Evaluation of a pre-formulated post-emergence herbicide mixture of topramezone and dicamba on annual weeds and Bermuda grass in maize in a sub-tropical agro-ecology

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A B S T R A C T

Weed infestation is one of the major causes of low maize grain yield in sub-Saharan Africa (SSA). The perennial grass weed, *Cynodon dactylon* (L.) Pers., is one of the most problematic weeds in maize in SSA. A pre-formulated post-emergence herbicide mixture (50 g a.i. topramezone litre^{-1} + 160 g a.i. dicamba litre^{-1}), sold under the trade name Stellar-Star®, was evaluated for *C. dactylon* and general weed control in the 2013/14 and 2014/15 season. The experiment was laid out as a randomized complete block design (RCBD) with six treatments replicated thrice, namely; weedy control, hoe weeding at 3 and 6 weeks after crop emergence (WACE), a label recommended dose of Stellar-Star at 3 WACE, a reduced Stellar-Star dose (75% of label dose) at 3 WACE, a double dose of Stellar-Star split applied at 3 and 6 WACE and a tank mix of label doses of Stellar-Star + Atrazine applied at 3 WACE. The Stellar-Star herbicide treatments did not significantly (P > 0.05) affect *C. dactylon* density at 5 WACE but significantly reduced (P < 0.001) its density at 10 WACE. The Stellar-Star herbicide treatments significantly reduced (P < 0.001) weed biomass compared to the weedy-check at 5 and 10 WACE in both seasons. The Stellar-Star double dose split application and the Stellar-Star Atrazine tank mix were most effective in controlling *C. dactylon* (90–97% control) followed by the Stellar-Star label dose and Stellar-Star reduced dose (75%–88% control), however, the results of this study suggest that the Stellar-Star Atrazine tank mix provided the most effective early season and overall weed control and resulted in the highest yield, rainfall use efficiency (RUE) and gross margin and is recommended.

1. Introduction

Maize *(Zea mays* L.*)* is the most commonly grown cereal crop in Zimbabwe with 99% of the total population using it as a staple food. However, average maize grain yield in smallholder (SH) sector has remained low, less than 1–2 tons ha^{-1}, compared to 8 tons ha^{-1} attained from regional research plots (Bishop-Sambrook, 2003; Tittonell et al., 2007). Apart from abiotic factors such as moisture stress and low soil fertility (Zingore et al., 2007), biotic factors such as insect pests, diseases and weeds are major causes of low yields experienced by SH farmers (Mashingaidze et al., 2009). The majority of SH farmers in sub-Saharan Africa (SSA) use hoe weeding as the main weed control method (Chivinge, 1990). However, hoe weeding is slow and labour intensive and the

majority of SH farmers weed the crop when weeds have already reduced crop growth and yield. Delays in weeding, resulting from shortages in labour are estimated to cause 15–90% in crop yield reduction in SSA (Kibata et al., 2002).

Bermuda grass or Couch grass (*Cynodon dactylon* (L.) Pers.) is a stoloniferous and rhizomatous C$_4$ grass that is found in tropics and subtropics including SSA. *C. dactylon* is listed second after purple nutsedge (*Cyperus rotundus*) as the most troublesome weed in the world (Holm et al., 1977). The weed reproduces both vegetatively and by seed and is highly invasive, rapidly colonising new areas forming dense mats (http://www.cabi.org/isc/datasheet/17463). The efficacy of hoe weeding in removing *C. dactylon* is limited as its rhizomes are found up to a depth of 35cm, too deep for effective removal using hoe weeding (Perez

and Labrada, 1985). Besides interfering with crop growth and yield through competition for resources, *C. dactylon* is reported to be a potential allelopathic plant (Labrada et al., 1986; Vasilakoglou et al., 2005).

The predominant use of the ox-drawn plough and hoe-weeding in the SH communal farming system in Zimbabwe, characterized by shallow penetration into the soil, has exerted selection pressure on the weed population in favour of perennial weeds, such as *C. dactylon* (Mabasa et al., 1995). Conservation agriculture (basin planting and rip-line planting) is widely being promoted in SH agriculture in Zimbabwe and other SSA countries (Rockström et al., 2009). A key principle in conservation agriculture of minimum soil disturbance is exerting additional selection pressure in favour of perennial weeds, like *C. dactylon* (Vogel, 1994). Herbicide use in the SH sector is increasing in SSA as a result of shortages and high prices of labour, increased commercialization of crop production and increased adoption of conservation tillage (Gianessi, 2013; Grabowski and Jayne, 2016). It is, therefore, necessary to evaluate herbicides in SH production systems to increase weed control options available to SH farmers, especially against recalcitrant weed species, like *C. dactylon*.

Topramezone{[3-(4,5-dihydro-3-isoxazolyl)-2-methyl-4-(methylsulfonyl)phenyl](5-hydroxy$-1-$nethyl-1H-pyrazol-4-yl) methanone} is a post-emergence herbicide belonging to the pyrazole chemical group used to control broadleaf and grass weeds, including *C. dactylon*, in maize. Topramezone was introduced in 2006 and inhibits 4-hydroxyphenylpyruvate dioxygenase (4-HPPD; EC 1.13.11.27), a key enzyme in the biosynthesis of prenylquinones, plastoquinone and tocopherols. Plastoquinone is a co-factor of the enzyme phytoene desaturase, a key enzyme in carotenoid biosynthesis (Norris et al., 1995). The lack of carotenoids in susceptible plants, when topramezone is applied, results in lack of protection of the photosynthetic system against photo-oxidation, leading to photo-oxidative degradation of chlorophyll and photosynthetic membranes, chlorophyll loss (bleaching) and necrosis of the leaves. The herbicide is systemically translocated both in the phloem and xylem and higher rates of metabolism of the herbicide and lower sensitivity of 4-HPPD target enzyme in maize compared to weeds forms the basis of selectivity (Grossmann and Ehrhardt, 2007).

Stellar-Star®(BASF) is a pre-formulated soluble liquid mixture of topramezone (50 g a.i litre^{-1}) and dicamba (160 g a.i. litre^{-1}) for the early post-emergent control of grasses and broadleaf weeds. Dicamba belongs to the benzoic acid chemical group, a class of auxin mimicking herbicides that cause uncontrolled growth, epinasty, chlorosis and necrosis and death in susceptible broadleaf weeds. Mixtures of two or more herbicides, in commercial herbicide formulations or as tank mixes, can increase the number of weed species controlled with one application (Damalas, 2004), hence we tested the efficacy of Stellar-Star plus atrazine tank mix to control weeds in maize in this study. Sequential applications of reduced doses of nicosulfuron exhibited greater levels of weed control than equivalent doses and the label recommended dose applied once in maize. The exposure of a higher number of emerging weed cohorts to the herbicide and the finishing off of weeds that are damaged by the first application increased weed control in sequential applications of herbicides (Mashingaidze, 2004). When a label dose of Stellar-Star was applied once at 3 WACE in previous seasons, we observed resurgence of

C. dactylon towards the end of the season, a phenomenon reported by other users in Zimbabwe. A Stellar-Star double dose split application consisting of the label dose applied at 3 and 6 WACE was evaluated to determine the efficacy of this treatment in providing control of *C. dactylon* for the whole season.

Stellar-Star was introduced in Zimbabwe in 2014 and there are no reports on its efficacy against *C. dactylon* and other annual grass and broadleaf weeds in sandy soils where the majority of SH farmers grow maize. The objective of the study was to evaluate the efficacy of Stellar-Star herbicide applied post-emergence in controlling *C. dactylon* and other annual broadleaf and grass weeds and on maize grain yield, rainfall use efficiency and gross margin at a sandy soil site in maize. The Stellar-Star herbicide treatments were compared to a weedy and twice hoe-weeded (at 3 and 6 WACE) check.

2. Materials and methods

2.1. Site description

The study was conducted in Village 15 of Masomera Resettlement Area, Marondera district, Mashonaland East Province in Zimbabwe, (18° 22' S, 31° 45' E) in the 2013/14 and 2014/15 seasons. Masomera resettlement area lies 40 km south of Marondera town and experiences a sub-tropical climate with average summer temperatures of 25 °C and annual precipitation of between 800 – 1 000 mm year^{-1}. Rainfall follows a unimodal pattern with rains received between November and April. The soils are coarse grained sandy soils derived from granite parent material which is characterized by low inherent fertility, poor water holding capacity and low organic matter content (Grant, 1981).

2.2. Land preparation and fertilizer application

The land was ploughed using an ox-drawn mouldboard plough followed by harrowing using a spike-tooth harrow to produce a fine tilth after the soil was moistened by the first effective rainfall on the 20th of November in both seasons. Planting furrows were marked using an ox-drawn plough and basal compound maize fertilizer (7% N: 14% P$_2$O$_5$: 7% K$_2$O) was then applied at 250 kg ha^{-1}. A short season three-way maize hybrid, SC 513 (Seed-Co®, Zimbabwe) was planted by placing two seeds per station at 0.9 m × 0.25 m spacing. The maize crop was thinned to one plant per station at two weeks after crop emergence (WACE) to achieve a final maize plant density of 44 000 plants ha^{-1}. The crop was side-dressed with 200 kg ha^{-1} of ammonium nitrate (34.5% N), one half applied at 3 WACE and the other half, at 6 WACE.

2.3. Weed management treatments and experimental design

To evaluate the efficacy of Stellar-Star in controlling annual weeds and the perennial grass *Cynodon dactylon* in maize, four herbicide treatments, a reduced dose, a label recommended dose, double the recommended rate split-applied at 3 and 6 WACE of Stellar-Star and a tank mix of recommended dosages of Stellar-Star plus Atrazine were compared to an unweeded control and normal farmer practice of hoe-weeded twice at

Table 1

Weed management treatments in a study to test the efficacy of Stellar-Star herbicide for general weed control and for the control of couch grass (*Cynodon dactylon* L.) in maize at Masomera village, Marondera, Zimbabwe.

Treatment Name	Treatment details
Weedy-check (Control)	No weeding throughout the season
Hoe weeding	Hoe-weeding twice at 3 and 6 WACE
Stellar-Star reduced dose	0.75 litres ha^{-1} Stellar-Star post-emergence at 3 WACE (37.5 g a.i. Topramezone +120 g a.i. Dicamba ha^{-1})
Stellar-Star label dose	1 litre ha^{-1} Stellar-Star post-emergence at 3 WACE (50 g a.i. Topramezone +160 g a.i. Dicamba ha^{-1})
Stellar-Star double dose split app.	2 litres ha^{-1} Stellar-Star post-emergence, split-applied 1 litre ha^{-1} each at 3 and 6 WACE (100 g a.i. Topramezone +320 g a.i. Dicamba ha^{-1})
Stellar-Star + Atrazine tank-mix	1 litre ha^{-1} Stellar-Star (50 g a.i. Topramezone +160 g a.i. Dicamba ha^{-1}) + 3 litres Atrazine (150 g Atrazine a.i. ha^{-1}) post-emergence tank mix at 3 WACE

3 and 6 WACE (Table 1). The gross plot size was 5 m × 4.5 m and the net plot was 1.8 m × 2 m. The herbicide was applied using a knapsack sprayer calibrated to deliver 200 litres of spray mixture ha^{-1}.

Weed density and biomass:- Weed density (weeds m^{-2}) was measured at 5 and 10 WACE using a 0.3 m × 0.3 m quadrat. Five quadrats were randomly thrown in the plot and weeds counted by species. For *C. dactylon* number of stolons within each quadrat were counted. The counted weeds were cut at ground level, packed in khaki paper bags, oven dried at 85 °C for 48 hours and weighed.

Rainfall use efficiency: The cumulative rainfall data for the season and maize grain yield was used to calculate rainfall use efficiency using the formulae; (Dardel et al., 2014)

$$\text{Rainfall use efficieny } = \frac{\text{Maize grain yield (kg ha}^{-1})}{\text{Total in} - \text{crop rainfall (mm)}} \left(\text{kg of maize grain mm}^{-1}\text{of rainfall season}^{-1}\right)$$

Gross margin: - Gross margin budgeting was done using the grain yield and variable costs for each treatment. Gross income was calculated by multiplying yield and the average maize producer price in Zimbabwe ($300 ton^{-1}) and the net benefit (gross margin) for each treatment was calculated by subtracting the total variable costs from the gross income.

Maize grain yield:- Maize ears were harvested from a net plot of 1.8 m × 2 m after physiological maturity and dry-down in the field in mid-April in each of the two seasons. The ears were dehusked and shelled, maize grain per plot weighed and percent moisture content determined using a moisture meter (agraTronix, Streetboro, Ohio). Maize grain yield per plot was adjusted to 12.5% moisture content and expressed per hectare before statistical analysis.

Statistical analysis:-Weed density data $\sqrt{x+0.5}$ transformed statistical analysis (Steel and Torrie, 1984). The data were subjected to analysis of variance (ANOVA) using Minitab Version 16 (State College, 2009) and means were separated using ±standard error of the difference when F test showed significant treatment effect at P ≤ 0.05. Linear correlations (Pearson r) were carried out among weed density at 5 and 10 WACE, weed biomass at 5 and 10 WACE, grain yield, rainfall use efficiency and gross margin.

3. Results

3.1. Rainfall

In 2013/14 season, the experimental site received a total of 722 mm
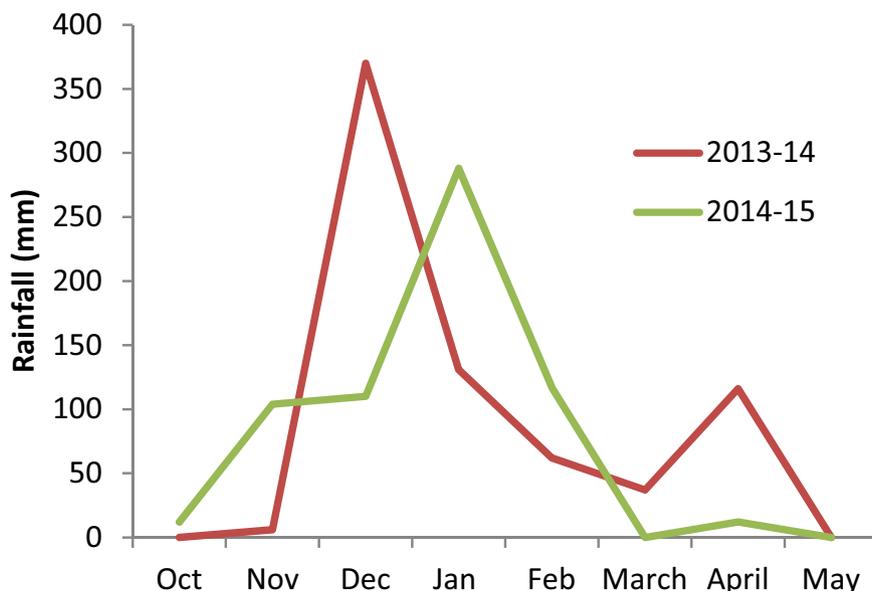
Fig. 1. Monthly rainfall totals at Masomera Village, Marondera district, Zimbabwe, in the 2013/14 and 2014/15 seasons.

Table 2
Mean density and percent abundance of weed species in unweeded control plots at Masomera village, Marondera district, Zimbabwe in the 2013/14 and 2014/15 seasons.

Scientific Name	Common Name	Mean density (weeds m^{-2})	Percent of total abundance
Richardia scabra (L.) St-Hil.	Mexican clover	228	71.04
[a]*Cynodon dactylon* (L.) Pers.	Couch grass	70	21.94
Cloeme monophylla L.	Spindlepod	14	4.21
Eleusine indica (L.) Gaertn.	Rapoko grass	6	1.79
Commelina benghalensis L.	Wandering Jew	2	0.66
Hibiscus meeusei Exell	Stockrose	1	0.35

[a] For *Cynodon dactylon*, weed density refers to density of stolons m^{-2}.

of rainfall of which 51, 18, 8.5, 5.1 and 16% of this total was received in December, January, February, March, and April; respectively (Fig. 1). In the 2014/15 season, the experimental site received a total of 631mm of rainfall of which 16.5, 17.4, 45.6, 18.5, 0, 2% of this total rainfall was received in November, December, January, February, March, and April; respectively (Fig. 1). More rainfall that was more evenly distributed was therefore received in the 2013/14 season than in the 2014/15 season. Rainfall in the 2014/15 season was characterized by an early end of the season in February, and little to no meaningful rainfall in March and April (Fig. 1). The maize was planted on the 20th of November in both seasons and reached anthesis 10 WACE (70 days after emergence) at the end of January and it accumulated dry matter in the ear (grain-filling) in a seven-week period and attained physiological maturity after 17 WACE (120 days after emergence) in the last week of March. The maize was allowed to dry down on the ear in the field for one and half months before harvesting in the middle of April in each season.

3.2. Weed species abundance

The density of each species of weeds in the untreated control plots averaged over the 2013/14 and 2014/15 season was used to calculate percent abundance of species in this study. *Richardia scabra* (L.) St-Hil. was the most abundant species, constituting more than 70% of the species found at this site (Table 2). *Cynodon dactylon* L. Pers. was the second most abundant species, making up more than a fifth of the weed population at the site (Table 2). *Cloeme monophylla* (L.), *Eleusine indica* L. Gaertn., *Commelina benghalensis* L and *Hibiscus meeusei* Exell were minor species at Mosomera village, constituting less than 5% of the weed population (Table 2).

3.3. Weed density

There was no significant effect (P > 0.05) of Stellar-Star herbicide weed management treatments on *C.dactylon* density at 5 WACE in the 2013/14 and 2014/15 season (Table 3). On the contrary, the Stellar-Star weed treatments significantly affected (P < 0.001) annual and total weed density at 5 WACE in the 2013/14 and 2014/15 seasons (Table 3). The Stellar-Star + Atrazine tank mix was the most effective treatment in reducing annual and total weed density at 5 WACE in both seasons. In the 2014/15 season, annual weed density at 5 WACE decreased in the order of weedy-check .> hoe-weeded > Stellar-Star reduced dose > Stellar-Star label dose and Stellar-Star double dose split application and was lowest in the Stellar-Star + Atrazine tank mix treatment (Table 3). In the 2013/14 season, overall weed control was 93, 76, 65, 56 and 36% for the Stellar-

Star + Atrazine tank mix, Stellar-Star label dose, hoe-weeded, Stellar-Star double dose split application and Stellar-Star reduced dose treatments at 5 WACE in comparison to the unweeded control, respectively (Table 3). In the 2014/15 season, overall weed control was 97, 94, 90, 80 and 54% for the Stellar-Star + Atrazine tank mix, Stellar-Star double dose split application, Stellar-Star label dose, Stellar- Star reduced dose and hoe weeding treatments, respectively, at 5 WACE (Table 3).

There was a significant effect (P < 0.001) of Stellar-Star weed management treatments on *C. dactylon* density at 10 WACE in the 2013/14 and 2014/2015 seasons. Percent *C. dactylon* control at 10 WACE was 97, 94, 86, 75 and 58% in the Stellar-Star double dose split application, Stellar-Star + Atrazine tank mix, Stellar-Star label dose, Stellar-Star reduced dose and hoe weeding treatments, respectively, in the 2013/14 season (Table 4). Percent *C.dactylon* control at 10 WACE was 91, 90, 88, 86 and 73% in the Stellar-Star double dose split application, Stellar-Star + Atrazine tank mix, Stellar-Star label dose, Stellar-Star reduced dose and hoe weeding treatments, respectively, in the 2014/15 season (Table 4). It is apparent that Stellar-Star weed management treatments were more efficient in controlling *C.dactylon* in the wet 2013/14 season than in the dry 2014/15 season and the hoe weeding treatment was more efficient in controlling the same weed species in the dry 2014/15 season than in the wet 2014/15 season.

Annual weed density at 10 WACE was significantly affected (P < 0.001) by the Stellar-Star weed management treatments in the 2013/14 and 2014/15 seasons. In both seasons, annual weed density at 10 WACE decreased in the order weedy-check > hoe weeding > Stellar-Star reduced dose > Stellar-Star label dose > Stellar-Star double dose split application > Stellar-Star Atrazine tank mix, showing that the Stellar-Star + Atrazine tank mix was the most effective treatment in controlling annual weeds at 10 WACE. However, there was no significant difference in annual weed density at 10 WACE among the Stellar-Star label dose, Stellar-Star double dose split application and the Stellar-Star + Atrazine tank mix in the 2013/14 season. There was no significant difference in annual weed density at 10 WACE between the Stellar-Star double dose split application and the Stellar-Star + Atrazine tank mix, in the 2014/15 season (Table 4).

Overall weed control was significantly affected (P < 0.001) by the Stellar-Star weed management treatments in the 2013/14 and 2014/15 seasons (Table 4). Overall weed control was 94, 97,86, 75, 58% at 10 WACE in the Stellar-Star + Atrazine tank mix, Stellar-Star double dose split application, Stellar-Star label dose, Stellar-Star reduced dose and hoe-weeded treatments, when compared to the weedy-check, respectively, in the 2013/2014 season (Table 4). Overall weed control was 90, 91, 88, 86, 73% in the Stellar-Star + Atrazine tank mix, Stellar-Star

Table 3

Effect of Stellar-Star weed management treatments on *C. dactylon*, annual and total weed density ($\sqrt{x+0.5}$ transformed) at Masomera Village, Marondera district, Zimbabwe at 5 WACE, in the 2013/14 and 2014/15 seasons.

Treatments	Weed density 2013/14 season at 5 WACE (weeds m^{-2})				Weed density 2014/15 season at 5 WACE (weeds m^{-2})			
	C. dactylon	Annual weeds	Total density	% weed control	*C. dactylon*	Annual weeds	Total density	% weed control
Weedy-check (Control)	11.68 (135.92)	[1]30.98[a] (959.26)	42.66[a] (1819.38)	0	5.56 (30.31)	35.76[a] (1278.28)	41.32[a] (1706.84)	0
Hoe weeding	7.65 (58.02)	17.50[bc] (305.75)	25.16[c] (632.53)	65	4.62 (20.84)	23.45[b] (549.40)	28.07[b] (787.42)	54
Stellar-Star reduced dose	8.63 (73.98)	25.55[ab] (625.30)	34.18[ab] (1167.77)	36	4.76 (22.16)	13.91[c] (192.99)	18.68[c] (384.44)	80
Stellar-Star label dose	9.95 (98.50)	10.98[cd] (120.06)	20.93[e] (437.57)	76	5.19 (26.44)	7.89[d] (61.75)	13.08[c] (170.59)	90
Stellar-Star double dose split app	8.17 (66.25)	20.29[b] (411.18)	28.45[bc] (808.90)	56	4.69 (21.50)	5.24[d] (26.96)	9.93[d] (98.10)	94
Stellar-Star + Atrazine tank mix	8.43 (70.56)	2.50[d] (5.75)	10.93[d] (118.97)	93	4.82 (22.73)	2.19[d] (4.30)	7.01[d] (48.64)	97
P value	0.552	0.001	0.001		0.627	0.001	0.001	
± s.e.d	2.305	4.289	4.297		1.456	3.941	3.697	
CV %	30.36	29.25	19.46		17.01	24.86	17.97	

Numbers in brackets are back-transformed (actual) weed numbers m^{-2}.

[1] Means followed by the same letter superscript are in a column are not significantly different at P < 0.05.

Table 4

Effect of Stellar-Star weed management treatments on *C. dactylon*, annual and total weed density ($\sqrt{x+0.5}$ transformed) at Masomera Village, Marondera district, Zimbabwe at 10 WACE, in the 2013/14 and 2014/15 seasons.

Treatments	Weed density 2013/14 season at 10 WACE (weeds m^{-2})				Weed density 2014/15 season at 10 WACE (weeds m^{-2})			
	C. dactylon	Annual weeds	Total density	% weed control	*C. dactylon*	Annual weeds	Total density	% weed control
Weedy-check (Control)	15.91[a] (252.63)	[1]41.32[a] (1706.8)	57.23[a] (3274.77)	0	9.53[a] (90.32)	27.17[a] (737.71)	36.69[a] (1345.66)	0
Hoe weeding	8.82[b] (77.29)	28.08[b] (787.99)	36.89[b] (1360.37)	58	7.02[b] (48.78)	12.13[b] (146.64)	19.15[b] (366.22)	73
Stellar-Star reduced dose	10.13[b] (102.12)	18.68[c] (348.44)	28.81[c] (829.52)	75	5.99[c] (35.38)	7.06[c] (49.34)	13.59[c] (184.19)	86
Stellar-Star label dose	9.13[b] (82.86)	11.1[d] (122.71)	21.23[d] (86.25)	86	5.77[d] (32.79)	6.72[c] (44.66)	12.49[cd] (170.59)	88
Stellar-Star double dose split app	0.5[c] (0)	9.52[d] (90.13)	9.75[c] (94.56)	97	5.5[e] (29.75)	5.74[d] (32.45)	11.24[d] (98.10)	91
Stellar-Star + Atrazine tank mix	7.45[b] (55.00)	7.01[d] (48.64)	14.45[c] (208.30)	94	5.55[e] (30.30)	5.97[cd] (35.14)	11.52[cd] (48.64)	90
P value	0.001	0.001	0.001		0.001	0.001	0.001	
± s.e.d	1.703	4.351	3.578		0.194	0.973	1.16	
CV %	24.09	27.66	15.62		3.62	10.95	8.14	

Numbers in brackets are back transformed (actual) weed numbers per m^{-2}.

[1] Means followed by the same letter superscript in a column are not significantly different at P < 0.05.

double dose split application, Stellar-Star label dose, Stellar-Star reduced dose and hoe-weeded treatments, when compared to the weedy-check, respectively, in the 2014/2015 season (Table 4). It is apparent that the Stellar-Star weed management treatments achieved greater levels of overall weed control in the wet 2013/14 season than the dry 2014/15 season and the opposite is true for hoe-weeding that achieved greater overall weed control in the dry 2014/15 season than in the wet 2013/14 season (Table 4).

3.4. Weed biomass

The Stellar-Star herbicide weed management treatments significantly affected (P < 0.001) weed biomass at 5 and 10 WACE in the 2013/14 and 2014/15 seasons (Table 5). At 5 WACE, weed biomass was significantly reduced by 58, 94, 85, 78 and 93% (2013/14 season) and by 87, 85, 97, 54 and 39% (2014/15 season) in the Stellar-Star double dose split application, Stellar-Star + Atrazine tank mix, Stellar-Star label dose, Stellar-Star reduced dose and hoe weeding treatments, compared to the weedy-check, respectively (Table 5). At 10 WACE, weed biomass was significantly reduced by 88, 85, 97, 55 and 39% (2013/14 season) and 91, 76, 82, 57 and 78% (2014/15 season) in the Stellar-Star double dose split application, Stellar-Star + Atrazine tank mix, Stellar-Star label dose,

Stellar-Star reduced dose and hoe weeding treatments, compared to the weedy-check, respectively (Table 5). It is apparent from the results that by 10 WACE in the 2013/14 season, the best treatment in reducing weed biomass was the label recommended dose, however, the final weed biomass achieved in this treatment did not significantly differ with the Stellar-Star + Atrazine tank mix (Table 5). Significantly higher weed biomass was recorded in the Stellar-Star double dose, Stellar-Star reduced dose and hoe-weeding treatments than the Stellar-Star label dose and Stellar-Star + Atrazine tank-mix treatments in the 2013/14 season (Table 5). It is also apparent that the best performing treatment in reducing weed biomass by 10WACE in the 2014/15 season was the Stellar-Star double dose split application, but the final weed biomass achieved in this treatment did not significantly differ with Stellar-Star label dose, Stellar-Star + Atrazine tank mix and hoe-weeded treatment (Table 5). Hoe weeding was less effective in reducing weed biomass in the 2013/14 season (39% reduction) than in the 2014/15 season (78% reduction) (Table 5).

3.5. Maize grain yield, gross margin, and rainfall use efficiency

The Stellar-Star herbicide weed management treatments significantly affected (P < 0.001) maize grain yield in the 2013/14 and 2014/15

Table 5

Effects of Stellar-Star weed management treatments on weed biomass (g m^{-2}) at Masomera Village, Marondera district at 5 and 10 WACE, in the 2013/14 and 2014/15 seasons.

Treatments	Weed biomass (g m^{-2}) at 5 WACE				Weed biomass (g m^{-2}) at 10 WACE			
	2013/14	% reduction in biomass	2014/15	% reduction in biomass	2013/14	% reduction in biomass	2014/15	% reduction in biomass
Weedy-check (Control)	[1]169.01[a]	0	507.54[a]	0	228.40[a]	0	308.15[a]	0
Hoe weeding	10.99[c]	93.5	309.19[b]	39	139.14[b]	39.1	68.89[bc]	77.6
Stellar-Star reduced dose	36.67[c]	78.3	230.73[b]	54.5	103.83[b]	54.5	132.59[b]	57.0
Stellar-Star label dose	24.81[c]	85.3	17.28[c]	96.6	7.78[c]	96.6	57.04[c]	81.5
Stellar-Star double dose split app	71.48[b]	57.7	66.67[c]	87.9	100.86[b]	55.8	28.89[c]	90.6
Stellar-Star + Atrazine tank mix	10.00[c]	94.1	74.90[c]	85.2	33.70[c]	85.2	74.07[c]	76.0
P-value	0.001		0.001		0.001		0.001	
±s.e.d	22.03		58.01		26.545		41.529	
CV	50.12		33.82		31.78		45.57	

[1] Means followed by the same letter superscript in a column are not significantly different at P < 0.05.

Table 6

Effects of Stellar-Star weed management treatments on maize grain yield, gross margin and rainfall use efficiency at Masomera village, Marondera district, Zimbabwe in the 2013/14 and 2014/15 seasons.

Treatment	Maize grain yield (t ha^{-1})		Rainfall use efficiency (kg grain mm^{-1}rainfall)		Gross margin (US $ ha^{-1})	
	2013/14	2014/15	2013/14	2014/15	2013/14	2014/15
Weedy-check	[1]0.831^c	0.00^c	1.317^b	0.000^c	−253.8^d	−503.00^b
Hoe weeding	2.026^b	0.805^a	3.210^{ab}	1.116^a	14.7^{bc}	−351.28^a
Reduced dose Stellar-Star	1.630^b	0.464^b	2.584^{ab}	0.644^b	−3.8^c	−353.54^a
Label dose Stellar-Star	1.909^b	0.392^b	3.026^{ab}	0.543^b	6.8^{bc}	−448.30^b
Double dose Stellar-Star split app	2.187^a	0.418^b	3.467^a	0.579^b	30.2^{bc}	−500.58^b
Stellar-Star + Atrazine tank mix	2.773^a	0.799^a	4.395^a	1.107^a	244.0^a	−348.15^a
P value	<0.001	<0.001	<0.001	<0.001	0.005	0.004
± sed	0.303	0.140	0.961	0.195	181.913	73.164
CV%	19.6	35.9	19.6	35.9	17.5	12.4

[1] Means followed by the same letter superscript in a column are not significantly different at P < 0.05.

season (Table 6). In the 2013/14 season, the Stellar-Star + Atrazine tank mix recorded the highest maize grain yield but it did not significantly differ with Stellar-Star double dose split application at 3 and 6 WACE. The hoe weeding treatment at 3 and 6 WACE had significantly lower maize grain yield than the Stellar-Star + Atrazine tank mix and the Stellar-Star double dose split application, but it did not significantly differ with the label dose of Stellar-Star and reduced dose of Stellar-Star. The lowest maize grain yield was recorded in the weedy-check (Table 6). In the 2014/15 season, yields were generally depressed compared to the 2013/14 season. The highest maize grain yield was recorded in the hoe weeding treatment, but it did not significantly differ with the Stellar-Star + Atrazine tank mix (Table 6). The reduced dose Stellar-Star treatment had the next highest maize grain yield, but it was significantly lower than the hoe weeding and the Stellar-Star + Atrazine tank-mix treatments, and did not significantly differ with the reduced dose Stellar-Star, Stellar-Star double dose split application at 3 and 6 WACE and the Stellar-Star label dose treatments (Table 6). No maize grain yield was harvested from the weed check treatment in the 2014/15 season (Table 6).

Rainfall use efficiency (RUE) was significantly (P ≤ 0.001) influenced by Stellar-Star weed management treatments in the 2013/14 and 2014/15 seasons. In the 2013/14 season, the highest RUE was recorded in the Stellar-Star + Atrazine tank mix and Stellar-Star double dose split applied

treatments, but it did not significantly differ with the hoe weeding, Stellar-Star label dose and Stellar-Star reduced dose treatments. The lowest RUE was recorded in the weedy-check but it did not significantly differ with the hoe weeding, Stellar-Star label dose and Stellar-Star reduced dose treatments (Table 6). In the 2014/15 season, the hoe weeding and Stellar-Star + Atrazine tank-mix treatments had the highest RUE. There was no significant difference in RUE among the Stellar-Star reduced dose, Stellar-Star double dose split application and the Stellar-Star label dose treatments but they had significantly lower RUE than the hoe weeding and Stellar-Star + Atrazine tank-mix treatments (Table 6).

The Stellar-Star herbicide dose treatments significantly affected (P < 0.01) gross margin from the maize crop in the 2013/14 and 2014/15 season (Table 6). In 2013/14 season, the Stellar-Star + Atrazine tank mix had the highest gross margin (Table 6). Gross margins were lower in the Stellar-Star double dose split application, hoe weeding, Stellar-Star label dose, and the Stellar-Star reduced dose treatments (Table 6). The lowest and negative gross margin was recorded in the weedy-check in the 2013/14 season. In the 2014/15 season, gross margins were negative for all treatments. The lowest gross margin was recorded in the weedy-check and the Stellar-Star double dose split application treatments, but it did not significantly differ from the Stellar-Star label dose treatment. Gross margin from the reduced Stellar-Star reduced dose, hoe weeding and Stellar-Star + Atrazine tank mix did not significantly differ but was significantly higher than from the weedy-check, Stellar-Star double dose split application and Stellar-Star label dose treatment in the 2014/15 season (Table 6).

3.6. Linear correlation (Pearson r) among selected variables

Weed density at 5 and 10 WACE had a significant positive correlation (P ≤ 0.05) with weed biomass at 5 and 10 WACE. There was a significant negative correlation between weed density at both 5 WACE and at 10 WACE with maize grain yield, gross margin ha^{-1} and RUE (Table 7). Weed biomass at 5 WACE did not significantly correlate (P > 0.05) with maize grain yield, gross margin ha^{-1} and RUE (Table 7). In contrast, weed biomass at 10 WACE had a significant negative correlation (P < 0.05) with maize grain yield, gross margin ha^{-1} and RUE. A highly significant (P < 0.001) positive correlation was recorded among maize grain yield, RUE and gross margin ha^{-1} (Table 7).

4. Discussion

The Stellar-Star weed management treatments did not significantly affect the density of *C.dactylon* at 5 WACE, two weeks after imposition of the treatments, because of the perennial nature of the weed and its large size. Foliar-applied herbicides need to be translocated for long distances to be distributed into the above ground stolons and leaves and subterranean rhizomes of *C. dactylon*, hence the slower development of symptoms of damage and death of herbicide-treated plants, by 5 WACE. In contrast, for smaller sized annual weeds, without perrenating vegetative structures, their density was significantly reduced by herbicide and hoe weeding treatments by 5 WACE. Poorer control of perennial species than

Table 7

Linear correlation (Pearson r) among weed density, weed biomass, maize grain yield, rainfall use efficiency and gross margin ha^{-1} for the 2013/14 and 2014/15 seasons.

	5 WACE Density	10 WACE Density	5 WACE Biomass	10 WACE Biomass	Grain Yield	GM	RUE
5 WACE Density	X	X	X	X	X	X	X
10 WACE Density	0.90*	X	X	X	X	X	X
5 WACE Biomass	0.92**	0.84*	X	X	X	X	X
10 WACE Biomass	0.97**	0.94**	0.93**	X	X	X	X
Grain Yield	−0.93**	−0.80*	−0.75 ns	−0.82*	X	X	X
GM	−0.94**	−0.82*	−0.78 ns	−0.85*	0.99***	X	X
RUE	−0.93**	−0.80*	−0.76 ns	−0.83*	0.99***	0.99***	X

WACE weeks after crop emergence, GM gross margin, RUE rainfall use efficiency, *P < 0.05, **P < 0.01, ***P < 0.001, ns not significant.

annual by post-emergence foliar-applied herbicides has been recorded in other studies (Whaley and Vangessel, 2002; Bradley et al., 2004).

Overall weed control was measured as percent reduction of weed density in this study and the Stellar-Star + Atrazine tank mix applied at 3 WACE, showed superior levels of weed control at 5 WACE than other treatments in both seasons. However, at 10 WACE, overall weed control was generally similar among the Stellar-Star + Atrazine tank mix, Stellar-Star double dose and Stellar-Star label dose treatments. An improved knock-down effect of topramezone plus atrazine tank mix was recorded on annual broadleaf weeds when used as an early and late post-emergence treatment (Rahman et al., 2013), similar to what we observed. Mixing herbicides may increase the spectrum of weed species controlled or may cause greater levels of mortality (synergistic effects) on the weed population compared to the individual herbicides (Damalas, 2004). The results of our study provide evidence of good compatibility of atrazine and Stellar-Star for overall weed control in maize.

In general, the reduction in weed biomass achieved at 10 WACE by the Stellar-Star label dose, Stellar-Star + Atrazine tank mix and Stellar-Star double dose split application was 82–97%, 56–91% and 76–85% respectively, in comparison to the control treatment in two seasons. These results show that the label dose of Stellar-Star was similarly efficacious in reducing overall weed biomass with the Stellar-Star + Atrazine tank mix and the Stellar-Star double dose split application, treatments that incurred addititional costs of herbicide and labour. However, maize grain yield and RUE was significantly higher in the Stellar-Star + Atrazine tank mix and the Stellar-Star double dose split application than Stellar-Star label dose, Stellar-Star reduced dose and hoe weeding treatments in the 2013/14 season. Gross margin was highest in the Stellar-Star + Atrazine tank mix in the 2013/14 season. These results suggest that treatments that achieve superior early weed control in the first third of the crop life-cycle, such as the Stellar-Star + Atrazine tank mix, are likely to show the smallest negative impact of weeds on crop growth and yield and produce the highest yield and profit (gross margin). This observation is buttressed by the higher levels of correlation that were recorded among weed density at 5 WACE and grain yield, rainfall use efficiency and gross margin than weed density at 10 WACE with the same parameters, in this study. Weeds that emerge late after canopy closure are generally less competitive than weeds that emerge early before canopy closure (Tharp and Kells, 2001; Mashingaidze et al., 2009). Late weeds are at a starting position disadvantage relative to the crop and are outcompeted by larger crop plant. Large plants are able to obtain a share of resources that is disproportionate to their relative size and suppress the growth of emerging under their canopies (Weiner et al., 1997).

Maize grain yield ranged from 0–0.8 and 0.8–2.8 t ha^{-1} in the unweeded check and the Stellar-Star + Atrazine tank mix in the dry 2014/15 and wet 2013/14 seasons, respectively. The 2014/15 season was characterized by the early cessation of rainfall and the maize crop was adversely affected by moisture stress during critical stages of flowering and grain-filling, reducing grain yield. Competition for moisture and other consumable resources in the weedy-check in the 2014/15 season was so intense that the maize crop was stunted and failed to produce any grain yield. In contrast, without weeding in the wet 2013/14 season the weedy-check achieved similar yield as the treatments with highest maize grain yield in the dry 2014/15 season showing that weeds caused more severe damage to crop growth and grain yield in dry than wet seasons. The efficiency of weed control exhibited by the Stellar-Star weed management treatments in this study determined the amount of soil moisture available to the crop as shown by the highly significant negative correlation between weed density at 5 and 10 WACE and weed biomass at 10 WACE with grain yield, RUE, and gross margin. These results show that Stellar-Star weed management treatments effectively controlled weeds and reduced soil water used and transpired by weeds, allowing more soil water to become available to the crop; increasing RUE, yield and gross margin in the maize crop.

Hoe weeding was more effective in controlling *C. dactylon* and all

weeds in the dry 2014/15 season than in the 2013/14 season. Weeds, including perennial weeds like *C.dactylon*, are more susceptible to hoe weeding in dry seasons, because after weeding they are exposed to dry conditions which desiccate S the uprooted plant parts including perennating structures, such as rhizomes and stolons. Hoe weeding was less effective under excessively wet conditions than dry conditions as hoe-damaged weeds re-rooted and re-established themselves, especially those with perrenating structures (Mashingaidze et al., 2012). Stellar-Star herbicide treatments were more efficacious during the wet 2013/14 than dry 2014/15 season. Dry conditions reduce the efficacy of post-emergence foliar-applied herbicides because plants develop thicker cuticles that reduce herbicide retention, absorption, and translocation. Foliar-applied herbicides are most efficacious when applied under humid and wet conditions when the cuticle is hydrated and provides both aqueous and lipophilic pathways into the leaf and the weeds are actively growing and translocating herbicides in the phloem (Kudsk and Kristensen, 1992). Topramezone is translocated both in the apoplastic and symplastic system (Grossmann and Ehrhardt, 2007). Dicamba, like all auxin mimicking herbicides, is translocated in the symplastic system (Grossmann et al., 2002). Under wet conditions when the plant is actively photosynthesizing and growing, the soluble photo-assimilates gradients are greatest between sources and sinks, enhancing translocation and efficacy of both the symplastically translocated Topramezone and Dicamba in Stellar-Star, as shown by the results this study. Higher rates of water movement in the xylem when soil moisture is available would also enhance the translocation and accumulation of topramezone at its active sites, since it is ambimobile in the plant, further enhancing the efficacy of Stellar-Star in the wet season, as determined in this study. Efficiency of herbicide translocation is critical in determining the efficacy of post-emergence foliar-applied herbicides in perennial weed species like *C. dactylon*, with their large plant sizes and biomass of aerial and subterranean perrenating structures, hence greater levels of *C. dactylon* control was achieved by the Stellar-Star weed management treatments in the wet 2013/14 season than in the dry 2014/15 season, in this study.

Because of the truncated growing season for maize, caused by the early cessation of rainfall in the 2014/15 season and consequent low maize grain yield, the gross margin was negative for all treatments, meaning that all the treatments registered a financial loss. Our results showed that in a droughty season like the 2014/15 season, farmers are likely to suffer financial losses regardless of the weed management strategy they deploy, and the extent of the losses depended on the efficacy of the weed management strategies in reducing weed infestation and averting the reduction in maize grain yield. In the 2013/14 season, when rainfall was more evenly distributed than in the 2014/15 season, higher maize grain yield ensured positive financial returns from all the Stellar-Star weed management treatments except the Stellar-Star reduced dose and hoe weeding treatments. Gross margin was negatively correlated to weed density at 5 WACE (r = −0.94, P < 0.01) and at 10 WACE (r = −0.82, P < 0.05) and weed biomass at 10 WACE (r = −0.85, P < 0.05) showing the importance of the efficacy of weed control by the Stellar-Star weed management treatments in determining the financial return from the maize crop.

All the Stellar-Star weed management treatments provided more than 75% reduction in *C.dactylon* density at 10 WACE with the Stellar double dose split application and the Stellar-Star + Atrazine tank mix achieving the highest (90–97%) and the Stellar-Star label dose and Stellar-Star reduced dose achieving the next highest reduction (75–88%) in *C.dactylon* density. These results confirm the high efficacy of topramezone against *C. dactylon* observed by other researchers. Brosnan and Breeden (2013) achieved 82–92% of *C. dactylon* by 52 days after application of topramezone plus triclopyr mixtures. The sequential application of Stellar-Star at 3 and 6 WACE in the Stellar-Star double dose split application treatment provided marginally superior levels of *C. dactylon* control than the label dose but it added to the cost of weed management and significantly reduced financial returns (gross margin) from the maize crop when compared to the Stellar-Star + Atrazine tank mix.

5. Conclusions

The results of this study show the reduction in *C. dactylon* density was much slower than for annual weeds as it knocked down annual weeds by 5 WACE and the perennial *C. dactylon*, by 10 WACE. The results of the study also demonstrated that the Stellar-Star Atrazine tank mix produced superior early-season control at 5 WACE, and as result, higher maize grain yield, RUE and gross margin than all the other Stellar-Star herbicide treatments and hoe weeding in both seasons. The higher levels of negative correlation between weed density at 5 WACE with maize grain yield, RUE, and gross margin compared to the correlation between weed density and biomass at 10 WACE with the same parameters, attests to the importance of early-season weed control in averting yield and financial loss caused by weed infestation. In the dry 2014/15 season, the early cessation of rainfall reduced yield below one ton and produced negative gross margins for all Stellar-Star weed management treatments, but the degree of yield reduction depended on the efficacy of the weed management treatment in reducing weed infestation, with the Stellar-Star + Atrazine tank mix and hoe weeding treatments producing the highest yield and RUE and the least negative gross margins. The results of this study also show that that hoe weeding was more efficacious in controlling weeds in a dry 2014/15 season than in the wet 2013/14 season and the Stellar-Star herbicide treatments were more efficacious in controlling weeds in the wet 2013/14 season than the dry 2014/15 season.

The Stellar-Star + Atrazine tank mix is recommended because of its superior early and late season general weed control, and higher maize grain yield, RUE and gross margin than the Stellar-Star double dose split application, Stellar-Star label dose, Stellar-Star reduced (75% of label dose) dose and hoe weeding. All the Stellar-Star weed management treatments achieved greater than 75% reduction in *C. dactylon* density, with the Stellar-Star double dose split application and the Stellar-Star + Atrazine tank mix achieving the largest reduction in *C. dactylon* density (90–97%). Stellar-Star is therefore recommended for *C.dactylon* control at current dosages, however, the results of this study suggest that its mixture with Atrazine will improve overall weed control by widening the spectrum of weeds controlled, hence achieving early season weed control, increasing yield and financial returns from the maize crop. The Stellar-Star double dose sequential application at 3 and 6 WACE, despite its similar efficacy in weed control to the Stellar-Star plus Atrazine tank mix, was not financially justifiable.

Declarations

Author contribution statement

Justin Chipomho, Solomon Mupeti, Caroline Chipomho: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Nilton Mashavakure, Arnold Bray Mashingaidze: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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