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

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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 of maize–cowpea rotation and first and second year of maize monocropping on a clay loam soil at Matopos Research Station (annual rainfall, 573 mm) 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 maize residue mulch rate (0, 2 and 4 t/ha) as a subplot factor, with threefold replication. All subplots were surface mulched and weeded by hoe at the same time. We hypothesized that 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 unmulched 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 intrarow 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 unmulched CONV. When planted on the same date, crop yield did not differ between CA and unmulched 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 organizations 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 burden of weeding 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 in 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, whereas weed seeds remaining on the soil surface layer are exposed to predators and harsh environmental conditions (Dekker, 1999). Furthermore, the other CA practices, 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*., 1992) and Zimbabwe (Vogel, 1994). Rotating crops with varied growth patterns and management practices can lead to better weed control through decreases

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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 hypothesized 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 with 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 decreases weed growth and increased crop yield relative to the farmers' practice of unmulched mouldboard ploughing.

Materials and methods

Experimental site

The study was conducted at Matopos Research Station, Zimbabwe (28°30.92′E, 20°23.32′S; 1344 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 °C with 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 2004/2005 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 2-year cereal/legume rotation and the current practice used by smallholder farmers of monocropping maize. Weeds were not controlled in fields 2 and 3 during the fallow. Each experiment had a split-plot randomized complete block design. To facilitate animal-drawn operations, tillage was the main-plot (63 × 6 m) factor at three levels: mouldboard ploughing (conventional tillage, CONV), noninversion 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 × 6 m subplots within each tillage system and replicated three times.

Hoeing was carried out on all plots in July of each year to kill weeds and was followed by maize residue applications in August. The PB and RT plots were then prepared following Zimbabwe Conservation Agriculture Task Force (ZCATF)

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

Field	Crop grown			
	2004/2005	2005/2006	2006/2007[a]	2007/2008[a]
1	Maize	Cowpea	Sorghum	Maize
2	Fallow	Maize	Cowpea	Maize
3	Fallow	Fallow	Maize	Maize

[a]Study seasons.

(2009) guidelines (Table 2). Planting basins, 0.15 × 0.15 × 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 subplots 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).

Early-maturing crop varieties (Table 2) were grown to take advantage of the short-growing period at Matopos. In 2007/2008 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 Zimbabwe Conservation Agriculture Task Force (ZCATF) (2009) to reduce weed seed addition to the soil seed bank. Weeding was carried out at the same time in all subplots. Thiodan 35EC (80 mL in 20 L water) was sprayed on cowpea at 4 WAP and at 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 2006/2007 and 2007/2008 cropping seasons from the tillage × mulch subplots 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 subplot 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 2006/2007 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 °C to constant weight and the dry weight determined. In the following season, weed density data were collected at 1 week before planting and at 3, 9 and 13 WAP. Crop density per subplot 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 were 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 carried out 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 unmulched 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.

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

	Sorghum			Cowpea			Maize		
Crop	Mouldboard plough	Ripper tine	Planting basin	Mouldboard plough	Ripper tine	Planting basin	Mouldboard plough	Ripper tine	Planting basin
Variety[a]	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[b]	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[c]	6.7	5.6	7.4	8.3	5.6	7.4	3.7	3.7	3.7

[a]Same crop variety grown in all tillage systems. [b]Yield potential. [c]Target crop density.

Results and discussion

Seasonal rainfall

Although 2006/2007 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 (Figure 1). Rainfall 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 (Figure 1b). Lengthy dry spells between 29 December 2006 and 6 February 2007 result in late application of N

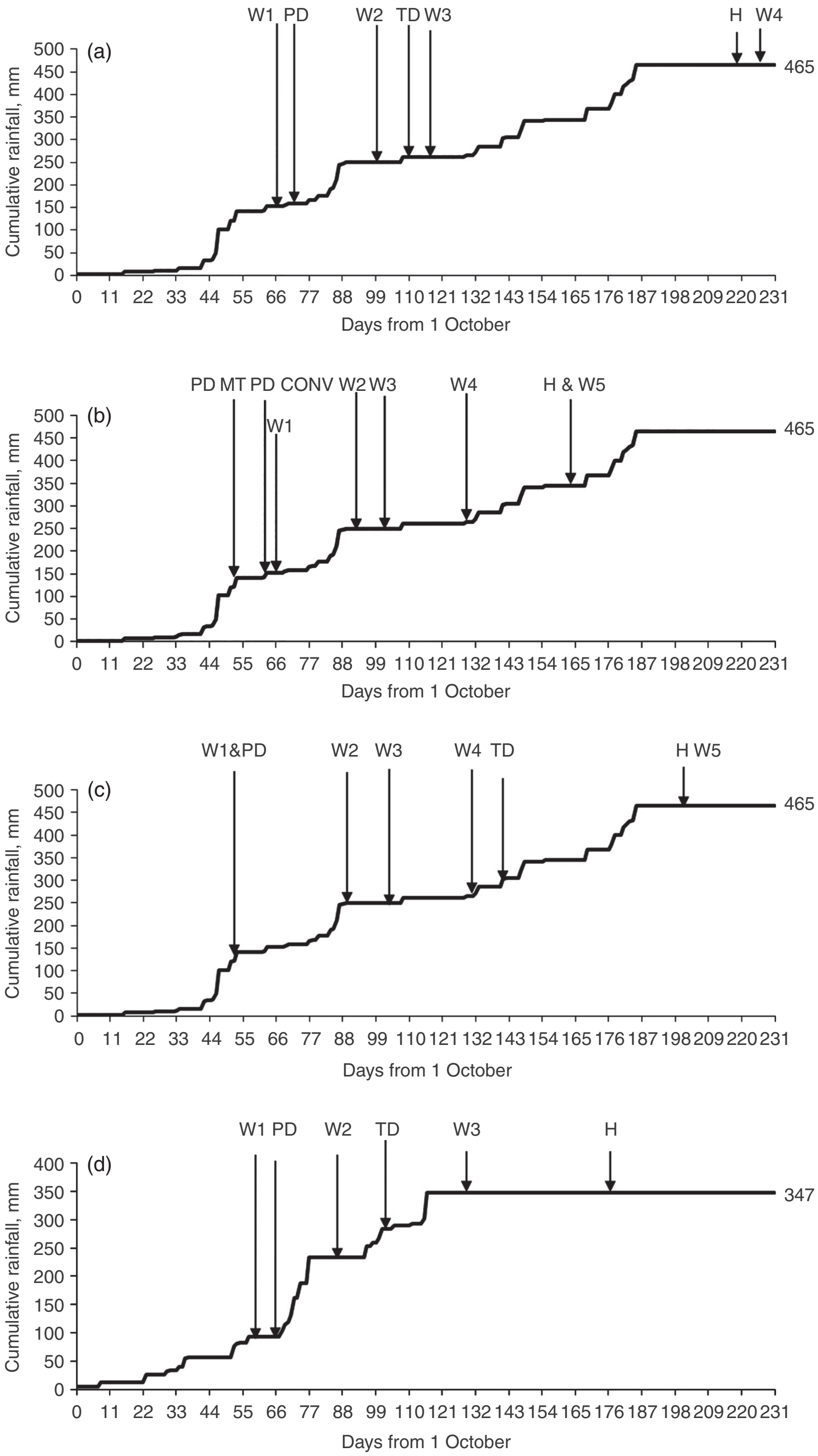

Figure 1 Cumulative daily rainfall received and the timing of crop management practices (a) sorghum, (b) cowpea (c) maize crops grown during the 2006/2007 season and (d) maize in 2007/2008 season at Matopos Research Station. W1 to W5: hoe weeding operations; PD, planting date; MT, minimum tillage; CONV,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

fertilizer to the cereal crops. These dry periods coincided with maize and sorghum anthesis and grain set. Although the first half of the 2007/2008 cropping season had better rainfall distribution than the 2006/2007 season, the season ended abruptly on 15 January 2008 (Figure 1d) during maize tasselling. This cessation resulted in small weed infestations in maize fields such that only three postplanting weedings were carried out compared to four in the previous season (Figure 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 monocropping. 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 plots. Weed suppression increased with maize residue mulch rate for most of this season (Figure 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 (Figure 2f) probably contributed to the smaller weed biomass in mulched MT relative to unmulched 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 1 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. Greater 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 under maize residue mulching (Table 3), weed density under mulched PB and RT still remained greater than unmulched 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 intrarow 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 greater postplanting weeding operations in cowpea than in other crops (Figure 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 (Figure 3). As observed in first year of maize, the strongest relationship between weed suppression and mulching was at 19 WAP (Figure 3c) when weed biomass was significantly reduced in mulched MT relative to unmulched 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 greater 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 unmulched 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 unmulched CONV showing a positive correlation between weed suppression and mulch rate. The high incidence of a tillage effect on weeds under maize has been due to the preceding cowpea crop having allowed some weeds to escape and set seeds. Dorado *et al.* (1999) observed greater 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 (Figure 4), contributing to

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

				P-value of treatments										
				Weed density at WAP				Weed biomass at WAP				Crop yield		
Rotation	Crop (season)	Source of variation	DF	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[b]	0.954	0.428	0.112	0.039[b]	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[a]	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
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[a]	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

Table 3 (continued)

Rotation	Crop (season)	Source of variation	DF	Weed density at WAP 3	5	9	19	Weed biomass at WAP 3	5	9	19	Crop yield Density	Grain	Residue
	Contrasts													
	CONVO vs. (mulched PB and mulched RT)/4		1	< 0.0001	0.262	0.019[b]	0.005					054	0.162	0.34
	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[a]	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

CONV0, unmulched mouldboard plough; PB, planting basin; RT, ripper tine; WAP, weeks after planting, −1[a], 1 week before planting, [b], contrast tests ignored as overall $P > 0.05$ for one-way ANOVA

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/m²															
		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/m²															
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/m²															
Maize (2007/08)		−1[a] 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					[a]			ns			
Mulched PB vs. mulched RT		ns				ns					ns			ns			

CONV, mouldboard plough; RT, ripper tine; PB, planting basins; CONV0, unmulched mouldboard plough; MT + mulch, average of mulched PB and mulched RT; WAP, weeks after planting, [a]−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.

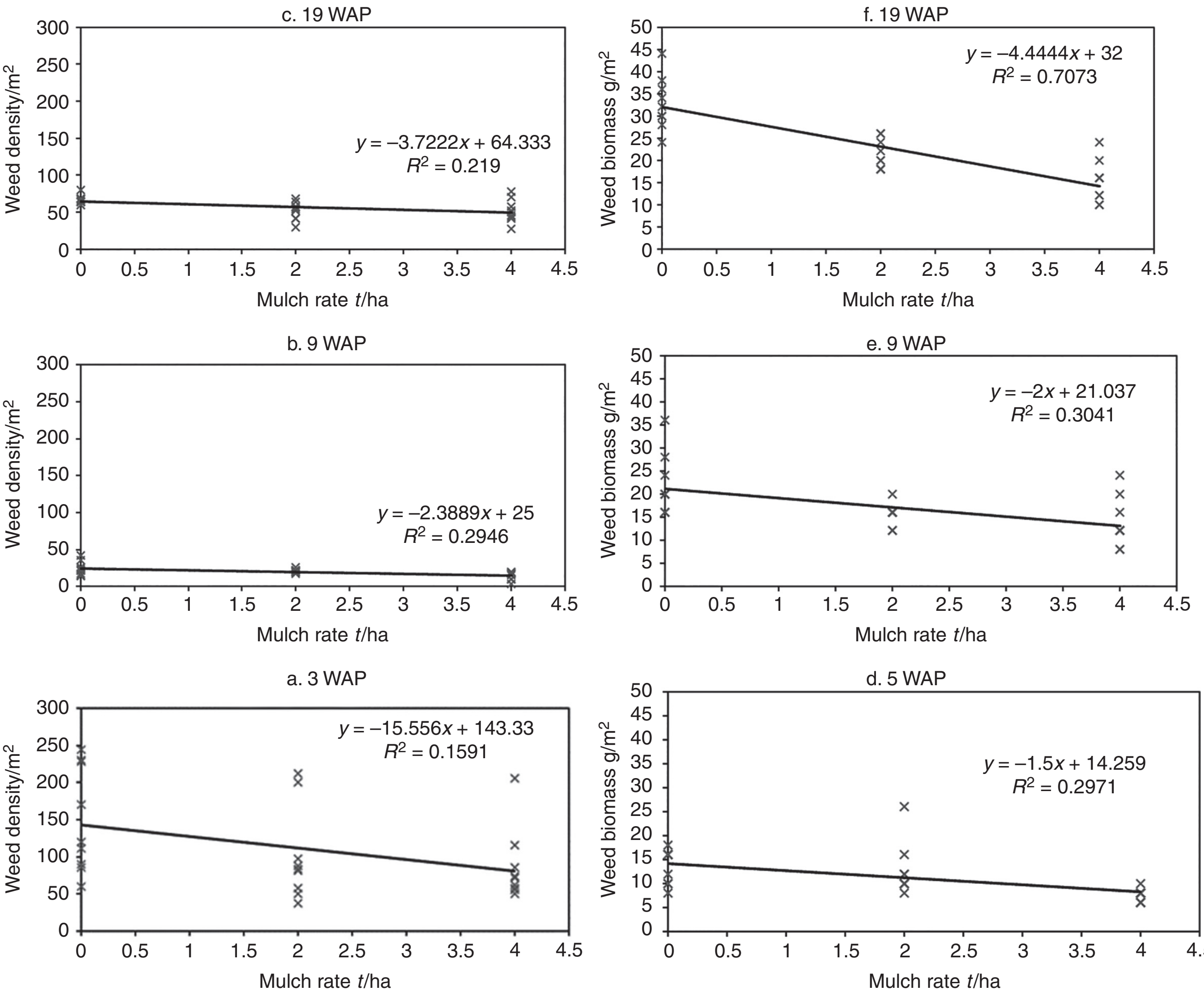

Figure 2 Responses of weed density (a, b, c) and weed biomass (d, e, f) to maize residue mulch rate in the first year of maize monocropping during the 2006/2007 season.

36% lower weed density at 5 WAP and between 18 and 26% reduction in weed biomass from 5 WAP in mulched MT relative to unmulched CONV (Table 6). This supports reports by CA proponents that CA reduces weed pressure compared to unmulched 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 unmulched CONV. However, at 1 week before planting maize residue, mulching was associated with increased weed density (Figure 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 a relatively dry first week of December 2007 (Figure 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 compositions, dominated by *Setaria* spp. and similar average weed density under maize during the 2007/2008 season (Figure 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

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

		Weed density/m^2															
		3 WAP				5 WAP				9 WAP				19 WAP			
Crop (Season)	Tillage/ Mulch rate	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 (2006/07)	CONV	41	36	29	36	36	32	34	34	23	16	21	20b	45	37	32	38
	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															
		3 WAP				5 WAP				9 WAP				19 WAP			
Cowpea (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															
		−1[a] WAP				3 WAP				9 WAP				13 WAP			
Maize (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, unmulched mouldboard plough; MT + mulch, average of mulched PB and mulched RT; WAP, weeks after planting; [a]−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.

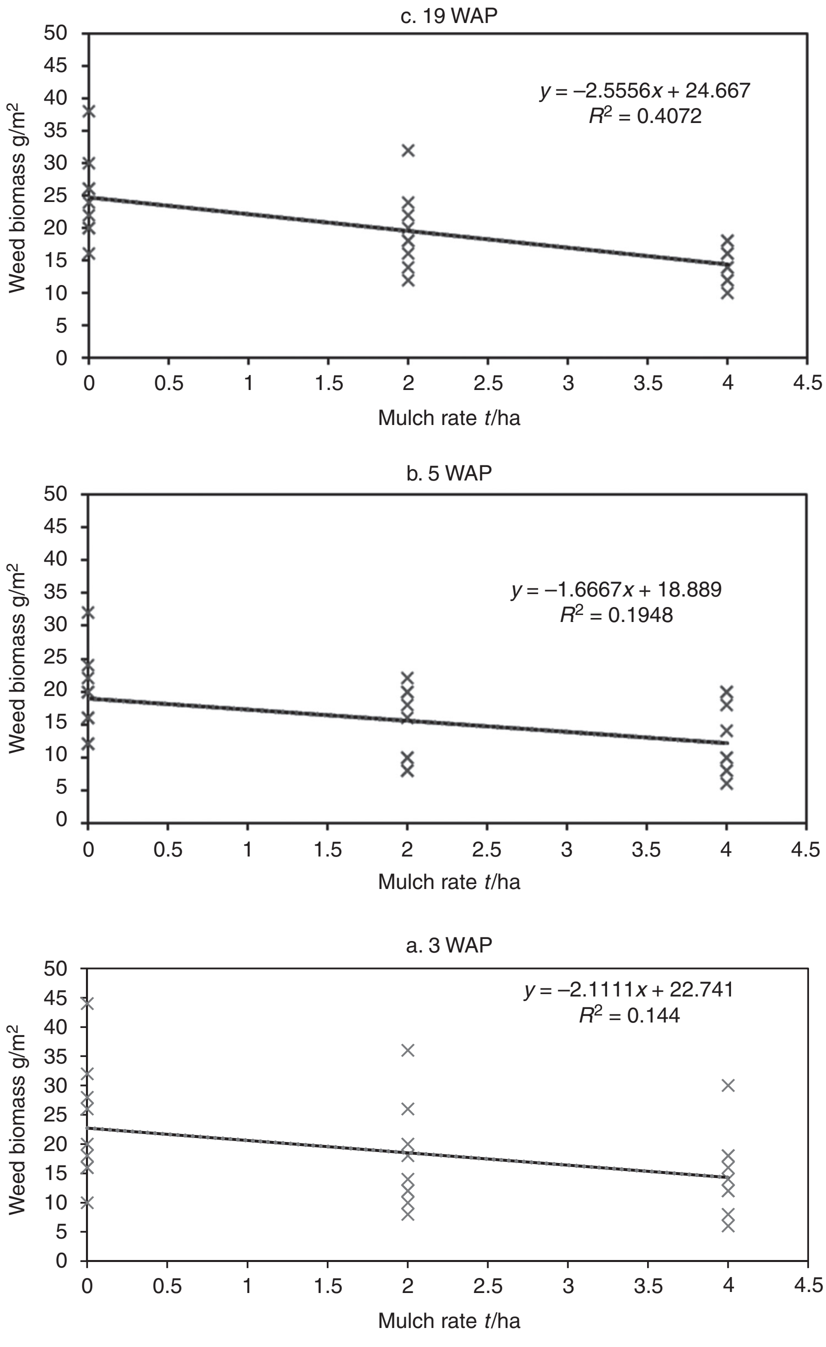

Figure 3 Responses of weed biomass to maize residue mulch rate in the second year of maize–cowpea rotation during the 2006/2007 season.

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 three to four times within the cropping season to maintain relatively weed-free conditions (Figure 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 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

		Weed density/m^2															
		3 WAP				5 WAP				9 WAP				19 WAP			
Crop (Season)	Tillage/ Mulch rate	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				a				ns				ns			
Mulched PB vs. mulched RT		ns				ns				ns				ns			

		Weed biomass g/m^2															
		3 WAP				5 WAP				9 WAP				19 WAP			
Sorghum (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	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				a				a				a			
Mulched PB vs. mulched RT		ns				ns				ns				ns			

		Weed density/m^2															
		−1[a]WAP				3 WAP				9 WAP				13 WAP			
Maize (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	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, unmulched mouldboard plough;MT + mulch, average of mulched PB and mulched RT, WAP, weeks after planting; a −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.

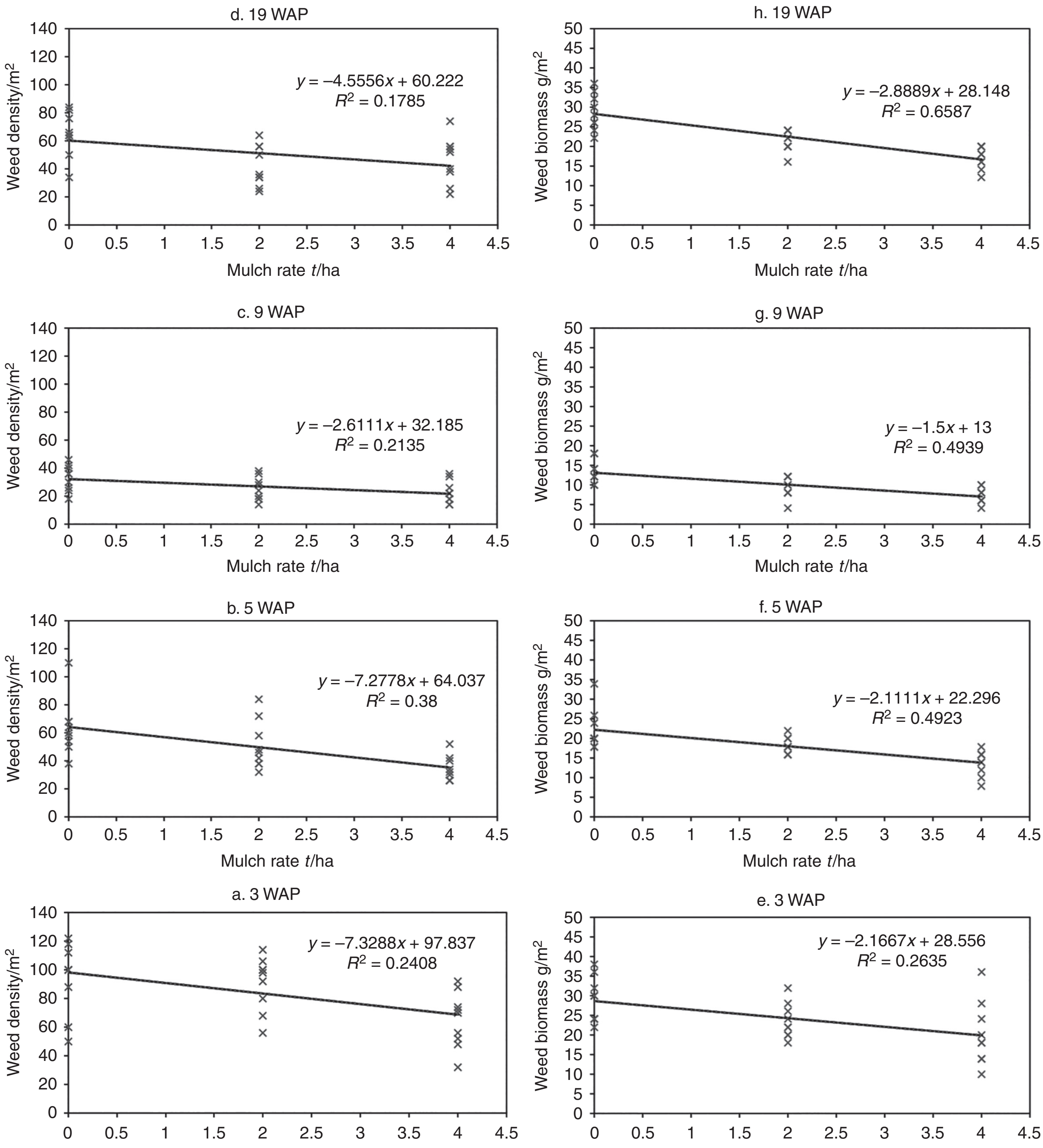

Figure 4 Weed density (a, b, c and d) and weed biomass (e, f, g and h) responses to maize residue mulch rate in the third year of maize–cowpea–sorghum rotation during the 2006/2007 season.

(Table 7) possibly through adverse changes in the maize seed environment. However, 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 unmulched CONV (Table 7). Mulching may have improved soil moisture during dry spells that coincided with maize anthesis. For maize

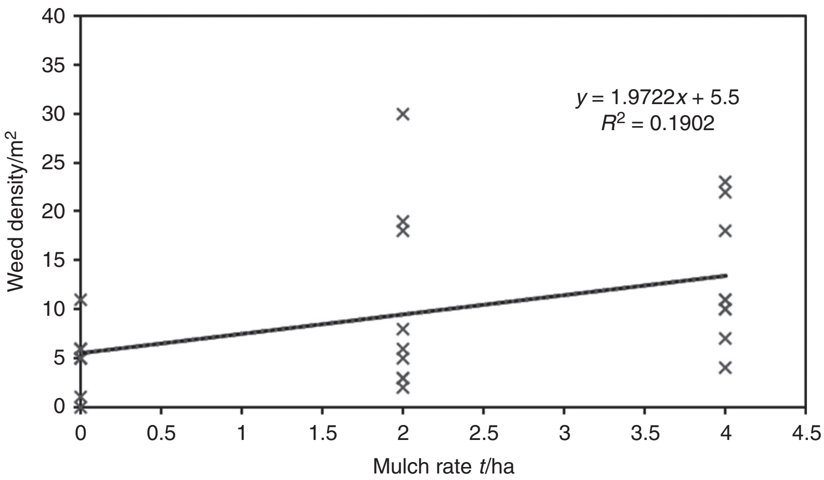

Figure 5 Response of weed density at 1 week before maize planting to maize residue mulch rate in the fourth year of a maize–cowpea–sorghum rotation during the 2007/2008 season.

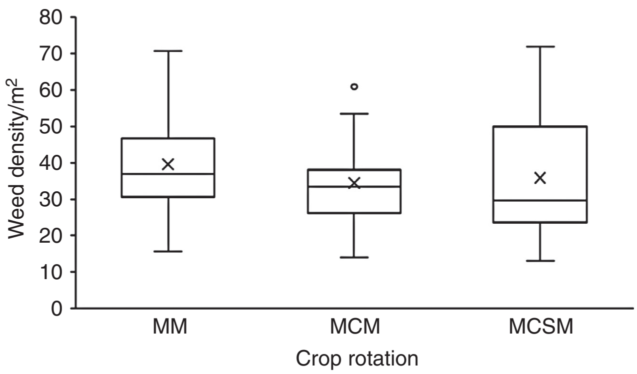

Figure 6 Boxplots showing the distribution of average weed density in maize grown under different crop rotation sequences during the 2007/2008 season at Matopos. The mean is marked by X within each boxplot. MCM, maize–cowpea-maize; MCSM, maize–cowpea–sorghum–maize; MM, maize–maize rotations.

residue, in RT, the greatest mulch rate out-yielded the unmulched CONV by 32%, whereas a residue yield depression of up to 32% occurred in PB. Consequently, mulched RT out-yielded mulched PB but with both being greater than unmulched 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 five times the residue yield in CONV (Table 7) with a similar trend observed for mulched MT and unmulched CONV. This greater yield relative to CONV is probably the result of early planting, cowpea being planted two weeks later in CONV (Figure 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 growth 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 small 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 unmulched 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

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 yield											
			Density/m^2				Grain yield kg/ha				Residue yield kg/ha			
Crop rotation	Crop (season)	Tillage/ mulch rate	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; unmulched 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 = $\times 60x+5061$; $r^2 = 0.11$; SE = 857

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

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 unmulched 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 (Figures 2 and 3) can potentially contribute to a decreased burden from weeding under CA.

Conclusion

Great weed growth was recorded in MT in the second year of 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 crops in rotations that are competitive with weeds. 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 less weed growth under mulched MT relative to unmulched CONV. We found that mulched MT had up to 36% less weed growth compared to unmulched CONV in the recommended maize–cowpea–sorghum rotation, providing evidence for claims that CA reduces weed pressure compared to conventional tillage. Early planting with 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 unmulched 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 unmulched 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.

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