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Full Length Research Paper

Efficacy and economics of manual and chemical weed control strategies in the first year of conservation agriculture adoption in the highveld areas of Zimbabwe.

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Adoption of conservation agriculture in Zimbabwe can be increased by the development of effective and economical weed control strategies. On station trials were carried out at two sites with contrasting soil textures namely, Domboshava Training Centre and Thornpark Estate in the 2007/8 rainy season to evaluate the effect of manual weeding, atrazine, glyphosate and a combination of the two herbicides on weed biomass, labour requirements for weed control, maize biomass, grain yield and economics of weed control. The experiment was laid out as Randomised Complete Block Design with three blocks and five treatments at each site. Weed counts were done whenever weeds were ten centimetres tall or ten centimetres length in weeds with a stoloniferous growth habit. Weed control strategy had no significant effect ($P > 0.05$) on weed biomass at Domboshava Training Centre and Thornpark Estate at first and second weeding, but had a significant effect ($P < 0.05$) at the third weeding at both sites. The Zamwipe (hand held weed wipe) strategy had significantly lower ($P < 0.05$) labour requirements than the other weed control strategies, but its use resulted in low plant populations and concomitantly low yields and economic returns at Domboshava Training Centre. The traditional manual hand hoe weeding strategy had the highest labour requirements at both sites. However, weed control strategy did not cause significant ($P > 0.05$) grain yield differences at both sites. The use of a tank mix of glyphosate and Atrazine resulted in the highest net benefit returns at Domboshava Training Centre and Thornpark Estate. Under the present circumstances, it can be concluded that the glyphosate + atrazine at planting + manual weeding strategy is the most economic weed control strategy in conservation agriculture.

Keywords: Conservation Agriculture, Weed Control Strategy, Economics, Herbicides, Manual weeding

INTRODUCTION

Conventional tillage (CT) which involves excessive soil movement due to the use of hand hoes and the mouldboard plough has resulted in excessive soil erosion and environmental degradation in most parts of Southern Africa (Penescu et al., 2001; Fowler and Rockston, 2001). In studies carried out by Munodawafa (2012), CT recorded the highest average soil losses of 15 tonnes per hectare (t/ha) due to erosion, while conservation tillage systems recorded between 1.2-1.3 t/ha. Furthermore, CT coupled with climate change effects such as increased surface evaporation due to increased heating, increased seasonal rainfall variability and an increase in the intensity and

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duration of droughts results in reduced crop productivity (Trenberth, 2011). To combat this scourge, conservation agriculture (CA), an approach to farming that was developed in the Americas is being promoted in the smallholder sector of Zimbabwe (Rusinamhodzi, 2011). CA is a resource saving technology (Haggblade and Tembo, 2003; Friedrich, 2009), which has been demonstrated to increase the soils biological, physical and chemical properties through minimum soil disturbance, use of diverse crop rotations and maintenance of a permanent soil cover (FAO, 2007). About 47 % of the technology is practised in Latin America, 39 % is practised in the United States of America and Canada, 9 % in Australia and about 3.9 % in the rest of the world including Europe, Africa and Asia (Derpsch, 2008). Minimum soil disturbance and permanent soil cover are the two CA principles that are currently being promoted in Zimbabwe (Thierfelder, 2012). The most common CA practise currently being promoted amongst the resource poor farmers in Zimbabwe is the use of planting basins. Planting basins are holes (0.15 m wide x 0.15 m long x 0.15 m deep) dug manually with a hoe in a weed free field into which a crop is planted (Mazvimavi and Tomlow, 2008; Thierfelder and Wall, 2008). Permanent soil cover is being achieved by the retention of previous crop residues and or relay intercropping with green manure cover crops (GMCCs) such as Lab lab (*Dolicos bean*), Tephrosia (*Tephrosia vogelli*), Raphanus (*Raphanus sativa*), Black bean (*Phasiolus vulgaris*), Grahamiana (*Crotalaria grahamiana*), Jack bean (*Canarvalia ensiformis*), Sunhemp (*Crotalaria ochraleuca*), Sunhemp (*Crotalaria juncea*), Velvet bean (*Mucuna pruriens*), Common vetch (*Vicia sativa*) and Cowpea (*Vigna unguiculata*). Apart from providing ground cover which reduces surface runoff, crop residues and GMCCs also play an important role in weed management through allelopathy (Runzika et al., 2013). Furthermore, less contamination of surface water occurs, and the emissions of CO_2 to the atmosphere are reduced in CA systems (Reicosky, 2008). Generally, CA reduces the energy consumption and work rate of farming operations in the range of 15-50 % and increases the energy productivity, that is, the yield output per input by 25-100 % (Garcia-Torres et al., 2001).

Giller et al. (2009) and Muoni et al. (2012) reported that one of the factors affecting widespread adoption of CA is weed control. Several researchers have found out that there is a general shift in weed composition from less problematic annual broadleaf and grasses to more difficult to control perennial weeds such as Couch grass (*Cynodon dactylon*) and Mexican clover (*Richardia scabra*) in CA systems (Vogel, 1994; Muliokela et al., 2001; Mashingaidze et al., 2012; Nyagumbo, 2008). As a result farmers are reluctant to adopt CA because of anticipated problems with weeds which result in reduced yields or total crop failure (Andreasen and Streibig, 2001; Mashingaidze et al., 2012). According to Nalewaja (2001), successful CA is highly dependent upon weed control. Currently smallholder CA farmers rely on manual hand hoeing which is both tedious and labour intensive (Chivinge, 1990; Vogel, 1994; Makanganise et al., 2001; Chikoye et al., 2007). In addition hand hoe weeding is not effective in controlling deep rooted perennial weeds with underground structures and has been cited as one of the major constraints to the adoption of CA in Zimbabwe (Mashingaidze et al., 2012). As a result, most of the CA farmers have not exceeded the 0.5 ha that they started with when CA programmes were introduced by Non Governmental Organisations that are promoting adoption of CA in Zimbabwe (Rugare, personal communication). The uptake of CA can be accelerated if efficious and environmentally friendly weed control strategies can be developed for smallholder farmers. The integration of chemical and manual weeding has become an attractive method of weed control due to its high efficacy and low cost (Jaya Suria et al., 2011). Despite the many benefits of herbicides, their use in the smallholder sector has been very low in Zimbabwe (Chivinge, 1984; Gatsi et al., 2001). The low uptake of herbicide use is due to lack of knowledge on how to use them as well as the unavailability of cheap herbicide application equipment (Gatsi et al., 2001). Herbicides are likely to increase the adoption of CA in Zimbabwe's smallholder sector where the labour base for weed control is declining due to poor health and rural urban migration as young people move to urban areas and neighbouring countries like South Africa in search of jobs (Gatsi et al., 2001, Locke et al., 2002). The use of pre emergent herbicides such as atrazine, supplemented with hand weeding has been reported to result in a fair degree of weed control (Pellerin and Webster, 2004). For maximum efficacy, atrazine should be applied to a moist soil in the first five days after planting (Jaya Suria et al., 2011). Atrazine is a plastoquinone binding site inhibitor herbicide that is commonly used in cereal based cropping systems. It can either be applied as a pre emergent herbicide for the control of broadleaved weeds and selected grasses but can also be applied early post emergence for the control of susceptible weed seedlings. Application of atrazine when weeds are older results in reduced efficacy on weeds because it is translocated in the apoplast where herbicides only move acropatally from the site of absorption. Inappropriate or wrong use of atrazine has resulted in reduced efficacy and carry over problems because it has a long half life and is very persistent hence the need to apply the recommended rates using properly calibrated spray equipment (Ross and Lembi, 1985). The other herbicide that has been widely used in areas where CA has been widely adopted is glyphosate. Glyphosate is a systemic non selective shikimate pathway inhibitor commonly used in CA systems, especially in countries where there is widespread production of glyphosate resistant crops (Bolliger et al., 2006). Post emergent application of glyphosate can be done in such crops

Table 1. **Treatment description**

Treatment 1:	Hand weeding whenever weeds were 0.1m tall or 0.1m in length for stoloniferous weeds prior to manual hand hoe weeding.
Treatment 2:	Glyphosate 0.96 kg active ingredient (a.i) per hectare in 200 litres of water at seeding, plus manual hand weeding whenever weeds were 0.1m long or 0.1m in length for stoloniferous weeds prior to manual hand hoe weeding.
Treatment 3:	Glyphosate 0.96 kg a.i per hectare in 200 litres of water at seeding, plus application of glyphosate 0.96 kg a.i per hectare in 5 litres of water using a hand held weed wipe (Zamwipe) after crop emergence whenever weeds were 0.1m tall or 0.1m in length for stoloniferous weeds prior to herbiciding.
Treatment 4:	Glyphosate 0.96 kg a.i per hectare, plus Atrazine 1.46 litres a.i /ha in 200 litres of water as a pre emergent herbicide at seeding plus manual weeding whenever weeds were 0.1m tall or 0.1m in length for stoloniferous weeds prior to manual hand hoe weeding.
Treatment 5:	Atrazine 1.46 litres a.i per hectare active ingredient in 200 litres of water at seeding plus manual weeding whenever weeds were 0.1m tall or 0.1m in length for stoloniferous weeds prior to manual hand hoe weeding.

without injuring the crops for the control of both annual and perennial weeds. Apart from being very effective in controlling a wide range of weeds, glyphosate is also environmentally friendly with a low mammalian toxicity (Wagner et al., 2003). Although glyphosate can be used to effectively control weeds in transgenic crops, its use in non transgenic crops has remained a challenge because even a single drop of glyphosate on the crop's leaves can result in the death of the whole plant. This is because glyphosate can be translocated from the site of absorption to the other parts of the plant making it impractical to apply glyphosate for selective control of weeds using ordinary shields. The use of glyphosate using a hand held weed wipe (Zamwipe) has been demonstrated in Zambia (Mashingaidze, 2012). A Zamwipe is a simple tool used to apply a highly concentrated solution of glyphosate by brushing the spongy wiping pad on interrow weeds that are 10-12 cm tall without the risk of crop injury due to drift. Very little is documented about the effectiveness of the weed wipe. Therefore, there is need to assess whether the use of the Zamwipe is a labour saving and economical method of weed control under CA. It was hypothesised that the use of weed control strategies that involve the use of herbicides results in better weed control, reduced costs of weed control than the traditional manual hand weeding only strategy and a concomitant increase in economic returns due to increased maize yields.

MATERIALS AND METHODS

Study sites

The experiments were carried out at two sites namely Domboshava Training Centre (DTC) and Thornpark Estate in the 2007- 08 rainy season. DTC (17^o 35' S, 310 10' E and 1560 meters above sea level (m.a.s.l)) is on sandy soils classified as *Aerosols* and *Luvisols* according to FAO classification. Thornpark Estate (17^o 80' S, 31^o 50' E and 1503 m.a.s.l) is characterised by red clay soils classified as *Chronic luvisol*. Total rainfall recorded in the 2007 – 08 season was 1288 mm and 953.6 mm at DTC and Thornpark Estate respectively. At DTC 75 % of the rainfall fell in December and January, while Thornpark Estate recorded 72.5 % during the same period.

Experimental design and treatment description

The experiments which were laid out as a randomised complete block design (RCBD) with three blocks consisted of five treatments as shown in Table 1. Blocking was according to slope of the field and there were three blocks at each site. Each block had five plots resulting in 15 plots per site and a total of 30 plots for the whole trial.

Experimental procedure

All the sites were planted between 6-15 December 2007 after the second rains typical of the time when smallholder farmers plant their maize crops. Land was not tilled and 2.5-3 t / ha maize residues were spread uniformly in the plots to achieve 50 % ground cover. The gross plot size was 472.5 m ^{2} (18.9 m x 25 m) and the net plot size was 31.5 m^2 (6.3 m x 5 m). Planting rows were marked out using an ox drawn ripper attached to an ox-drawn plough to ensure minimum disturbance of soil. Maize seed was planted at 0.9 m by 0.25 m spacing giving a plant population of 44 444 plants/ha. Maize Fert (Compound D) (7 % N, 14 % P_2O_5, 7 % K_2O) was applied in the planting furrow as a basal application before planting at a rate of 150 kg/ha using a 3.38 g fertilizer cup. Two seeds were planted per planting station and later thinned to one plant three weeks after crop emergence (WACE). Gap filling was done a week after crop emergence. Maize was top dressed using ammonium nitrate (AN) (34.5 % N) in equal splits of 75 kg/ha at five and nine WACE. Weed control was done whenever weeds were 0.1 m tall and/or 0.1 m in length for weeds with a stoloniferous growth habit as is the practice of smallholder farmers in Zimbabwe.

Data collection

Weed biomass measurements were taken by placing a 0.5 m x 0.5 m quadrant three times in a plot whenever weeds were 0.1 m tall or 0.1 m in length for stoloniferous weeds prior to weed control. Weeds inside the quadrant were cut at ground level and oven dried at 80^0 C for 48 hours and then weighed. The time taken to complete each weed control operation in the different plots was recorded in minutes and converted to labour days per hectare (Ld/ha). Each Labour Day is equivalent to eight hours. Grain and biomass yield was recorded at physiological maturity from 5 rows x 5 m net plots. Grain and biomass weight were recorded after drying in an oven at 80^0 C for 48 hours and grain yield was adjusted to 12.5 % moisture content using the formula below:

$$\text{Adjusted grain yield} = \frac{A(100 - \text{M})}{100 - 12.5}$$

Where, M is moisture content at weighing and A is actual measured seed weight.

Statistical analysis

Weed biomass and weed density data were square root transformed [√(x+1)] and were analysed using Statistix 9 for windows. Mean separation was done using a least significance difference test (LSD) where Analysis of Variance (ANOVA) indicated significant treatment effect at $P < 0.05$.

Economic analysis

Economic analysis was done using the method of (CIMMYT, 1988). The evaluation included partial budgets, dominance and marginal analysis.

Partial budgeting

Partial budgeting was done using the average grain yields for each treatment, the adjusted yields and the gross field benefit. Researchers have judged that farmers using the same technologies would obtain yields 10 % lower than those obtained by the researchers (CIMMYT, 1988). Therefore grain yields were adjusted downwards by 10 % to account for yield difference due to better management of the small plots. Gross benefits for each treatment were calculated by multiplying adjusted yield by the field price of maize. Field price for maize used was US$285.00 per tonne. Costs that vary for each weed control strategy were calculated. The total costs that vary for each weed control strategy is the sum of the individual costs that vary. In this case, the costs that vary were those associated with weed control (i.e. cost of herbicide, cost of labour to apply herbicide and cost of labour for hand hoe weeding). The final line of the partial budget shows the net benefits which were calculated by subtracting the total costs that vary from the gross field benefits. Costs of labour to carry out weed control operations (herbiciding and hand hoe weeding) were calculated by multiplying the total labour requirements per treatment by the daily wage of US$ 3.75.

Dominance and Marginal analysis

Dominance analysis was carried out by listing the weed control strategies in order of increasing costs that vary. Any weed control strategy that had net benefits that were less than or equal to those of a weed control strategy with lower costs that vary were dominated and were thus eliminated from further consideration. The marginal rate of return was calculated for the non dominated treatments at Thornpark Estate using the formula below.

$$\text{Marginal rate of return} = \frac{\text{Marginal benefit(i. e change in net benefits)}}{\text{Marginal cost (i. e change in costs)}} x100$$

Marginal analysis of the partial budget examined the marginal rate of return of changing from one weed control strategy to another. The marginal rate of return indicates what farmers can expect to gain on the average in return for their investment when they decide to change from one practice (or set of practices) to another (Cimmyt, 1988).

RESULTS

Effect of weed control strategy on weed biomass

The effect of weed control strategy on weed biomass (g/m^2) is shown in Table 2. Manually weeded plots had a significantly ($P < 0.05$) higher weed biomass than other weed control strategies at third count, but weed control strategy did not cause any significant differences ($P > 0.05$) in weed biomass at first and second weed count.

Effect of weed control strategy on early, mid and late season weed pressure (Days to first, second, third and fourth weeding) at both sites.

To achieve effective good weed control at all the sites, three post emergence weeding runs were required for the manually weeded plots and two for the herbicide treated plots (Table 3). At Domboshava, four weeding runs for the manually weeded plots were carried out. This was because a pre planting weeding was done to remove existing *Cynodon dactylon* weeds in these plots before planting was done. AT DTC weeds reached the threshold for

Table 2. Effect of weed control strategy on weed biomass (g/m²) at DTC and Thornpark Estate.

Weed control Strategy	Weed Biomass (g) First weed count	Second weed count	Third weed count
DTC			
Manual weeding	2.208	3.710	4.734[a]
Glyphosate+Manual weeding	6.269	3.325	0.00[b]
Glyphosate+Zamwipe	4.953	7.570	0.00[b]
Glyphosate+Atrazine+Manual weeding	5.687	3.344	0.00[b]
Atrazine+Manual weeding	2.580	5.618	0.00[b]
P-value	0.323	0.062	0.005
SED	1.687	1.402	0.993
$LSD_{0.05}$	NS	NS	2.289
Thornpark Estate			
Manual weeding	4.153	4.769	7.976[a]
Glyphosate+Manual weeding	3.677	6.157	0.00[b]
Glyphosate+ Zamwipe	3.092	5.672	0.00[b]
Glyphosate+Atrazine+Manual weeding	5.798	4.306	0.00[b]
Atrazine+Manual weeding	3.785	5.501	0.00[b]
P-value	0.346	0.233	0.00.
SED	1.084	0.791	1.132
$LSD_{0.05}$	NS	NS	2.610

Means with different letters in the column are significantly different at P<0.05.

Table 3. Effect of weed control strategy on early, mid and late season weed pressure (Days to first, second, third and fourth weeding) at both sites.

Site	Weed control strategy	Days to first weeding	Days to second weeding	Days to third weeding	Days to fourth weeding
DTC	Manual weeding only	0	34	55	92
	Glyphosate + manual weeding	35	55	-	-
	Glyphosate + Zamwipe	35	92	-	-
	Glyphosate + Atrazine + manual weeding	45	55		-
	Atrazine +manual weeding	34	55	92	
Thornpark Estate	Manual weeding only	43	67	108	-
	Glyphosate + manual weeding	43	67	-	-
	Glyphosate + Zamwipe	46	89	-	-
	Glyphosate + Atrazine + manual weeding	43	67	-	-
	Atrazine +manual weeding	43	67	-	-

- **Indicates that no weeding (manual or chemical) run was done**

Table 3. Effect of weed control strategy on grain and biomass yield (kg/ha) at both sites

Weed control strategy	DTC		Thornpark Estate	
	Grain yield	Biomass yield	Grain yield	Biomass yield
Manual weeding	1520.9	2157.3[a]	4378.7	4212.0
Glyphosate+Manual weeding	1860.4	3125.7[a]	4434.3	4042.3
Glyphosate+ Zamwipe	847.1	1146.4[b]	4150.6	3439.1
Glyphosate+Atrazine+manual weeding	2947.3	3328.5[a]	5002.4	4246.0
Atrazine+manual weeding	2216.7	1933.4[a]	4711.9	3904.4
P-value	0.1491	0.0348	0.6846	0.2394
SED	732.51	601.42	609.36	352.58
$LSD_{0.05}$	NS	1386.9	NS	NS

Means with different letters in the column are significantly different at P<0.05.

Table 5. Effect of weed control strategy on total labour requirement (in labour days) at Domboshava Training Centre and Thornpark Estate during the 2007/08 season.

Weed control strategy	DTC	Thorn park Estate
	Labour Days	Labour Days
Manual weeding only	124.96[a]	75.71[a]
Glyphosate+manual weeding	83.51[b]	54.90[b]
Glyphosate+Zamwipe	28.86[c]	49.43[b]
Glyphosate+atrazine+manual weeding	40.54[c]	45.14[b]
Atrazine+manual weeding	101.00[a]	44.07[b]
P-value	0.002	0.001
SED	15.978	5.093
$LSD_{0.05}$	36.845	11.744

Means with different letters in the column are significantly different at P<0.05
NS means Not Significant

weeding in all plots 35 days after planting (DAP), except where glyphosate and atrazine were applied at seeding which reached the threshold 10 days later.

Although weed control was done at different times after planting, the same trend was observed at Thornpark Estate. At Thornpark Estate, all the weed control strategies had the same effect on initial weed control. More DAP to second weed control in plots where the weed wipe was used were recorded at both sites

Effect of weed control strategy on grain and biomass yield (kg / ha) at both sites

The effect of weed control strategy at DTC was not significant (P > 0.05). However, the Zamwipe strategy resulted in 44 % grain yield losses compared to the manual hand hoe weeding only strategy. The weed wipe strategy also resulted in significantly lower (P < 0.05) biomass yield than all the other weed control strategies. The effects of weed control strategy on both biomass and grain yield were not significant (P > 0.05) at Thornpark Estate.

Labour requirements for weed control

At DTC total labour requirements for the manual hand hoe weeding only strategy and the Atrazine plus manual weeding strategy were the same but, both were significantly higher (P < 0.05) than those for the other chemical weed control strategies where glyphosate was applied (Table 5). The Zamwipe strategy and the glyphosate plus atrazine weed control strategy had statistically similar labour requirements which were significantly lower than the other chemical weed control strategies. At Thorn Park Estate manually weeded plots had significantly higher (P < 0.05) labour requirements than all the other chemical weeding strategies. However, no significant differences in labour requirement were observed among the chemical weed control strategies.

Table 5. Partial Budgets for Thorn Park Estate

Weed control strategy	Manual weeding	Glyphosate+manual weeding	Glyphosate+ Zamwipe	Glyphosate+ Atrazine	Atrazine
Average yield (kg/ha	4.38	4.43	4.15	5.00	4.71
Adjusted yield (kg/ha)	3.94	3.99	3.74	4.50	4.24
Gross field benefits ($/ha)	**1122.9**	**1137.15**	**1065.90**	**1282.50**	**1208.40**
Cost of herbicide ($/ha)	0.00	12.52	110.91	23.95	9.56
Cost labour to apply herbicide ($ / ha)	0.00	3.75	185.36	3.75	3.75
Cost of labour to hand weed ($ / ha)	283.90	205.88	0.00	169.29	165.25
Total costs that vary ($/ha)	**283.90**	**222.15**	**296.27**	**196.99**	**178.56**
Net Benefits ($/ha)	**839.00**	**915.00**	**769.63**	**1085.51**	**1029.84**

Yield adjustment=10 %
Field Price of maize per tonne =US$ 285

Table 6. Partial Budgets for Domboshava Training Centre (DTC)

Weed control strategy	Manual weeding	Glyphosate+Manual weeding	Glyphosate+ Zamwipe	Glyphosate+ Atrazine	Atrazine
Average yield (kg/ha)	1.59	2.20	0.91	2.65	1.75
Adjusted yield (kg/ha)	1.43	1.98	0.82	2.39	1.58
Gross field benefits ($/ha)	**407.55**	**564.30**	**233.70**	**681.15**	**450.30**
Cost of herbicide ($/ha)	0.00	12.69	115.07	22.12	9.57
Cost of labour to apply herbicide ($/ha)	0.00	3.75	108.23	3.75	3.75
Cost of labour to hand weed ($/ha)	468.60	313.163	0.00	152.03	378.75
Total costs that vary ($/ha)	**468.60**	**329.60**	**223.30**	**177.90**	**392.07**
Net Benefits ($/ha)	**-61.05**	**234.70**	**10.4**	**503.25**	**58.23**

Yield adjustment=10 %
Field Price of maize per tonne =US$ 285

Economic analysis of weed control strategies

The partial budget for Thorn Park Estate (Table 5) shows that the glyphosate plus atrazine, and the atrazine plus hand hoe weeding and the weed wipe strategy had costs that vary that were 30.6, 37.1 and 21.8 % lower than the traditional manual hand weeding only strategy. The lower costs that vary and higher yields in the two weeding strategies where atrazine was applied resulted in higher net benefits than the other weed control strategies. At DTC, the glyphosate plus Atrazine strategy had the lowest total costs that vary and concomitantly the highest net benefits (Table 6) due to high yields. Overally, the glyphosate plus atrazine weed control strategy was the most profitable weed control strategy at both sites.

Further economic analysis was done to select the most economically feasible weed control strategy. Dominance analysis at DTC shows that the glyphosate plus manual hand hoe weeding, manual weeding only and the glyphosate plus weed wipe strategy had higher costs that vary but lower net benefits than the strategies where atrazine was used and were therefore dominated and excluded for marginal analysis. Atrazine plus manual weeding strategy was the most economic strategy with a marginal rate of return of 306% over glyphosate plus Atrazine strategy (Table 7, Figure 1). At Thorn Park Estate,

Table 7. Dominance and marginal analysis for Thorn Park Estate

Thorn park Estate Farm			
Weed control strategy	**Costs that vary ($/ha)**	**Net Benefits ($/ha)**	**Marginal rate of return (%)**
Atrazine **(T5)**	178.56	1029.84	306 %
Glyphosate+Atrazine **(T4)**	196.99	1085.51	
Glyphosate+manual weeding **(T2)**	222.15	915.00 D[a/]	
Manual weeding only **(T1)**	283.90	839.00 D[a/]	
Glyphosate+ Zamwipe **(T3)**	296.27	769.63 D[a/]	

Minimum rate of return=100%
D[a/] Dominated alternatives

all the other chemical weed control strategies were dominated except for glyphosate plus atrazine weed control strategies, as a result marginal analysis was not done because only one weed control strategy was not dominated.

DISCUSSION

The most dominant weed species identified at Domboshava Training Centre (DTC) were *Cynodon dactylon*, *Cyperus esculentus, Fimbrystitis exilis* and *Richardia scabra*. At Thornpark Estate dorminant weeds were *Galinsoga parviflora, Richardia scabra, Conyza spp* and *Tagetes minuta* while *Cynodon dactylon, Cyperus esculentus* and *Datura stramonium* were minor weeds. Results in this study show that manual and chemical weed control strategies were equally effective in controlling weeds. The application of atrazine did not result in better weed control because the first weeding in atrazine treated plots was done at 35 DAP, the same time when all the other plots received their first weeding. Atrazine is a broadleaf pre-emergence herbicide which had no effect on *Cynodon dactylon* at DTC. This resulted in atrazine treated plots being manually weeded at the same time as the other plots, which resulted in the breaking of the herbicide seal. The herbicide seal is a herbicide treated layer of soil, about one to three centimeters thick which prevents the emergence of susceptible weed species. Tillage or manual weeding of a soil treated with a pre-emergent herbicide breaks the herbicide seal and reduces the efficacy of the pre-emergent herbicide. The results also show a similar effect of manual hand weeding and glyphosate in weed control. Similar results were obtained by Mashingaidze *et al*. (2009). This can be attributed to the fact that glyphosate has no soil activity in soils (Ross and Lembi, 1985) and has therefore the same effect on ungerminated seeds as manual weeding.

Significantly lower biomass yields were obtained where the Zamwipe was used because its use in sandy soils (at DTC) resulted in the death of plants due to glyphosate phytotoxicity. The use of glyphosate in sandy soils has been reported to result in phytotoxic damage to crops because the herbicide remains active in such soils where it can be absorbed by the roots of crops (Wagner *et al*., 2003). In sandy soils with a low cation exchange capacity very few herbicide molecules will adsorb to the soil particles, leaving a lot of available free herbicide molecules for root uptake by the plants. Glyphosate is a systemic herbicide that can be translocated in the plant resulting in the death of the whole plant. The phytotoxic effects of glyphosate were not observed in clay soils of Thornpark Estate probably because the herbicide molecule were absorbed by clay particles and rendered unavailable for root uptake by the plant. However, the observation at DTC contradicts earlier reports that glyphosate has no soil activity and can be used in any soil with no effect on plants when not applied directly to the plant (Ross and Lembi, 1985).

No significant differences in grain yield were observed amongst the five weed control strategies at both sites. Similar results were obtained by Muoni (2012). This can be explained by the fact that all the weed control strategies were equally effective in controlling weeds especially during the critical period of weed control in maize (4-6 weeks). The presence of weeds during the first four to six week of maize growth results in yield reductions in maize, thereafter the presence of weeds does not have a yield reducing effect on this crop (Weil, 1981, Rupende, 1997). It therefore suggests that the benefits of herbicides can only be realized where the application of the herbicides results in increased weed control during the critical weed free period of maize. The addition of a pre emergent grass killer to the glyphosate + atrazine + manual hand weeding strategy is likely to result in increased control of a wide range of weeds thereby lengthening the time from planting to first weeding.

At all sites, the manual hand hoe weeding strategy proved to be more labour intensive compared to the other weed management strategies even where weed densities were low. Vogel (1994) obtained similar results and reported that with hoe weeding, even low weed densities require high labour inputs because traditionally most of the surface area is weeded even in the case of scattered weed growth. Although the use of the Zamwipe proved to be a labour saving weed control strategy, it was not profitable in the sandy soils of Domboshava for two reasons. Firstly, a highly concentrated herbicide solution is used when glyphosate is applied using a Zamwipe. 0.96 kg a.i of glyphosate are applied in 5 litres of water compared to 0.96 in 200 litres of water which translates to an 851 % increase in glyphosate cost per hectare when the herbicide is applied using a Zamwipe. Secondly, the death of maize plants which was observed when the Zamwipe was used in sandy soils resulted in reduced plant population which caused a reduction in biomass and grain yield. Mashingaidze et al. (2009) also obtained similar results and attributed the decline in yield where the Zamwipe was used to greater weed growth than in hoe weeded plots.

The net benefit figures in the partial budgets showed that combining atrazine (pre-plant herbicide) and glyphosate (post–plant herbicide) was the most economic weed control strategy at both sites although it was equally effective in controlling weeds when compared to other weed control strategies used in this study. These results were similar to those obtained by several researchers who reported that the use of pre emergent and post emergent herbicides resulted in higher net benefits than manual weeding (Findlay and Hutchinson, 1999; Muoni et al., 2013; Islam et al., 2000; Hussain et al., 2008). Findlay and Hutchinson (1999) in Ghana reported that the use of pre and post-emergent herbicides (glyphosate plus alachlor plus atrazine) gave a net profit of US$713 which is US$353 more than the traditional hand hoeing method which gave US$360. Under the present situation of labour scarcity and soaring wages, manual weeding is not economic. Hence, chemical weed control appears to hold a great promise in providing effective, timely and economic weed suppression (Wibawa et al., 2010). Mixtures of glyphosate and atrazine supplemented by manual weeding resulted in better economic returns because the two herbicides were able to control annual broadleaved weeds that existed at seeding and later in the season through the residual effect of atrazine. Initial broad leaf weed control was achieved by atrazine which is also effective as an early post-emergent herbicide and emerged weeds were controlled by glyphosate.

Although weeding operations were less where glyphosate only was applied than in manually weeded plots, net benefits were lower at DTC. This is at least partly in accordance with results presented by other researchers, who argue that a reduction in tillage intensity does not mean an increase in yield (Sandoval-Avila et al., 1994). Instead, the advantages of these systems are to be found in other aspects such as lower production costs and conservation of resources (Tapia and Camacho, 1988). Atrazine, when applied alone, was the second best control method in terms of net benefits at both sites, but its effectiveness was lower than where it was used as a mixture with glyphosate because it is only effective against broad leaved weeds and has no effect on grasses. As a result, it did not control grasses, resulting in the need to manually weed atrazine treated plots early, an operation that resulted in early weed pressure proliferation in these plots due to the breaking of the herbicide seal during manual weeding.

At both sites the cost of manual weeding was greater than where atrazine plus glyphosate were used because manually weeded plots were weeded 4 times instead of three times. Overally the results are in agreement with findings by Jaya Suria et al. (2011) who reported that weed control efficiency cannot be considered as the only criterion to determine the suitability of a chemical weed control strategy, rather economics of weed control should also be taken into consideration while making any decision.

CONCLUSION

Based on the results from this study it can be concluded that under the present circumstances chemical weed control strategies are more economical than the traditional manual hand hoe weeding strategy in the first year of CA adoption. The use of Glyphosate + Atrazine could be an economic way of managing weeds in CA systems. However, there is need to include a grass herbicide like Metolachlor or Alachlor to enhance early season grass weed control. Apart from being costly, the use of the Zamwipe in sandy soils is not recommended because it resulted in the death of maize plants and reduced plant population. This suggests that glyphosate may be mobile in sandy soils and could end up being absorbed by plant roots and translocated apoplastically from the roots to the leaves of the plant. These results suggest that glyphosate is active in sandy soils with a low cation exchange capacity (CEC) and can be absorbed by plant roots resulting in crop damage since it is a systemic herbicide that can be translocated both in the xylem or phloem. There is therefore to need to study the effect of soil texture on the soil activity of glyphosate in order to determine the minimum amount of clay that allows the use of glyphosate without causing damage to crops.

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