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Evaluation of chemical and non-chemical weed control practices on weed communities and maize yield in two agroecological zones of Swaziland

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Manual weeding, maize-cowpea intercropping, pre-emergence (PRE) and early post-emergence (EPOST) herbicide applications comprised ten weed control practices evaluated in the 2015-16 cropping season on weed species structure and maize (*Zea mays* L.) yield in the Middleveld and Highveld of Swaziland. The herbicides used were Harness (acetochlor) and Dual Gold (S-metolachlor) as pre-emergence applications and Micro-Tech (alachlor) and Callisto (mesotrione) as early post-emergence applications. PRE and EPOST herbicides were used as once-off or combined applications besides manual weeding or intercropping practices. Results indicated that the combination of PRE and EPOST herbicides reduced both species richness (number) and evenness (dominance) but weed species composition (types) were not distinguished amongst treatments. Manual weeding in combination with PRE herbicides or maize-cowpea intercropping resulted in significantly lower weed density and biomass as compared to singular or combinations of PRE or EPOST herbicides in both locations. The effects of weed control practices on grain yield of maize were not significantly distinguished among weed control practices between the two sites. The study reaffirmed that herbicides may need to be supplemented with other weed control strategies to obtain acceptable weed control.

Key words: Herbicides, maize, Shannon-Wiener diversity index, Simpson's dominance index, Steinhaus coefficient index, weeds.

INTRODUCTION

Despite benefits that have been reported from chemical weed control practices in small scale crop production, effective control of weeds remains a major impediment to productivity as weed infestations continue to cause debilitating effects on crop health and human welfare under subsistence production (Gianessi and Williams, 2011). Although, awareness and use of herbicides for weed control in Swaziland has been increasing over the

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last decade, few smallholder farmers use herbicides and generally perform one manual-weeding operation (Mncube et al., 2017). The narrow range of herbicides available in the country and lack of knowledge on their correct use remains a big challenge for many farmers (Dlamini et al., 2016). In addition, most herbicide applications are limited to post-emergence (Mncube et al., 2017) and farmers do not practice soil cultivation practices to reduce weed escapes.

Sustainable agriculture calls for limiting use of herbicides either by reducing application rates (Zhang et al., 2013), herbicide rotations, use of selective narrow-spectrum products, containing the most ecologically detrimental range of products (Norsworthy et al, 2012) or using alternative soil and crop management methods (Pacanoski et al., 2015; Saudy, 2015). However, development of effective strategic combinations of weed control techniques, where herbicides are a part, remains a major limitation to farmers and their agents in emerging agriculture already beset with poor adoption of herbicide technology.

Armengot et al. (2012) reported that increasing intensity of various agricultural measures has led to strong changes in the structure of weed communities in developed agriculture. These changes have especially been attributed to altered standards of crop rotation and higher efforts in fertilizing and crop protection measures that include herbicides. In contrast, the present work suggests that intensive monoculture practices and lower efforts in weed control measures practiced by small scale farmers may have influenced weed community diversity, for instance, by altering the variation in both the numbers and kinds of species present. There remains inadequate information on weed community structure and abundance based on singular and combinations of manual, cultural and chemical weed control as a prelude to possible and potential approaches to practical weed management for small scale farmers. Arable fields in Swaziland are dominated by continuous maize production that occurs on 80% of 80,000 ha of total rain-fed cultivable land (Swaziland Government, 2016) where weeds are marginally controlled. A clear understanding of how the timing and longevity of different weed control practices condition weed communities is a key component in the development of integrated weed management programs to maintain low and consistent weed abundance and enhance yields of staple crops (Romero et al., 2008).

Ryan et al. (2010) suggested that weed management practices may filter specific characteristics that determine the trajectory of community change even in the short term. Most changes in biological community structure are reflected by distinct parameters of diversity which may be expressed by means of various measures and indices (Booth et al., 2003). The use of ecological indicators such as Shannon-Wiener Diversity index and Simpsons Dominance Index have been cited to provide information on species richness, evenness and dominance of weeds in croplands while measure of similarity or distinctiveness between communities within the landscape have been described by indices such as the Sørensen and Steinhaus Coefficient Indices (Nkoa et al., 2015). These indices have aided identification of floristic composition and characterization of weed populations of crops under varying management practices (Izquierdo et al., 2009; Concenço et al., 2011; Ramirez et al., 2014). The study hypothesized weed species diversity and abundance to be higher where manual and cultural methods were applied because of the lack of herbicide treatment and where singular methods were used because of weed escapes.

MATERIALS AND METHODS

Experimental sites

Experiments were conducted on experimental farms between November 2016 and March 2017 at Luve (26.32°S, 31.47°E, elevation 400-800 m.a.s.l.) and Mangcongco (26.58°S, 30.99°E, elevation 1200-1800 m.a.s.l.) in the Middleveld and Highveld of Swaziland, respectively. The total rainfall during the experimental period at Luve was 332 mm whose distribution was 76, 20, 54, 72.9, 108.8 mm and a total of 871.2 mm at Mangcongco with a distribution of 236.5, 165.4, 198.3, 152.9 and 118.1 mm for the months of November through March, respectively. The soil type at Luve was determined as sandy-loam with clay content of 19.3% while at Mangcongco, soils were characterized as sandy clay loams with clay content of 30%.

Experimental procedures

The experiment was designed as a randomized complete block design with four replications. The weed control practices shown in Table 1 were included in the study. The tillage method used in both locations was mouldboard ploughing to a depth of 20 cm followed by disc-harrowing. Maize, variety SC403 (Seed-Co®, Zimbabwe), was planted at a spacing of 0.9 m × 0.25 m. In plots with cowpeas, the variety IT18 was planted two seeds per hill in two hills at 0.10 m from maize planting hills. Basal fertilizer [N: P: K, 2: 3:2 (22)] was applied two weeks after planting maize at the rate of 400 kg ha^{-1} for Luve and 500 kg ha^{-1} at Mangcongco. Five weeks after emergence, the crop was side-dressed with LAN (28% N) at a rate of 100 kg ha^{-1} for Luve and 115 kg ha^{-1} at Mangcongco.

Pre-emergence (PRE) herbicide plots were planted as previously described and then sprayed with herbicides one day after sowing with rates of application adjusted based on soil clay content. Early post-emergence (EPOST) herbicides were applied when the crop had reached four- to five-leaf stage. Herbicides were applied using a hand-pumped CP-3 knapsack sprayer with Defy 3D angled nozzles calibrated to deliver 250 l ha^{-1} at 210 kPa. Manual weeding in particular plots was done once at five weeks after planting. This simulated the smallholder farmer practice in Swaziland of planting into a clean seedbed after mouldboard ploughing and then manual weeding 40 or more days after planting.

Crop yield and weed observations

In each sampling row for grain yield of maize, the crop was cut at the soil surface and yield at a predetermined moisture content of

Table 1. Weed control practices, time of application and expected efficacy

Treatment	Active ingredient	Time of application*	Expected efficacy
T1: Maize-cowpea + manual weeding	-	5 WAP	General
T2: Manual weeding (control)	-	5 WAP	General
T3: Harness	900 g/l Acetochlor	PRE	Annual grasses and broadleaf weeds; not effective for control of emerged seedlings
T4: Dual gold	960 g/l S-metolachlor	PRE	Control of several annual grasses; not effective for control of most broadleaves
T5: Micro-Tech	384 g/l Alachlor	EPOST	Control of several annual grasses; not effective for control of most broadleaves
T6: Callisto	Mesotrione	EPOST	Control of broadleaves; not effective for control of most grass weeds
T7: Harness + Micro-Tech	Acetochlor + Alachlor	PRE + EPOST	Annual grasses and broadleaf weeds;
T8: Dual gold + Callisto	s-Metolachlor + mesotrione	PRE + EPOST	Control of several annual grasses and broadleaves
T9: Harness + Manual weeding	Acetochlor	PRE + 5 WAP	General
T10: Dual gold + Manual weeding	s-Metolachlor	PRE + 5 WAP	General

*PRE = Preemergence, EPOST = early postemergence, 5 WAP = weeding 5 weeks after planting.

12.5% was determined. Weed samples were collected at physiological maturity (R6 growth stage) of the maize crop. Each sampling row for weeds was divided into three sub-units of equal length, and one sample quadrat of 0.5 m^2 was placed in line in each sub-unit. Thus, three samples were taken from each replication. All weed individuals of up to 5 cm in height were cut at the soil surface and taken to the laboratory for sorting and counting. Weed density was the number of plants rooted within each quadrat. Counted weeds were oven-dried at 80°C for 48 h and weighed to obtain weed biomass. Both weed biomass and density per quadrat were extrapolated to a square metre. Following observation of preponderance of *Cynodon dactylon*, density and biomass of *C. dactylon* was similarly and simultaneously assessed. The nomenclature of plant species followed that of botanical keys supported by regional field identification guides (Lightfoot, 1970; Vernon, 1983).

Rank-abundance was used to display species relative abundance data to provide a complete description of the community diversity and simultaneously show both components of species diversity, species number, and evenness under each weed control treatment (Ramírez, 2015). The relative abundance of a species indicates its degree of dominance or subordination in the weed community (that is, the lower the number, the greater the relative abundance of a species in the weed community and the higher its dominance).

The amount of diversity of weeds within weed control practices, termed alpha diversity, was determined by the Shannon-Wiener index (*H'*) and the Simpson dominance index (*D*). The Shannon-Wiener index is based on the proportional abundance of each species and specifies both species richness (number of species in a given area) and evenness (how relative abundance is distributed among species). However, the method is considered moderately sensitive to sample size. The Simpson index is based on the probability that two individuals in a community sample will be of the same species. The method does not provide an assessment of species richness but measures the state of dominance within the community which is useful in describing evenness. This method is considered less sensitive to sample size. Weed species diversity between weed control practices was based on determining similarity of the composition of weed communities through the calculation of the Steinhaus Coefficient Index (S_A). The index estimates the smallest abundance for each species established in different communities as a proportion of the average community abundance (Booth et al., 2003). The ten weed control practices were compared pairwise and a matrix of values of index of similarity of weeds between treatments established. The indices were computed in accordance with the equations below cited by Booth et al. (2003):

$$H' = -\sum p_i \times \ln p_i$$

$$D = \Sigma\{[ni\ (ni - 1)] / [N(N - 1)]\}$$

$$S_A = W/[(A + B)/2] = 2W/(A + B)$$

Where, ln = natural logarithm; *ni* = number individuals per species; *N* = total number of all species in the community; *pi* = proportional abundance of each species (n_i/N); W = sum of the lower of the two abundances of each species in the community; A = total number of individuals in population A; B = total number of individuals in population B.

Statistical analysis

Prior to statistical analysis, weed density and biomass data were square root transformed ($\sqrt{x + 0.5}$) to homogenize variances (Palaniswamy and Palaniswamy, 2006). All data (weed density, weed biomass and crop yield) were subjected to analysis of variance using GenStat Release 9.1. The means of the treatments were separated by least significant difference (LSD) at 5% level of significance. Data are presented as untransformed means.

RESULTS

Weed species composition and diversity

Five common weed species from each of the weed control practices obtained from ranking of the frequency of the occurrence of the species are presented in Table 2. Except for *Tigetus minuta* at Luve and *Cleome monophylla* at Mangcongco, the two locations shared the same most abundant weed species. *Cyanodon dactylon* was the only species that was observed to exist in all the

Table 2. Rank of abundance of five most prevalent weed species existing in each of the weed control practices at Luve and Mangcongco.

Location/species name	Weed control practice*									
	T1	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**	**T9**	**T10**
Luve (*S* = 10)[†]										
Tigetus minuta	-	2	-	-	4	3	-	-	-	3
Cynodon datylon	2	1	1	1	1	1	1	1	1	1
Acanthospermum hispidum	-	-	2	2	3	-	-	-	2	-
Richardia scabra	1	3	-	-	2	2	2	-	3	2
Xanthium strumonium	-	3	3	3	4	3	3	-	-	-
Number of species	*2*	*4*	*4*	*4*	*5*	*5*	*3*	*1*	*6*	*5*
Mangcongco (*S* = 8)										
Cleome monophylla	-	-	-	-	2	2	-	-	-	-
Cynodon datylon	2	1	1	1	1	1	2	1	1	1
Acanthospermum hispidum	1	3	4	3	-	4	-	-	-	-
Richardia scabra	2	2	3	-	3	3	1	-	2	2
Xanthium strumonium	2	2	2	-	4	-	3	-	-	-
Number of species	*4*	*4*	*5*	*4*	*4*	*4*	*3*	*1*	*2*	*2*

*T1: Maize-cowpea + manual weeding; T2: Manual weeding only; T3, Harness (PRE); T4: Dual gold (PRE); T5: Micro-Tech (EPOST); T6: Callisto (EPOST); T7: Harness (PRE)+ Micro-Tech (EPOST); T8: Dual gold (PRE)+ Callisto (EPOST); T9: Harness (PRE) + manual weeding; T10: Dual gold (PRE) + manual weeding; †*S* = total number of species or species richness in research area.

Table 3. Weed species diversity based on Simpson's Dominance Index (*D*) and Shannon-Wiener Diversity Index (*H'*) at Luve and Mangcongco.

Treatment	Simpson Index (*D*)		Shannon–Wiener Index (*H'*)	
	Mangcongco	**Luve**	**Mangcongco**	**Luve**
T1: Maize-cowpea + manual weeding[a]	4.7	2.0	0.60	0.29
T2: Manual weeding only	4.4	3.8	0.60	0.56
T3: Harness (PRE)	5.2	3.7	0.68	0.57
T4: Dual gold (PRE)	3.4	3.6	0.55	0.47
T5: Micro-Tech (EPOST)	4.1	3.4	0.60	0.59
T6: Callisto (EPOST)	4.4	3.6	0.60	0.61
T7: Harness (PRE)+ Micro-Tech (EPOST)	2.7	2.2	0.44	0.38
T8: Dual gold (PRE)+ Callisto (EPOST)	1.0	1.0	0.00	0.00
T9: Harness (PRE) + manual weeding	2.0	5.5	0.30	0.73
T10: Dual gold (PRE) + manual weeding	2.1	4.5	0.30	0.64

weed control practices and was predominantly ranked first in terms of abundance at both locations. *Richardia scabra* was the second-most prevalent in either location. There was residual presence of *C. monophylla*, an important edible plant in Swaziland, in two EPOST weed control practices at Mangcongco.

The Shannon-Wiener Diversity Index (*H'*), and the Simpson's Dominance Index (*D*) were computed as an estimate of weed species diversity within weed control practices (alpha-diversity) (Table 3). At both Mangcongco and Luve, the lowest values of evenness (*D*) and species richness (*H'*) were evident with combination of Dual gold (PRE) + Callisto (EPOST) (T8). In addition, at Mangcongco, Harness (PRE) + Micro-Tech (EPOST) (T7), and manual weeding in combination with pre-emergence herbicides (T9 and T10) also showed lower species evenness and richness. At Luve, manual weeding and intercropping (T1) and Harness (PRE) + Micro-Tech (EPOST) (T7), additionally showed lower species evenness (*D*) and the same treatments with the addition of Dual gold (PRE) (T4) showed lower species richness (*H'*).

The measure of similarity or distinctiveness of weed species composition between weed control treatments (beta diversity) using the Steinhaus Coefficient Index (S_A) is given in Table 4 for Luve. The combination of manual

Table 4. Similarity matrix of weed species based on Steinhaus Coefficient Index (S_A) at Luve.

Treatment	Treatments								
	T2	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**	**T9**	**T10**
T1*	0.49	0.54	0.56	0.49	0.39	0.37	0.26	0.59	0.44
T2		0.74	0.51	0.69	0.50	0.52	0.28	0.71	0.73
T3			0.78	0.85	0.54	0.67	0.41	0.60	0.57
T4				0.77	0.49	0.85	0.56	0.51	0.52
T5					0.58	0.69	0.49	0.69	0.63
T6						0.50	0.11	0.64	0.58
T7							0.57	0.44	0.53
T8								0.21	0.28
T9									0.78

*T1: Maize-cowpea + manual weeding; T2: manual weeding only; T3, Harness (PRE); T4: Dual gold (PRE); T5: Micro-Tech (EPOST); T6: Callisto (EPOST); T7: Harness (PRE)+ Micro-Tech (EPOST); T8: Dual gold (PRE)+ Callisto (EPOST); T9: Harness (PRE) + manual weeding; T10: Dual gold (PRE) + manual weeding.

Table 5. Similarity matrix of weed species based on Steinhaus Coefficient Index (S_A) at Mangcongco

Treatments	Treatments								
	T2	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**	**T9**	**T10**
T1*	0.87	0.74	0.69	0.69	0.72	0.62	0.21	0.42	0.50
T2		0.66	0.74	0.77	0.77	0.61	0.31	0.46	0.54
T3			0.71	0.82	0.77	0.63	0.32	0.57	0.64
T4				0.83	0.73	0.68	0.52	0.65	0.60
T5					0.83	0.68	0.39	0.68	0.73
T6						0.74	0.22	0.47	0.53
T7							0.21	0.48	0.56
T8								0.63	0.53
T9									0.85

*T1: Maize-cowpea + manual weeding; T2: manual weeding only; T3, Harness (PRE); T4: Dual gold (PRE); T5: Micro-Tech (EPOST); T6: Callisto (EPOST); T7: Harness (PRE)+ Micro-Tech (EPOST); T8: Dual gold (PRE)+ Callisto (EPOST); T9: Harness (PRE) + manual weeding; T10: Dual gold (PRE) + manual weeding.

weeding with maize-cowpea intercropping (T1) showed lower similarity of weed community contrasted with six other weed control practices using S_A values ranging from 0.26 to 0.49. Similar results were obtained with the combination of Dual gold (PRE) and Callisto (EPOST) (T8) against five weed control practices using S_A values between 0.11 and 0.49. Based on S_A values >0.5, 71% of the treatment pairs showed similarities between weed communities at Luve. At Mangcongco (Table 5), S_A values of the combination of Dual gold (PRE) and Callisto (EPOST) versus other weed control practices were similar to that at Luve. Similarities between weed communities at Mangcongco accounted for 78% treatment pairs that subtended S_A values >0.5.

Weed density and biomass

Manual weeding in combination with pre-emergence herbicides or maize-cowpea intercropping resulted in significantly lower weed density as compared to pre- or post-emergence herbicide weed control in both locations (Table 6). There were no significant differences in weed density amongst pre- and post-emergence herbicides or their combined applications. There were no significant differences in efficacy of weed control practices on weed density between the two locations except with the combination of Dual gold (PRE) + Callisto (EPOST) which resulted in significantly lower weed density at Mangcongco when compared with Luve.

The effect of weed control practices on weed biomass is similar to that of weed density at Luve where manual weeding in combination with pre-emergence herbicides or maize-cowpea intercropping resulted in significantly lower weed biomass as compared to pre- or post-emergence herbicide weed control. At Mangcongco, Harness (PRE), Dual gold (PRE) and Micro-Tech (EPOST) were similarly and significantly less efficacious than other weed control practices. Using combined applications of PRE and EPOST herbicides (T7 and T8)

Table 6. Density and biomass of weeds at Luve and Mangcongco.

Treatment	Weed density (No. m^{-2})		Weed biomass (g m^{-2})	
	Luve	Mangcongco	Luve	Mangcongco
T1: Maize-cowpea + manual weeding	16.2^{b}	20.9^{d}	22.3^{c}	22.7^{b}
T2: Manual weeding only	20.7^{b}	24.9^{cd}	26.3^{c}	30.8^{b}
T3: Harness (PRE)	35.8^{a}	35.9^{abc}	46.9^{ab}	44.5^{a}
T4: Dual gold (PRE)	37.8^{a}	42.5^{a}	55.8^{a}	50.7^{a}
T5: Micro-Tech (EPOST)	37.3^{a}	39.6^{a}	43.4^{ab}	49.3^{a}
T6: Callisto (EPOST)	35.5^{a}	36.7^{ab}	41.6^{bA}	27.2^{bB}
T7: Harness (PRE) + Micro-Tech (EPOST)	32.9^{a}	25.6^{bcd}	44.4^{abA}	24.4^{bB}
T8: Dual gold (PRE) + Callisto (EPOST)	37.3^{aA}	26.2^{bcdB}	47.3^{abA}	27.1^{bB}
T9: Harness (PRE) + manual weeding	19.7^{b}	25.2^{cd}	26.8^{c}	26.9^{b}
T10: Dual gold (PRE) + manual weeding	21.7^{b}	23.3^{d}	28.9^{c}	22.1^{b}
SE (between treatments)	4.84	5.47	6.01	7.91
LSD (between treatments)	9.90	11.17	12.27	16.15
SE (between locations)	3.66		4.97	
LSD (between locations)	7.31		9.93	

*Different lower case letters in each column indicate a difference between treatments according to Fisher protected LSD test at α = 0.05; †Different uppercase letters between columns indicate a difference between locations for each variable and respective treatment according to Fisher protected LSD test at α = 0.05; ‡Data were square root transformed before analysis.

Table 7. Density and biomass of *Cynodon dactylon* at Luve and Mangcongco.

Treatment	*C. dactylon* density (No. m^{-2})		*C. dactylon* biomass (g m^{-2})	
	Luve	Mangcongco	Luve	Mangcongco
T1: Maize-cowpea + manual weeding	7.0^{d}	9.7^{c}	13.3^{c}	18.1^{c}
T2: Manual weeding only	13.3^{c}	13.4^{c}	18.7^{c}	19.2^{c}
T3: Harness (PRE)	29.3^{b}	30.9^{a}	34.3^{ab}	35.6^{b}
T4: Dual gold (PRE)	30.0^{ab}	29.6^{ab}	35.5^{a}	38.5^{b}
T5: Micro-Tech (EPOST)	27.5^{b}	28.3^{ab}	32.3^{b}	35.6^{b}
T6: Callisto (EPOST)	24.8^{Bb}	32.4^{aA}	37.7^{b}	32.4^{b}
T7: Harness (PRE) + Micro-Tech (EPOST)	29.9^{b}	23.5^{b}	27.3^{b}	40.2^{ab}
T8: Dual gold (PRE) + Callisto (EPOST)	37.8^{aA}	27.5^{abB}	31.0^{aA}	51.1^{aB}
T9: Harness (PRE) + manual weeding	9.9^{cd}	13.3^{c}	15.8^{c}	16.3^{c}
T10: Dual gold (PRE) + manual weeding	12.3^{c}	13.4^{c}	14.6^{cA}	18.8^{cB}
SE (between treatments)	3.07	3.49	4.29	3.86
LSD (between treatments)	6.27	7.12	8.76	7.88
SE (between locations)	2.32		2.88	
LSD (between locations)	4.64		5.77	

*Different lower case letters in each column indicate a difference between treatments according to Fisher protected LSD test at α = 0.05; †Different uppercase letters between columns indicate a difference between locations for each variable and respective treatment according to Fisher protected LSD test at α = 0.05; ‡Data were square root transformed before analysis.

resulted in significantly lower weed biomass at Mangcongco when compared with Luve.

The efficacy of weed control practices on density and biomass of *C. dactylon* is similar to that of the weed complex (Table 7). Manual weeding in combination with pre-emergence herbicides or maize-cowpea intercropping resulted in significantly lower weed density and biomass as compared to performance of pre- or post-emergence herbicides or their combinations on *C. dactylon* at both locations. Dual gold (PRE) in combination with either Callisto (EPOST) or manual weeding, significantly resulted in lower biomass of *C. dactylon* in Mangcongco when compared with Luve. Contrasting results were obtained for weed density where Callisto (EPOST)

Table 8. Effect of weed control practices on grain yield of maize at Luve and Mangcongco.

Treatment	Yield (kg ha^{-1})	
	Luve	Mangcongco
T1: Maize-cowpea + manual weeding	2903.1^{abcdB}	4348.9^{aA}
T2: Manual weeding only	2625.2^{abcd}	3023.1^{bc}
T3: Harness (PRE)	2763.2^{abcd}	2358.5^{c}
T4: Dual gold (PRE)	3814.1^{abc}	3300.4^{abc}
T5: Micro-Tech (EPOST)	1624.5^{d}	2646.4^{c}
T6: Callisto (EPOST)	2152.9^{cd}	3455.7^{abc}
T7: Harness (PRE) + Micro-Tech (EPOST)	4244.2^{a}	4055.7^{ab}
T8: Dual gold (PRE) + Callisto (EPOST)	2733.2^{abcd}	3235.4^{abc}
T9: Harness (PRE) + manual weeding	3921.0^{ab}	3990.8^{ab}
T10: Dual gold (PRE) + manual weeding	2474.5^{bcdB}	4146.3^{abA}
SE (between treatments)	839.34	564.56
LSD (between treatments)	1714	1153
SE (between locations)	505.77	
LSD (between locations)	1400.99	

*Different lower case letters in each column indicate a difference between treatments according to Fisher protected LSD test at α = 0.05; †Different uppercase letters between columns indicate a difference between locations for each variable and respective treatment according to Fisher protected LSD test at α = 0.05.

significantly reduced weed density in Luve as compared to Mangcongco but the reverse was observed where Dual gold (PRE) in combination with Callisto (EPOST) showed greater suppression of weed numbers in Mangcongco than Luve. The effects of the remaining weed control practices on density and biomass of *C. dactylon* were not significantly distinguished between the two sites.

Crop yield

There were no significant differences in grain yield amongst weed control practices at Luve although the highest yield (4244.2 kg ha^{-1}) was obtained with the combination of Harness (PRE) + Micro-Tech (EPOST) application (T7) (Table 8). Similarly, the highest kernel yield (4348.9 kg ha^{-1}) obtained with maize-cowpea + manual weeding at Mangcongco was not significantly different from yields obtained with other weed control practices. The lowest yield (1624.5 kg ha^{-1}) was obtained with Micro-Tech (EPOST) at Luve, while Harness (PRE) gave the lowest kernel yield (2358.5 kg ha^{-1}) at Mangcongco. The effects of weed control practices on grain yield were not significantly distinguished between the two sites with the exception of manual weeding in combination with either maize-cowpea intercropping or Dual gold (PRE) that respectively performed 30-40% better at Mangcongco than Luve.

The relationship between maize yield and weed biomass for each of the weed control practice are indicated in Figures 1 and 2. At Luve, weed control practices that were combined with manual weeding (T1, T2, T9, T10) reduced weed biomass to less than 30 g m^{-2} where Harness (PRE) plus manual weeding (T9) showed the highest yield, 3,921 kg ha^{-1}, amongst the treatments (Figure 1). The combination of Harness and Micro-Tech (T7) and pre-emergence application of Dual Gold (T4), respectively, showed higher yields amongst the herbicide-based treatments. At Mangcongco (Figure 2), the performance of manual weeding combined with pre-emergence herbicides (T9, T10) or with maize-cowpea intercropping (T1) is similar at Luve. Amongst the herbicide treatments, the combination of Harness (PRE) and Micro-Tech (EPOST) (T7) showed higher yield (4,056 kg ha^{-1}) and weed suppression with biomass of less than 30 g m^{-2}.

DISCUSSION

Weed diversity

The present study considered that knowledge on distribution of weed diversity amongst weed control treatments may be useful for identifying variety of weed management practices. Derksen et al. (1995) reported that although herbicides may affect species richness because of their selectivity patterns, they generally affect relative abundance more than species composition. Gaba et al. (2016) however suggested a reappraisal of how herbicides affect yields of major crops following use and efficacy on weed infestations. They argued that herbicides affected rare species (species at low abundance in absence of herbicide application) rather than common weed species and non-targeted species rather than

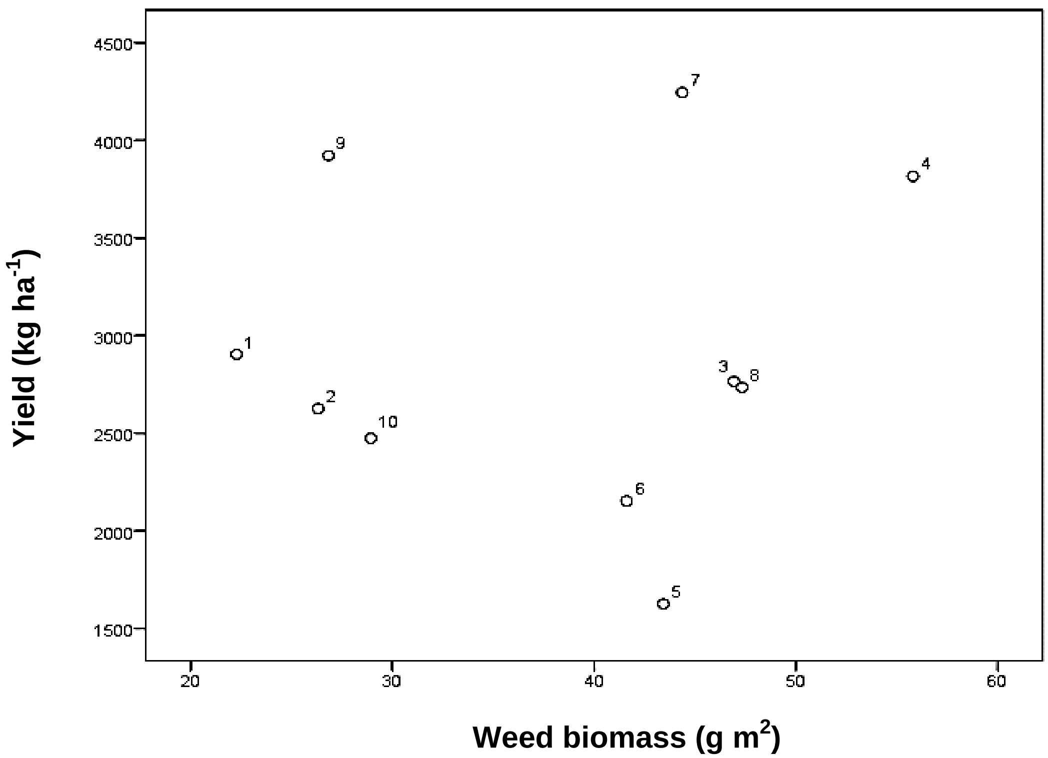

Figure 1. Box-plot of maize yield and weed biomass at Luve. Individual weed control treatments are identified by a number corresponding to their description given in Table 1.

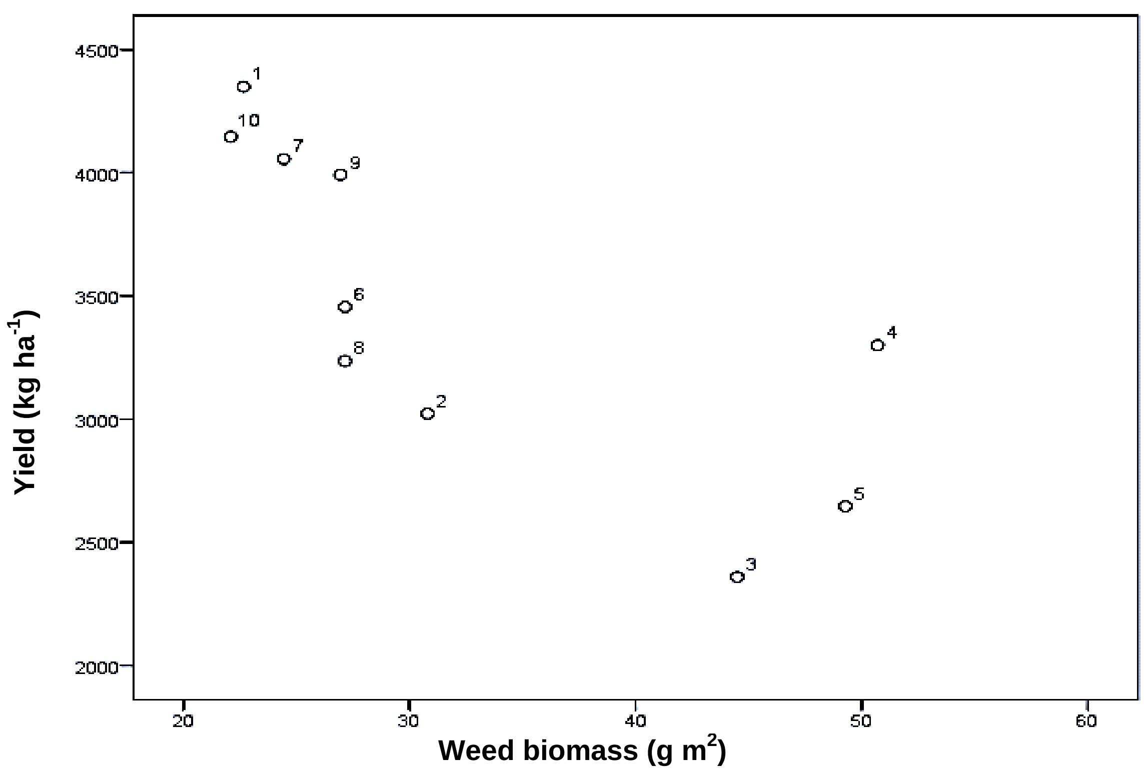

Figure 2. Box-plot of maize yield and weed biomass at Mangcongco. Individual weed control treatments are identified by a number corresponding to their description given in Table 1.

noxious species. The study expected that weed communities would differ between weed control treatments because of the timing and efficacy of control measures. The Steinhaus Coefficient Index showed that only 29 and 22% of paired comparisons of weed control treatments at Luve and Mangcongco, respectively, exhibited distinctiveness of weed species composition. The rank of abundance of five most prevalent weed species existing in each of the weed control treatments as well the Steinhaus Coefficient Index showed that the combination of Dual Gold (PRE) with Callisto (EPOST) was most effective against existing weed spectrum at either sites. In addition, at Luve, the combination of intercropping and manual weeding also showed differences in weed species composition versus other weed control treatments. It is considered that PRE applications which have residual activity through the soil may provide control of most common weed species. However, the application of PRE or EPOST herbicides alone, represent ‘one shot’ tool for the control of weeds. In this study, the Steinhaus Coefficient Index showed similarity in weed species composition amongst these treatments.

Weed density and biomass

Change in susceptibility of weed species associated with different weed control practices provides only part of the picture of the weed flora in arable fields. Weed density and biomass were significantly reduced by manual weeding and its combination with PRE herbicides or maize-cowpea intercropping at Luve. At Mangcongco, similar but insignificant trends were observed for weed density while greater weed biomass was obtained with singular applications of PRE or POST herbicides. Tesfay et al. (2014) showed lowest weed density recorded in plot treated with hand weeding and hoeing, while Kebede and Anbasa (2017) found statistically similar minimum weed density in plots hand weeded twice when compared with evaluated herbicides. Typically weed infestations are not uniform within and amongst agricultural fields with some areas within fields and across farmers’ fields having higher weed densities than others. However weed management practices tend to be applied uniformly across fields. Weed density and biomass (and diversity) data may allow development of recommendations that adjust rates of soil or foliar applied herbicides based on experiences of probable weed vegetation in addition to other factors at different agronomic landscape scales.

The study showed that *T. minuta*, *C. dactylon*, *Acanthospermum hispidum*, *R. scabra*, *Xanthium strumonium* and *C. monophylla* were species that occurred with rather high abundance in the researched areas. However, only manual weeding and its combination with PRE herbicides or maize-cowpea intercropping significantly reduced both density and biomass of *C. dactylon.* Despite 500 mm difference in rainfall during the cropping season between Luve and Mangcongco, only three treatments showed significant difference in weed density and biomass between them. The former location, with a lower rainfall regime, subtended higher weed biomass in those treatments. While environmental and other factors can result in sub-optimal performance from herbicide treatments (Izquierdo et al., 2009), the results showed that none of the herbicide treatments were efficacious against *C. dactylon* which prevailed in all treatments. Many farmers struggle to achieve effective weed control, largely due to lack of knowledge in selecting appropriate herbicides. In the present case, materials available at retail outlets appeared ineffective in the diminution of *C. dactylon* infestation.

Crop yield

There were no significant differences in grain yield amongst weed control practices at Luve although the highest yield (4244.2 kg ha^{-1}) was obtained with the combination of Harness (PRE) + Micro-Tech (EPOST) application. Similarly, the highest kernel yield (4348.9 kg ha^{-1}) obtained with maize-cowpea intercropping + manual weeding at Mangcongco was not significantly different from yields obtained with other weed control practices. In the current study, the box plots of weed biomass and maize yield showed that at Luve, manual weeding and its combination with PRE herbicides or maize-cowpea intercropping resulted in a reduction in weed biomass to below 30 plants m^{-2}. The highest crop yield amongst these treatments was where manual weeding was combined with application of Harness (PRE). Additionally, Dual Gold (PRE) and the combination of Harness (PRE) + Microtech (EPOST) also produced higher yields with the latter treatment showing better reduction in weed biomass. Similar trends in maize yield and weed biomass reduction under manual weeding and its combination with PRE herbicides or maize-cowpea intercropping practices were evident at Mangcongco.

While these results relate to other recent work in the region (Tesfay et al., 2014; Kebede and Anbasa, 2017), effects of crop yield-herbicides-weeds relationships will tend to be inconsistent experimentally amongst researchers and in practice versus farmers’ experiences based on an interplay of herbicide use, weeds and environment. While numerous studies have experimentally shown a relationship between herbicide use and crop yield, Gaba et al. (2016) suggested a reappraisal of how herbicides affect yields of major crops by taking into account, farmers’ decisions and adaptive practices. These attributes are considered to influence effectiveness of treatment through elements such as herbicide application mode (timing and dose), choice of active ingredient, depending on the observed or expected weed species, and the agricultural techniques used.

Earlier work has shown that weeds that emerge together with the crop or shortly thereafter cause greater yield reduction than weeds emerging later in the growth cycle of the crop (Swanton et al., 1999). Appropriate timing of control whether by application of PRE and POST herbicide combinations or by other means was shown to represent a significant opportunity to introduce control at the optimum time (Janak and Grichar, 2016). However, the efficacy of some PRE herbicides requires incorporation which is either machine- or rain-dependent. In the present study, Luve showed higher weed density and biomass due to lower rainfall to facilitate incorporation. On the other hand, post-emergence manual or chemical weed control practices are often compromised by continuous wet conditions post-planting which is characteristic of the beginning of the growing season in the region (Mashingaidze, 2004). There is still need for rigorous farmer support in the timely use of appropriate techniques for suitable PRE or POST herbicides in combination with recommended agronomic practices.

Implication of findings

The efficacy of weed control practices on simultaneous weed biomass reduction, lower weed diversity and high yield were evident for Harness (PRE) + Micro-Tech (EPOST) and for the combination of manual weeding with Harness (PRE). At Mangcongco, this was evident for manual weeding in combination with Dual Gold (PRE) or intercropping practice. This study argues that the employment of herbicides to reduce weed populations as an innovation in technology-deprived low-input systems is not enough; rather, the introduced technology should be evaluated together with rigorous reassessment of prevailing cropping systems and patterns. For instance, the prevailing annual cycle of tractor tillage and manual weeding allows *C. dactylon* (and other weeds) to survive in field headlands and crop edges or its stolons and rhizomes incorporated into the soil through soil inversion. The weed species is known to be a poor competitor for light but adaptively adjusts patch extension rate enabling it to grow in empty gaps and sustain field colonization (Guglielmini and Satorre, 2002). Santín-Montanyá et al. (2013) suggested that some factors (tillage and crop rotation), which have a species-specific effect on plant composition, may provide quicker and more detailed data on weed competitiveness processes occurring in an arable field. Thus, it may be necessary to explore the changes on weed communities according to species. Invariably, according to the present study, strategic tillage operations, competitive cropping practices and herbicide technologies should synergistically be evaluated as pillars of crop intensification to improve weed management and yields of staple crops.

Conclusion

The study showed that the combination of PRE and EPOST herbicides reduced both species richness and evenness like the combinations of manual weeding and PRE herbicides at Mangcongco or manual weeding and intercropping at Luve. Further, the study expected that weed communities would differ between weed control practices because of the timing and efficacy of control measures. Results showed that only 29 and 22% of paired comparisons of weed control treatments at Luve and Mangcongco, respectively, exhibited distinctiveness of weed species composition. The rank of abundance of five most prevalent weed species existing in each of the weed control treatments and dissimilarity index showed that the combination of Dual Gold (PRE) with Callisto (EPOST) was most efficacious against existing weed species composition at either sites. There were no significant differences in grain yield amongst weed control practices at Luve although the highest yield (4244.2 kg ha^{-1}) was obtained with the combination of Harness (PRE) + Micro-Tech (EPOST) application. Similarly, the highest kernel yield (4348.9 kg ha^{-1}) obtained with maize-cowpea intercropping + manual weeding at Mangcongco was not significantly different from yields obtained with other weed control practices.

The results suggest that weed control may move from being a predominantly post-emergence activity as practiced by small scale farmers to one split between controlling weeds pre- and early post-emergence, to impact weed management that is often considered for current season infestation than long-term diminution of the weed problem. In addition, there is potential for reducing weed infestation where manual weed control, which often occurs a month after planting, follows suitable pre-emergence herbicides rather than post-emergence herbicide application alone. Maize-legume intercropping significantly suppressed weed density and biomass of the intractable weed *C. dactylon* signifying potential for incorporating crop intensification techniques to address weed problems. The weed species was not controlled by any of the herbicide treatments suggesting need for integrative research insight into this problem that include strategic tillage practices and diversifying the range and weed spectrum of herbicides available at retail outlets for farmers' use.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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