disturbance in CONV and RT than in PB may have promoted increased weed germination through **uncovering** of previously buried seed, creation of favourable conditions for germination and improved seedling emergence. The lack of a tillage effect on weed density for the remainder of the season suggests similar weed pressure in fourth year CA and un-mulched CONV. However, at 1 week before planting maize residue mulching was associated with

Table 6. Tillage effects at different maize residue mulch rates on weed density and biomass under the third-year sorghum and fourth-year maize crop in maize–cowpea–sorghum rotation during the 2006/2007 and 2007/2008 cropping seasons at Matopos Research Station

Crop (Season)	Tillage / Mulch rate	Weed density /m^2															
		3 WAP				5 WAP				9 WAP				19 WAP			
		0 t/ha	2 t/ha	4 t/ha	*Mean*	0 t/ha	2 t/ha	4 t/ha	*Mean*	0 t/ha	2 t/ha	4 t/ha	*Mean*	0 t/ha	2 t/ha	4 t/ha	*Mean*
Sorghum (2006/07)	CONV	87	99	78	*88*	65	56	33	*51*	33	21	17	*23*	49	47	49	*48*
	RT	81	98	65	*82*	66	37	41	*48*	31	27	24	*28*	71	41	45	*52*
	PB	109	75	51	*78*	59	59	29	*49*	35	27	27	*30*	75	39	45	*53*
CONVO vs MT + mulch		ns				*				ns				ns			
Mulched PB vs mulched RT		ns				ns				ns				ns			
		Weed biomass g/m^2															
Sorghum (2006/07)		3 WAP				5 WAP				9 WAP				19 WAP			
		0 t/ha	2 t/ha	4 t/ha	*Mean*	0 t/ha	2 t/ha	4 t/ha	*Mean*	0 t/ha	2 t/ha	4 t/ha	*Mean*	0 t/ha	2 t/ha	4 t/ha	*Mean*
	CONV	24	20	16	*20*	21	18	15	*18*	11	7	6	*8c*	25	19	17	*20*
	RT	30	26	25	*27*	24	17	13	*18*	13	9	7	*10b*	27	21	17	*22*
	PB	33	25	20	*26*	21	19	13	*18*	16	11	9	*12a*	33	23	17	*25*
CONVO vs MT + mulch		ns				*				*				*			
Mulched PB vs mulched RT		ns				ns				ns				ns			
		Weed density/ m^2															
Maize (2007/08)		-1$^{\infty}$ WAP				3 WAP				9 WAP				13 WAP			
		0 t/ha	2 t/ha	4 t/ha	*Mean*	0 t/ha	2 t/ha	4 t/ha	*Mean*	0 t/ha	2 t/ha	4 t/ha	*Mean*	0 t/ha	2 t/ha	4 t/ha	*Mean*
	CONV	7	13	16	*12a*	104	48	61	*71*	20	16	21	*19*	14	17	18	*16*
	RT	6	13	12	*10a*	92	109	87	*96*	28	29	27	*28*	12	12	15	*13*
	PB	2	6	11	*6b*	145	50	140	*112*	22	22	44	*29*	13	18	23	*18*
CONVO vs MT + mulch		ns				ns				ns				ns			
Mulched PB vs mulched RT		ns				ns				ns				ns			

CONV- mouldboard plough, RT- ripper tine, PB- planting basins, CONV0- un-mulched mouldboard plough, MT + mulch – average of mulched PB and mulched RT, WAP, weeks after planting; $^{\infty}$-1, one week before planting. Within columns, means followed by the same letter are not significantly different according to $LSD_{0.05}$, ns – not significantly different at $P< 0.05$, * Denotes when the contrast is significant at the 0.05 level

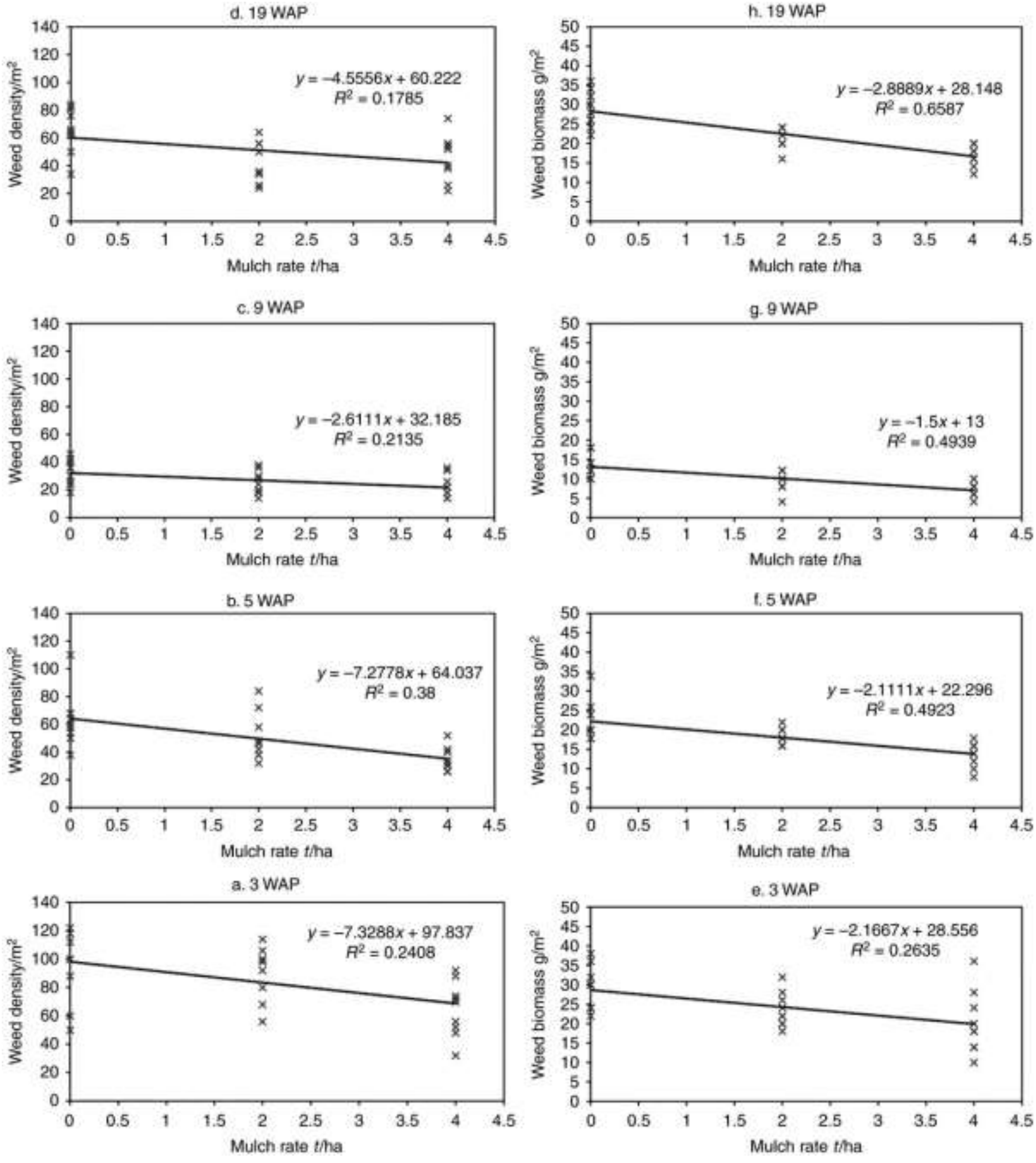

Fig 4. Weed density (a, b, c and d) and weed biomass (e, f, g and h) responses to maize residue mulch rate in the third year of maize–cowpea–sorghum rotation during the 2006/2007 season.

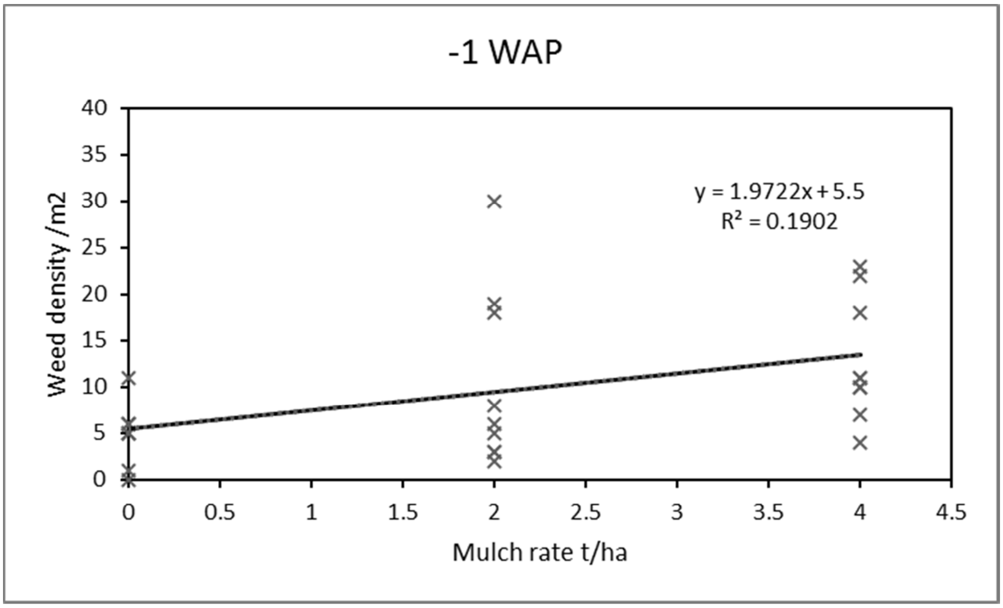

Fig. 5. Response of weed density at 1 week before maize planting to maize residue mulch rate in the fourth year of a maize–cowpea–sorghum rotation during the 2007/2008 season.

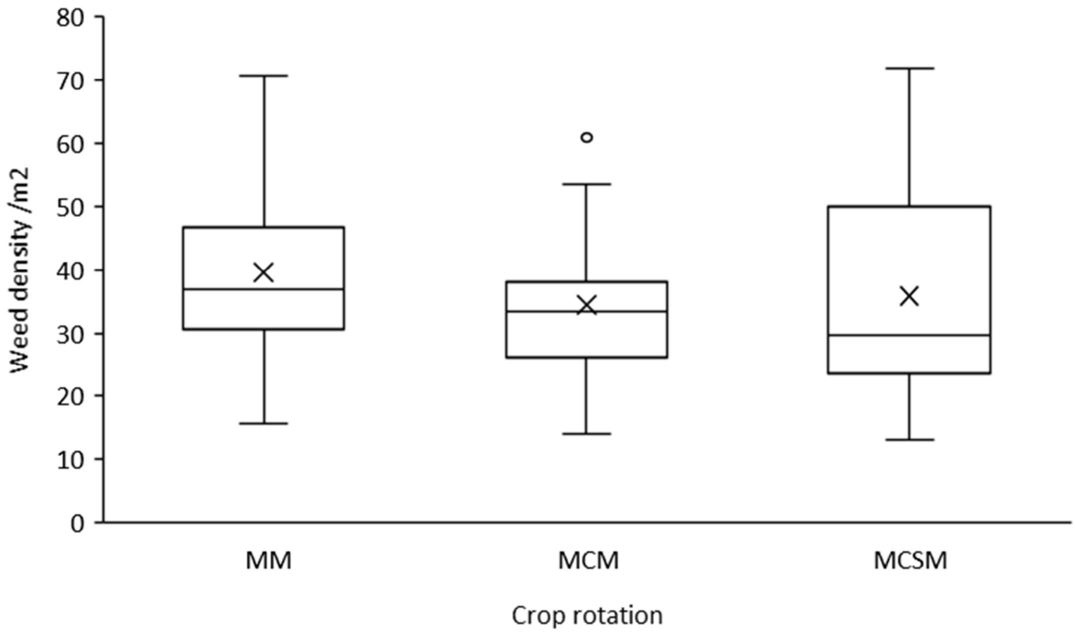

Figure 6. Boxplots showing the distribution of average weed density in maize grown under different crop rotation sequences during the 2007/2008 season at Matopos. The mean is marked by X within each boxplot. MCM, maize–cowpea-maize; MCSM, maize–cowpea–sorghum–maize; MM, maize–maize rotations.

increased weed density (Fig. 5). Mupangwa *et al*. (2007) **reported** that **a** mulch rate of 4 t/ha **resulted in** the **largest** soil water content at this site. Improvements in soil moisture may have contributed to the increased weed growth under this mulch rate with **the** effect more pronounced during the relatively dry first week of December 2007 (Fig. 1d). Increased weed growth on mulching has also been reported by Buhler *et al*. (1996) and Mashingaidze *et al*. (2012). Thus, **the effect of** maize residue mulching on weed growth **results from** interactions with other factors including tillage, management and environmental conditions.

The fields had similar weed composition**s,** dominated by *Setaria* spp. and **similar** average weed density under maize during the 2007/08 season (Fig. 6). Although the median of the average weed density in the maize-cowpea-sorghum was the **smallest**, this rotation had the greatest variation in weed density distribution probably reflecting the interaction between the treatments, the environment and management over the course of 4 years. **Although** there was a decrease in weed growth under recommended CA in the third year, it is important to note that in this study hoe weeding was carried 3 to 4 times within the cropping season to maintain relatively weed-free conditions (Fig. 1). This may not be feasible in labour-constrained households. According to Nyamangara *et al.* (2014) smallholder farmers weeded their CA fields on average 2.7 times per season which translated into about 41% more man hours/ha relative to CONV. Pedzisa *et al*. (2015) identified the **large** labour requirements for land preparation and weeding as one of the main deterrents to expansion of area under CA by smallholders.

Crop productivity

Maize ***monocropping***

Tillage had no effect on maize density, grain and residue yield in the first year maize (Table 3). Mulching reduced maize density in MT by up to 51% (Table 7) possibly through adverse changes in the maize seed environment. **H**owever, **there** was no relationship between maize density and maize yield in this season. The significant (P=0.006) relationship ($y = 142x + 725$; $r^2=0.23$) between **mulching** and grain yield translated into mulched MT producing double the grain yield in un-mulched CONV (Table 7). Mulching may have improved soil moisture during dry spells that coincided with maize anthesis. For maize residue, in RT, the **greatest** mulch rate

Table 7. Crop productivity responses to tillage at different maize residue mulch rates under the different crop rotation sequences during the 2006/2007 and 2007/2008 cropping seasons at Matopos Research Station

Crop rotation	Crop (season)	Tillage / mulch rate	Crop yield											
			Density/m^2				Grain yield kg/ha				Residue yield kg/ha			
			0 t/ha	2 t/ha	4 t/ha	*Mean*	0 t/ha	2 t/ha	4 t/ha	*Mean*	0 t/ha	2 t/ha	4 t/ha	*Mean*
Maize - maize	**Maize (2006/07)**	CONV	7.8	14.1	8.1	*10.0*	596	1383	796	*925*	1494	2420	2086	*2000*
		RT	25.8	12.6	19.8	*19.4*	827	1203	1593	*1208*	3086	3790	4086	*3654*
		PB	24.5	15.8	15.1	*18.5*	606	730	1343	*894*	4111	2642	3000	*3251*
		Mean	*19.4a*	*10.1b*	*14.3b*		*677b*	*1105a*	*1245a*		*2897*	*2951*	*3058*	
	CONVO vs MT + mulch		*				*				*			
	Mulched PB vs mulched RT		ns				ns				*			
	Maize (2007/08)	CONV	34.4	35.4	27.8	*32.6*	1519	1655	1077	*1417*	2000	2086	1309	*1798*
		RT	36.8	38.0	34.6	*36.5*	1320	1095	1115	*1176*	1790	1494	1519	*1601*
		PB	32.6	36.8	31.9	*33.7*	953	86	1230	*1015*	1210	1148	1765	*1374*
		Mean	34.6	36.7	31.4		1264	1204	1140		1667	1576	1531	
	CONVO vs MT + mulch		ns				ns				ns			
	Mulched PB vs mulched RT		ns				ns				ns			
Maize-cowpea	**Cowpea (2006/07)**	CONV	22.6	20.2	19.4	*20.7*	220	191	293	*235B*	781	543	731	*685B*
		RT	39.9	44.0	24.2	*36.0*	570	675	410	*552A*	4213	4267	5013	*4498A*
		PB	37.3	27.8	30.8	*32.0*	439	548	583	*523A*	4640	4800	4640	*4693A*
		Mean	*33.2*	*30.7*	*24.8*		*410*	*472*	*429*		*3211*	*3203*	*3462*	
	CONVO vs MT + mulch		ns				*				*			
	Mulched PB vs mulched RT		ns				ns				ns			
	Maize (2007/08)	CONV	26.4	27.4	23.6	*25.8*	2836	2783	2863	*2827*	2235	2432	2235	*2300*
		RT	31.1	29.2	20.8	*27.0*	2812	2562	1469	*2289*	2568	2383	1321	*2091*
		PB	23.8	25.7	23.5	*24.4*	2511	210	2018	*2279*	2494	1963	2012	*2156*
		Mean	*27.1a*	*27.4a*	*22.7b*		*2720*	*2552*	*2117*		*2432*	*2259*	*1856*	
	CONVO vs MT + mulch		ns				ns				ns			
	Mulched PB vs mulched RT		ns				ns				ns			
Maize-cowpea-sorghum	**Sorghum (2006/07)**	CONV	21.2	20.2	22.3	*21.2A*	2012	1805	2084	*1967A*	3975	4346	4000	*4107*
		RT	20.3	20.1	19.2	*19.9A*	1865	2294	2594	*2221A*	4086	4494	4233	*4235*
		PB	7.7	9.7	9.4	*8.9B*	1390	1435	1340	*1388B*	2370	2790	3250	*2807*
		Mean	*16.4*	*16.7*	*17.0*		*1756*	*1844*	*1916*		*3477*	*3877*	*3794*	
	CONVO vs MT + mulch		*				ns				ns			
	Mulched PB vs mulched		*				*				*			

RT													
Maize (2007/08)	CONV	31.2	30.5	30.8	*30.8A*	3362	3756	2955	*3358*	2901	3099	3148	*3049*
	RT	18.3	23.4	20.9	*20.9B*	2507	2762	3899	*3056*	2321	3049	3975	*3115*
	PB	19.4	25.3	24.7	*23.1B*	2674	3484	2892	*3016*	2753	3370	2914	*3012*
	Mean	*23.0*	*26.4*	*25.5*		*2848*	*3334*	*3249*		*2658b*	*3173ab*	*3346a*	
CONVO vs MT + mulch		*				ns				ns			
Mulched PB vs mulched RT		ns				ns				ns			

CONV- mouldboard plough, RT- ripper tine, PB- planting basins, CONV0- un-mulched mouldboard plough, MT + mulch – average of mulched PB and mulched RT. For the main effects, means within a column or row followed by the same letter are not significantly different according to $LSD_{0.05}$, ns – not significantly different at $P < 0.05$, * Denotes when the contrast is significant at the 0.05 level

Table 8. Regression equations of significant relationships between crop yield and weed growth during the 2006/2007 and 2007/2008 cropping seasons at Matopos Research Station

Crop rotation	Crop (season)	Independent variables	
		Weed density /m^2	Weed biomass g/m^2
Maize -Maize	Maize (2006/07)	9 WAP: Grain =-23.2x+1478; r^2=0.10; SE=438	19 WAP: Grain = -23.9x+ 561; r^2=0.18; SE=420
Maize-Cowpea	Cowpea (2006/07)	3 WAP: Grain = 2.4x+267; r^2=0.10; SE=194	3 WAP: Grain = 9.7x + 257; r^2=0.14; SE=201
		9 WAP: Grain = 7.5x + 252; r^2=0.10; SE=205	3WAP: Residue = 125x+986; r^2=0.31; SE=1667
	Maize (2007/08)	13 WAP: Grain = -63.3x+3713; r^2=0.32; SE=747 13 WAP: Residue = -39x+2960; r^2=0.26; SE=532	
Maize-Cowpea-Sorghum	Sorghum (2006/07)		9 WAP: Residue = -115x+4870; r^2=0.18; SE=862 19 WAP: Residue = -60x+5061; r^2=0.11; SE=857

SE; standard error of observations, Significance at $P < 0.05$

out-yielded the un-mulched CONV by 32%**, whereas** while a residue yield depression of up to 32% occurred in PB. Consequently, mulched RT out-yielded mulched PB but with both **being greater** than un-mulched CONV (Table 7). Yield **was unaffected by** treatments in the second year maize crop (Table 7). Although the relationship was weak, mid to late season weeds reduced first year maize grain yield (Table 8).

Maize-cowpea rotation

In cowpea, PB and RT produced double the grain yield and 5 times the residue yield in CONV (Table 7) with a similar trend observed for mulched MT and un-mulched CONV. This **greater** yield relative to CONV is probably **the** result of early planting**;** cowpea **being** planted two weeks later in CONV (Fig.1b). The cowpea grain yield obtained was **greater** than the national yield of 300 kg/ha but **less** than > 1000 kg/ha obtained by Mupangwa *et al.* (2012) in a season with over 800 mm of **well-distributed** rainfall. The low **density of cowpea together with aphid infections** probably reduced grain yield in this season. The **large** residue yield produced under MT can **provide** fodder and alleviate livestock feed shortages in the mixed **crop-livestock** systems common in semi-arid areas. There were no tillage differences in maize yield in the following season. (Table 7). The reduction of maize density at a mulch rate of 4 t/ha may point to potential problems with maize germination under mulch. In cowpea, treatments **giving large** yields also increased weed growth**,** whereas in the following season late weed **growths** decreased maize yield (Table 8)**, indicating** weak and inconsistent weed and crop yield relationships.

Maize-cowpea-sorghum rotation

In sorghum, the **smallest** yield was obtained **under** PB probably due to poor establishment (Table 7)**,** as there was a weak but significant relationship ($y = 1116 + 0.042x$; $r^2=0.25$) between grain yield and sorghum density. The low sorghum density was probably due to waterlogging after planting and seedling attack by rodents. The average sorghum grain yield was quadruple the average grain yield of 500 kg/ha reported for semi-arid Zimbabwe**,** demonstrating the beneficial effect of early planting, integrated soil fertility management and timely weeding on sorghum grain yield. The sorghum residue yield was comparable to that of maize and can be used for mulching while the more palatable maize residue is fed to livestock. There were no differences in maize grain yield **due to tillage** (Table 7.) Although mulched MT had a lower maize density relative to un-mulched CONV this did not translate into yield decreases. The increase in maize residue yield on mulching ($y = 171.8x + 2754$; $r^2=0.22$) suggests improvements in availability of residues with time in CA. Improvements in soil physical and chemical properties in this rotation probably contributed to the high maize productivity**,** **which** was double that **from** the other fields. Mupangwa *et al*. (2012) recorded the **smallest** soil bulk density and **largest** soil organic carbon in this rotation. However, the **reduced** sorghum and maize density relative to un-mulched CONV suggests problems with crop establishment under CA**,** **which** may be due to adverse changes in crop seed micro-environment. As observed in the other experiments, mid to late season weeds decreased sorghum residue yield (Table 8). The suppression of late season weeds **by** mulching (Fig. 2 and 3) can potentially **contribute to a** decrease**d** weeding burden under CA.

Conclusion

Great weed growth was recorded in MT in the second **of** year maize **monocropping** and in PB for both seasons of the maize-cowpea rotation. The increased weed growth in PB under the maize-cowpea rotation was probably due to the wide row spacing and a poorly competitive cowpea variety highlighting the importance of selecting weed competitive crops in rotations. In contrast, there were no weed growth differences between CONV and MT except at a week before planting in the 4th year when PB had the **smallest** weed density in the maize-cowpea- sorghum rotation. In all cropping systems, maize residue mulching suppressed weed growth for most of the first season which translated, at times, to lower weed growth under mulched MT relative to un-mulched CONV. We found that mulched MT had up to 36% **less** weed growth compared to un-mulched CONV in the recommended maize-cowpea-sorghum rotation providing evidence for claims that CA reduces weed pressure compared to conventional tillage. Early planting in MT increased cowpea grain yield compared to CONV where planting was delayed due to waterlogged soils. The **smaller densities of** sorghum and maize in CA relative to un- mulched CONV in the maize-cowpea-sorghum rotation is suggestive of **problems with** crop establishment or rodents that may require further research to avert crop density-related yield losses. The maize-cowpea-sorghum rotation maize grain yield (3143 kg/ha) was 2.6 times the yield in the maize **monocropping** probably due to improvements in soil physical and chemical properties. When crops were planted on the same date, there was no yield difference between CA and un-mulched CONV. Interactions of treatments with management and climate suggest that on-farm demonstrations can be valuable for participatory evaluation and adaptation of CA to local conditions.

Acknowledgements

We wish to thank the Department for International Development of the United Kingdom, National Research Fund of South Africa and the International Foundation for Science for funding this study.

References

Andersson, J.A. & Giller, K.E. 2012. On heretics and God's blanket salemen: contested claims for conservation agriculture and the politics of its promotion in African smallholder farming. In: Sumberg, J. & Thompson, J. (eds.) *Contested Agronomy: Agriculture research in a changing world*. London. Earthscan. Chapter 2.

Baudron, F., Mwanza, H.M., Tiomphe, B. & Bwalya, M. 2007. *Conservation agriculture in Zambia: a case study of southern Province.* Nairobi; African Conservation Tillage Network, Centre de Cooperation Internationale de Recherche Agronomique pour le Development, Food and Agriculture Organizatiom of the United Nations.

Blubaugh, C.K. & Kaplan, I. 2016. Invertebrate seed predation reduces weed emergence following seed rain. *Weed Science* **64**, 80-86.

Chauhan, B.S., Singh, R.G. & Mahajan, G. 2012. Ecology and management of weeds under conservation agriculture: A review. *Crop Protection,* **38**, 57-65.

Dekker, J. 1999. Soil weed seed banks and weed seed management. In: Buhler D.D. (ed.) *Expanding the Context of Weed Management*. New York. The Haworth Press. pp. 139-166.

Dorado, J., Rel Monte, J.P. & Lopez-Fando, C. 1999. Weed seedbank response to crop rotation and tillage in semi-arid agroecosystems. *Weed Sci,.* **47**, 67-63.

Ekboir, R.J. (ed.) 2002. *CIMMYT 2000-2001 World Wheat Overview and Outlook: Developing No-till Packages for Small-Scale Farmers.* Mexico, DF: CIMMYT.

Food and Agriculture Organisation (FAO). 2016. Conservation agriculture: Controlling weeds. Available at: http://www.fao.org/ag/ca/africatrainingmanualcd/pdf%20files/07WEEDS.PDF accessed 1/13/2016

Genstat Release 10DE. Lawes Agricultural Trust. 2011. Rothamstead Experimental Station. VSN International Ltd. Hertfordshire HP1 1ES, UK.

Nyamangara, J., Mashingaidze, N. Masvaya, E.N., Nyengerai, K., Kunzekweguta, M., Tirivavi, R., & Mazvimavi, K. 2014. Weed growth and labour demand under hand-hoe based reduced tillage in smallholder farmers' fields in Zimbabwe. *Agriculture, Ecosystems & Environment,* **187**, 146-156.

Mafongoya, P., Rusinamhodzi, L., Siziba, S., Thierfelder, C., Mvumi, B. M., Nhau, B., Hove, L. & Chivenge, P. 2016. Maize productivity and profitability in Conservation Agriculture systems across agro-ecological regions in Zimbabwe: A review of knowledge and practice. Agriculture, Ecosystems & Environment, **220**, 211–225.

Mashingaidze, N., Madakadze, I.C., Twomlow, S.J., Nyamangara, J. & Hove, L. 2012. Crop yield and weed growth under conservation agriculture in semi-arid Zimbabwe. *Soil and Tillage Research,* **124**, 102-110.

Mashingaidze, N. 2013. *Weed dynamics in low-input dryland smallholder conservation agriculture systems in semi-arid Zimbabwe*. PhD Thesis. University of Pretoria. 205 pp.

Mavunganidze Z., Madakadze , I.C., Nyamangara, J & Mafongoya, P. 2014. The impact of tillage system and herbicides on weed density,diversity and yield of cotton (*Gossipium hirsutum* L.) and maize (Zea mays L.) under the smallholder sector. *Crop Prot.,* **58**, 25-32.

Mohammed, I.B., Olufajo, O.O, Singh, B.B., Miko, S. and Mohammed, S.G.2008. Growth and development of components of sorghum/cowpea intercrop in northern Nigeria .*ARPN Journal of Agricultural and Biological Science* 3, 7-13.

Moyo, M. 2001. Representative soil profiles of ICRISAT research sites. Chemistry and Soil Research Institute. Soils Report No. A666. AREX, Harare, Zimbabwe

Muoni, T., Rusinamhodzi, L., Rugare J.T., Mabra, S., Mangosho, E., Mupangwa, W. & Thierfelder, C. 2014. Effect of herbicide application on weed flora under conservation agriculture in Zimbabwe. *Crop Protection*, **66**, 1-7.

Mupangwa, W., Twomlow, S., Walker, S. & Hove, L. 2007. Effect of minimum tillage and mulching on maize (*Zea mays* L.) yield and water content of clayey and sandy soils. Phys. Chem. Earth **32**, 1127-1134.

Mupangwa, W., Twomlow, S. & Walker, S. 2012. Reduced tillage, mulching and rotational effects of maize (*Zea mays* L.), cowpea (*Vigna unguiculata* (Walp) L.) and sorghum (*Sorghum bicolor* L. (Moench)) yields under semi-arid conditions. *Field Crops Research*, **132**, 139-148.

Pedzisa, T., Rugube, L., Winter-Nelson, A., Baylis, K. & Mazvimavi, K. 2015. Abandonment of conservation agriculture by smallholder farmers in Zimbabwe. *Journal of Sustainable Development* **8**, doi.10.5539/jsd.v8n1p69.

Pittelkow, C.M., Liang, X., Linquist, B.A., van Groenigen, K.J., Lee, J., Lundy, M.E., van Gestel, N., Six, J., Venterea, R.T. & van Kessel, C. 2014. Productivity limits and potentials of the principles of conservation agriculture. *Nature*, 517, 365-368.

Teasdale, J.R. & Mohler, C.L. 1993. Light transmittances, soil temperature and soil moisture under residue of hairy vetch and rye. *Agron. J*., **85**, 673-680.

Vogel, H. 1994. Weeds in single crop conservation farming in Zimbabwe. *Soil Tillage Res*. **31**, 169-185.

Wall, P.C., Thierfelder, C., Ngwiza, A., Govaerts B., Nyagumbo, I. & Bauldron, F. 2013. Conservation agriculture in Eastern and Southern Africa. In: Jat, R.A., Graziano de Silva. (eds). *Conservation agriculture Global perspectives and challenges*. CABI, Cambridge, USA

Zimbabwe Conservation Agriculture Task Force (ZCATF). 2009. *Farming for the future: A guide to conservation agriculture in Zimbabwe*. Blue Apple Design, Harare, Zimbabwe.