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Evaluation of pre-emergence herbicides for weed control in maize

[1]Keotshephile Kashe*, [2]Dikungwa Ketumile, [3]Paul Kristiansen, [2]Cornelius Mahilo,
[4]Thebeetsile S. Moroke,

[1]*University of Botswana, Okavango Research Institute, Private Bag 285, Maun, Botswana*
[2]*Department of Agricultural Research, Private Bag 0033, Gaborone, Botswana*
[3]*University of New England, School of Environment and Rural Science, Armidale NSW 2351 Australia*
[4]*Botswana University of Agriculture and Natural Resources, Private Bag 0027, Gaborone, Botswana*

Abstract

Weed management is an ongoing constraint in southern Africa for conventional farming systems and in emerging conservation agriculture systems, which are more heavily reliant on herbicides for primary weed control. The challenge of rising labour costs and decreasing availability creates a greater need to develop effective and efficient weed management methods in key crops such as maize. Field experiments were conducted at Sebele Agricultural Research Station, Botswana in the 2011/12 and 2012/13 cropping seasons to evaluate the pre-emergence application of atrazine at 1,000 and 2,000 g a.i. ha^{-1} and *S*-metolachlor at 1,440 and 2,880 g a.i. ha^{-1}, and a tank mixture of atrazine at 1,000 and *S*-metolachlor at 1,440 g a.i. ha^{-1}. Atrazine at both rates effectively controlled annual broadleaf weeds: *Acanthospermum hispidum*, *Datura ferox* and *Sesamum alatum*, but failed to control annual grass weeds (*Tragus berteronianus* and *Urochloa* spp.). Conversely, sole application of *S*-metolachlor at both rates provided complete control of annual grass weeds, but poorly controlled annual broadleaf weeds except small-seeded *Amaranthus hybridus* and *Amaranthus thunbergii*. A tank mixture of atrazine and *S*-metolachlor provided broad-spectrum weed control and successfully controlled both annual broadleaf and grass weeds. Atrazine alone and in tank mixture with *S*-metolachlor significantly reduced annual broadleaf weed density and biomass and increased maize grain yield by more than 80% when compared with the weedy treatment (untreated). High weed density and biomass of annual broadleaf weeds in *S*-metolachlor treatments significantly reduced maize grain yield to levels similar to the weedy treatment. A pre-mixture of atrazine and *S*-metolachlor is recommended for broad-spectrum weed control. Using a combination of herbicides with different modes of action may reduce selection pressure for herbicide resistance.

Keywords: Atrazine, *S*-metolachlor, weed density, weed biomass, grain yield.

1. Introduction

Crop production in developing countries of Africa, Asia and Latin America is dominated by resource-constraint smallholder farmers who grow crops for sustenance (Johansen, Haque, Bell, Thierfelder, & Esdaile, 2012). Grain crops such as maize, sorghum, wheat and barley are in high demand to alleviate

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dire food insecurity worldwide (Owen, Martinez, & Powles, 2015). Production of these crops, however, is limited by weeds (Khan, Hussain & Khan, 2008), found to be one of the significant constraints to efficient crop production (Mhlanga et al., 2015).

Maize (*Zea mays* L.) is only surpassed by wheat and rice globally, as the essential cereal (Ishaya, Tunku, & Kuchinda, 2008). In many countries in Africa, it plays as significant a role in most diets as rice and wheat in Asian countries (Cutts & Hassen, 2003). It is the cereal most consumed in Africa with Southern Africa, accounting for 32% of the total global maize consumption (Setimela, Crossa & Bänziger, 2010; UNECA, 2009). In Botswana, it is the main cereal consumed and dominates most of the diets of Batswana (Lekgari & Setimela, 2002). The number of farmers who cultivate maize and the area planted is a reflection of the high consumption. In the 2013 agricultural season, more farmers (64,651) planted maize than sorghum (39,454) or millet (18,699), and there was more area (126,091 ha) planted under maize than sorghum (67,552 ha) and millet (11,752 ha) (Statistics Botswana 2016). However, production of maize and other crops faces weed control challenges (Muoni et al., 2014), which cause detrimental effects on crop yield and quality of produce (Arif et al., 2006). The impact of weeds is more pronounced in resource-poor smallholder farmers with limited labour and capital for effective weed control and management (Mhlanga et al., 2015). Weeds efficiently compete with crops for inadequate nutrients, light, available water and space (Khan, Hassan, Khan, & Khan, 2004; Zimdahl, 2004) and inhibit crop growth and development (Jabran, Mahajan, Sardana &, Chauhan, 2015). A season-long weed infestation in abundance has the potential to significantly reduce crop yields (Plaza et al. 2015) from ~34% (Jabran et al., 2015) to more than 80% (Karlen, Buhler, Ellusbury, & Andrews, 2002). These yield losses are more than losses caused by all other types of crop pests (Oerke, Dehne, Schönbeck, & Weber, 1999). Weed infested crop fields create habitats for insect and diseases that will eventually negatively affect yields (Shrestha, Knezevic, Roy, Ball-Coelho, & Swanton, 2002). Weeds in maize and reduced soil fertility have been reported to lower grain yield to a paltry 1 t ha^{-1} (Gianessi, 2009).

Traditionally, smallholder farmers cultivate by use of mouldboard plough followed by disc harrow to control weeds and prepare the seedbed for germination and seedling establishment (Johansen et al., 2012; Moret, Braud, & Arrue, 2007; Ozpinar, 2006). In Zimbabwe, farmers with no access to draft power, control weeds by hand hoes or hand weeding when an area is small (Muoni, Rusinamhodzi, & Thierfelder, 2013). In Botswana, hoe weeding and tillage by an animal or tractor-drawn mouldboard ploughs are important weed control methods for smallholder farmers. The traditional hoe or hand weeding, however, is limited by availability and high cost of labour (Ishaya et al., 2008; Gianessi, 2013). In northern Nigeria it has been established that to hand weed one hectare of sorghum and maize, a total of 324 and 309 man-hours are needed respectively, in contrast to 100 and 91 man-hours ha^{-1} for herbicide application (Ishaya et al., 2008). The constraints associated with hand or hoe weeding calls for an alternative weed control method. Herbicides have emerged as an alternative to manual weeding and have improved crop yields in developing countries (Baghestani et al., 2008; Ishaya et al., 2008).
S-metolachlor is a pre-emergence herbicide in the chloroacetamide family with its action on the root and shoot (Bangwara, Norsworthy, & Gbur, 2009; Sikkema, Shropshire, & Soltani, 2009) to suppress the growth of germinating seedlings (Vencill, 2002; Osborne, Shaw, & Ratliff, 1995). Atrazine is a triazine herbicide that controls many annual broadleaves and some annual grass weed species in sorghum and maize (Williams, Boerboom, & Rabaey, 2010). Atrazine herbicide is used in maize, mainly because of its low cost and high efficacy in season-long residual control of a variety of problematic weeds (Bollman, Kells, & Penner, 2006; Swanton, Gulden, & Chandler, 2007; Williams, Boydston, Peachy, & Robinson, 2011). Maize weed management programs are traditionally based on the pre-emergence application of atrazine plus chloroacetamide (e.g. *S*-metolachlor) for annual broadleaf and grass weed control respectively (Whaley, Armel, Wilson, & Hines, 2009; Odero & Wright, 2013). Such mixture improves the efficacy of a single herbicide by providing a broad-spectrum

weed species control (Green & Owen, 2011; Stewart, Nurse, Hamill, & Sikkema, 2010).In Botswana, an arid country with increasingly erratic rainfall patterns and rising summer temperatures, broadleaf weeds such as *Amaranthus hybridus*, *Datura ferox*, *Acanthospermum hispidum* and *Verbesina encelioides* (Abdullahi, 2004; 2006; Phillips, 1992) and grass weeds such as *Urochola* spp., *Tricholaena monachne*, *Tragus berteronianus*, *Digitaria eriantha* and *Eleusine indica* (Abdullahi, 2006; Phillips, 1991:1992) make arable farming challenging. Even though these weeds limit efficient crop production in Botswana, there is limited information on chemical weed control in maize production. Therefore, the objective of this study was to evaluate the efficacy of *S*-metolachlor or atrazine applied alone or in tank mixture for weed control in maize. We hypothesized that a tank mixture of *S*-metolachlor and atrazine would increase the number and range of weed species controlled.

2. Materials and methods

2.1 Site description

We conducted field experiments in the 2011/12 and 2012/13 crop growing seasons at Sebele Agricultural Research Station in two blocks, B33 (S 24° 35' 03.5", E 025° 57´ 01.3") and D33 (S 24° 34' 4.9’’, E 025° 53´ 08.2”), located near Gaborone, the capital city of Botswana. Botswana’s climate is classified as semi-arid to arid, with the Kalahari Desert occupying about 70% of the country (Batisani and Yarnal, 2010). The rainfall pattern is unimodal with one distinct rainy season from November to March (Fig. 1). Soils at Sebele Agricultural Research Station are classified as Ferric Luvisols (sandy clay loam) (Moroke, Dikinya, & Patrick, 2007) and contain 0.31 % organic carbon, with a pH of 5.8 and cation-exchange capacity of 6.5 cmol g^{-1}. The Station recorded a total annual rainfall of 217.6 mm and 482.2 mm in 2011/12 and 2012/13, respectively. Mean monthly temperatures varied from 12–15 ºC in the morning to 30–40 ºC in the afternoon.

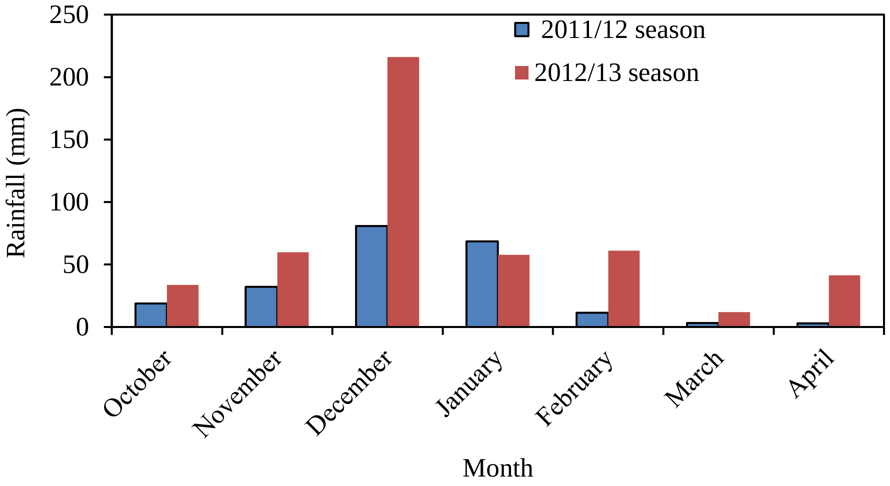

Fig. 1. Mean monthly rainfall for Sebele Agricultural Research Station in 2011/12 and 2012/13 crop growing season

2.2 Experimental design

In both years, the experiment was arranged in a randomised complete block design with six treatments;

1. Atrazine at 1,000 g a.i. ha^{-1} (AtraH)
2. Atrazine at 2,000 g a.i. ha^{-1} (AtraF)

3. S-melachlor at 1,440 g a.i. ha^{-1} (S-metH)
4. *S*-metolachlor at 2,880 g a.i. ha^{-1} (S-metF)
5. Tank mixture of atrazine at 1,000 + *S*-metolachlor at 1,440 g a.i. ha^{-1} (S-met plus atra)
6. Weedy (untreated)

Each treatment was replicated four times.

Land preparation in both years was done with a mouldboard plough followed by disc harrow to create a fine soil tilth conducive for seed germination and seedling establishment. Each plot was 8 m long with four rows, and maize (*Zea mays* (L.) var. Kalahari Early Pearl) was seeded at 0.9 m x 0.3 m plant spacing. Single superphosphate was applied at 20 kg ha^{-1}. We immediately applied herbicide treatments, using a knapsack sprayer calibrated to deliver 300 L ha^{-1} at a pressure of 200 kPa. Maize injury and weed control were assessed visually 2 and 4 weeks after herbicide application on a scale ranging from 0% implying no weed control or plant response to 100% meaning complete weed control or plant death.

2.3 Field measurements

In all plots, we counted weed seedlings at 2 and 4 weeks after sowing by placing a one squared meter quadrat at 0.5 m interval four times along the centre row of each plot. We identified weeds to species level following guidelines by Phillips (1991) and Abdullahi (2006), Specimens of unidentified weeds were collected for identification at Gaborone National Herbarium (GAB). Weed counts were averaged across the four quadrats and converted to seedlings per square metre (weed density). Within the same quadrants, each weed species was clipped at the soil surface, packaged in oven-proof envelopes and oven-dried at 80ºC for 72 hours. We then recorded dry biomass of the different weed species after 72 hours. We measured maize grain yield from plants sampled from the centre row and determining grain yield at 15% moisture content.

2.4 Data analysis

Data were analysed using the R statistical software program (R Core Team 2017). We ran a two-way analysis of variance (ANOVA) of herbicide treatment and weed species for all weed density, weed biomass and maize grain yield data. The two seasons were analysed separately as the weed species present were different. The ANOVA models were checked for homogeneity of variance and normality, and $\log_{10}$ transformations were required for weed density and biomass, but not maize grain yield. The data for these response variables were compared using 95% confidence intervals (95% CI = 1.96 × standard error of the mean) and represented as error bar plots (Brennan and Acosta-Martinez 2017).

Linear regression was used to evaluate the relationship between weed biomass and weed density (2012–2013 season only). Non-linear regression was used to assess the relationship between weed biomass and grain yield (2012–2013 season only) using the decay function (Thornley and Johnson 1990),

$$y = \frac{a \times b^c}{(b^c + x^c)}$$

Where y = maize grain yield, x = weed biomass and a, b and c are the regression parameters.

3. Results

Rainfall accumulated in the first ten days after the application was much higher than what we received in the last ten days in both years (Table 1). Rainfall in 2011 was higher than in 2012 for both recordings, and similarly, total rainfall was also more in 2011 than in 2012.

Table 1. Cumulative rainfall (mm) for 20 days after application of pre-emergence herbicides in 2011 and 2012.

Days after application	2011	2012
0–10	42.8	24
11–20	5.5	3
Total	48.3	27

3.1 Effect of herbicides on weed density

Weed density as a measure of weed control indicated that each weed species responded differently to the application of pre-emergence, i.e. herbicides had a significant effect on weed density ($p < 0.001$). In 2011–2012 season at block B33, broadleaf weeds (*Acanthospermum hispidum*, *Datura ferox*, *Sesamum alatum* and *Ipomoea* sp.) had significantly higher densities in both rates of *S*-metolachlor and non-treated weedy treatment than both rates of atrazine and tank mixture of *S*-metolachlor plus atrazine (Fig. 2). For instance, the density of the dominant weed *A. hispidum* was 68, 58 and 55 weeds m^{-2} in *S*-metolachlor at 1,440 and 2,880 g a.i. ha^{-1} and non-treated weedy treatment, respectively, compared with less than one weed m^{-2} in both treatments of atrazine and tank mixture of *S*-metolachlor plus atrazine. The grass weeds *Tragus berteronianus* and *Urochloa* spp. were conspicuously absent in both rates of *S*-metolachlor. The density of these grass weeds in both rates of atrazine was similar to the non-treated weed control area and was significantly higher than in all other treatments. A tank mixture of *S*-metolachlor plus atrazine recorded density of less than one weed m^{-2} for either broadleaf or grass weeds .i.e. this treatment was almost weed-free.

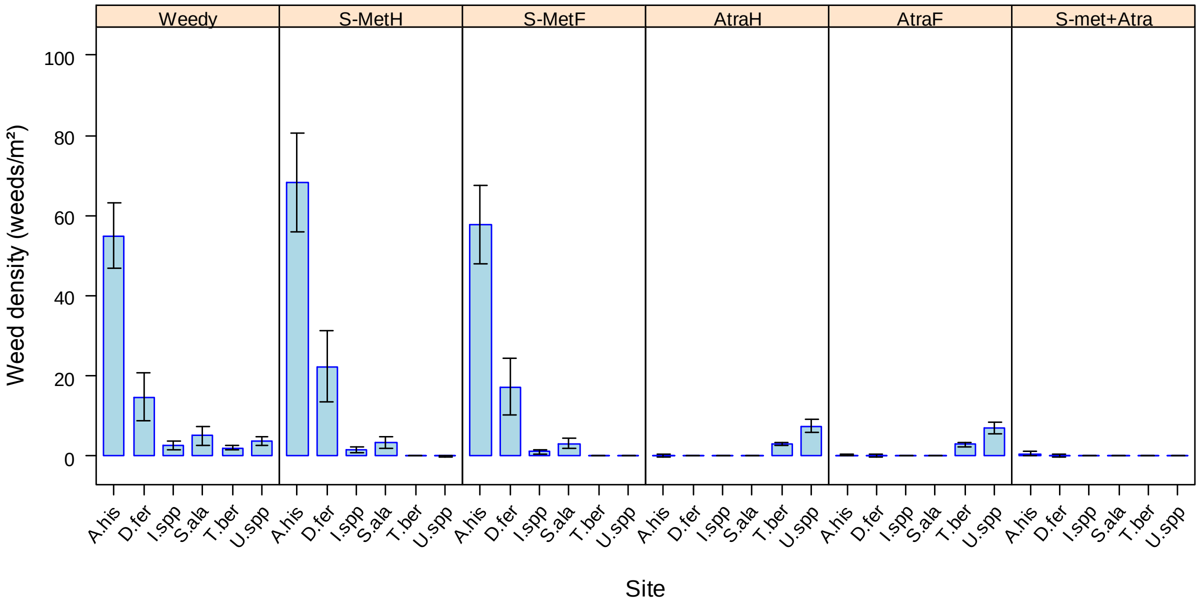

Fig. 2. Effect of pre-emergence herbicides on weed density in 2011–2012 season. Means and 95% confidence intervals are shown. *A. his–Acanthospermum hispidum*, *D. fer–Datura ferox*, *I. spp–Ipomoea* spp., *S. ala–Sesamum alatum*, *T. ber–Tragus berteronianus*, *U.* spp–*Urochloa* species.

Similarly, in 2012–2013 season at block D33, herbicide treatments had a significant effect ($p < 0.001$) on weed density. Comparably, weed density in this season was low compared with 2011 – 2012 season (Fig. 3). Like the previous season, both rates of *S*-metolachlor had a high density of broadleaf weeds (*A. hispidum*, *Ipomoea* sp. and other weeds) compared with both rates of atrazine which recorded high density of *Urochloa* spp. Other weeds comprised of *Chenopodium* sp., *Hibiscus* sp., *Tribulus terrestris* and *S. triphyllum*. Interestingly, broadleaf weeds *Amaranthus hybridus* and *A. thunbergii* were observed in the non-treated weedy treatment with a density of 23 and 13 weeds m-2, respectively. These *Amaranthus* species were not recorded in the treated plots. A tank mixture of *S*-metolachlor and atrazine was weed-free with no traces of broadleaf or grass weeds.

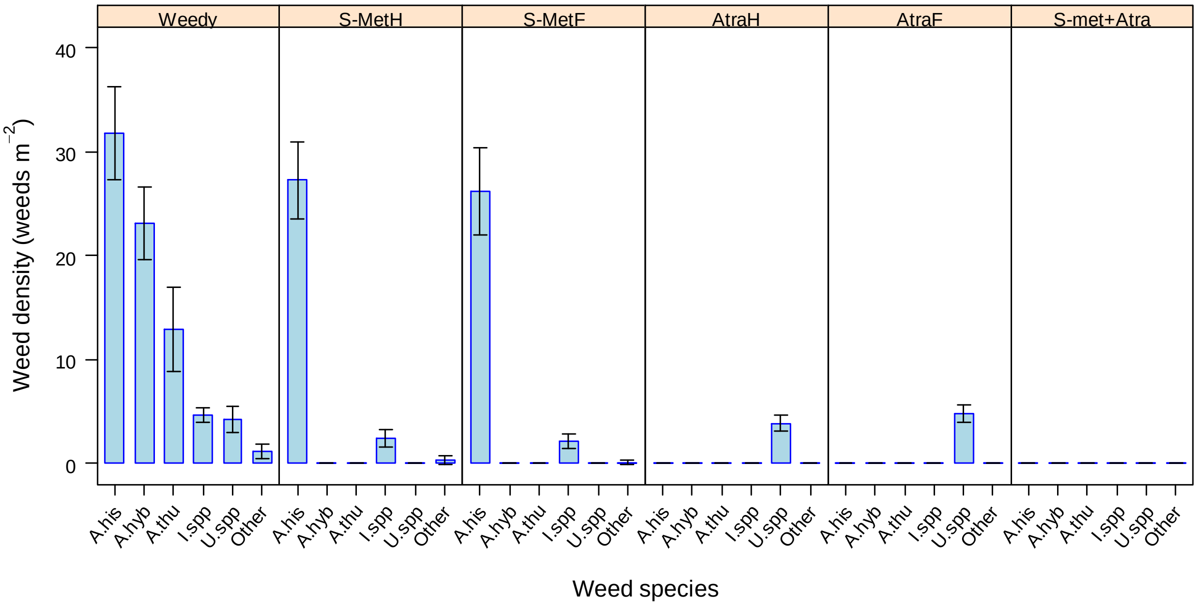

Fig. 3. Effect of pre-emergence herbicides on weed density in 2012–2013 season. Means and 95% confidence intervals are shown. *A. his–Acanthospermum hispidum*, *A. hyb–Amaranthus hybridus*, *A. thu–Amaranthus thunbergii*, *I.* spp–*Ipomoea* spp., *U.* spp–*Urochloa* species.

3.2 Effect of herbicides on weed biomass

In 2011–2012 season, at block B33, weed biomass was significantly influenced by herbicide treatments ($p < 0.001$). Both rates of *S*-metolachlor and non-treated weedy treatment produced similar biomass for dominant broadleaf weeds *A. hispidum* and *D. ferox* (Fig. 4). These weeds had biomass of 62, 53 and 68, and 22, 21 and 24 g m^{-2} in *S*-metolachlor at 1,440 and 2,880 g a.i. ha^{-1} and non-treated weedy treatment, respectively. Broadleaf weeds were not present in both rates of atrazine. In stark contrast, both rates of atrazine and non-treated treatment produced similar biomass of *T. berteronianus* and *Urochloa* spp. A tank mixture of *S*-metolachlor plus atrazine was weed-free.

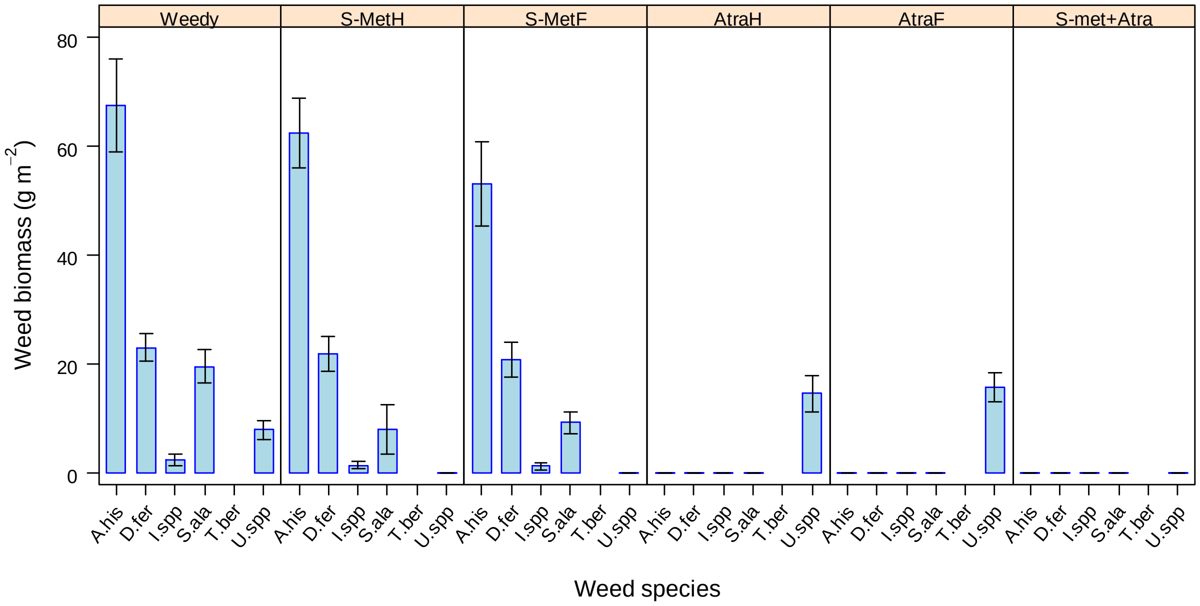

Fig. 4. Effect of pre-emergence herbicides on weed biomass in 2011–2012 season. Means and 95% confidence intervals are shown. *A. his–Acanthospermum hispidum*, *A. hyb–Amaranthus hybridus*, *A. thu–Amaranthus thunbergii*, *I.* spp–*Ipomoea* species, and *U.* spp–*Urochloa* species.

In 2012–2013 season, both rates of *S*-metolachlor and non-treated weedy treatment were dominated by *A. hispidum*, which produced a similar amount of biomass in both these treatments (Fig. 5). Unlike other broadleaf weeds, *A. hybridus* and *A. thunbergii* produced biomass in the weedy treatment plot but were not recorded in all herbicide treatment plots. Either test rate of atrazine produced only Urochloa spp. biomass. No weed biomass was produced in tank mixture of *S*-metolachlor plus atrazine.

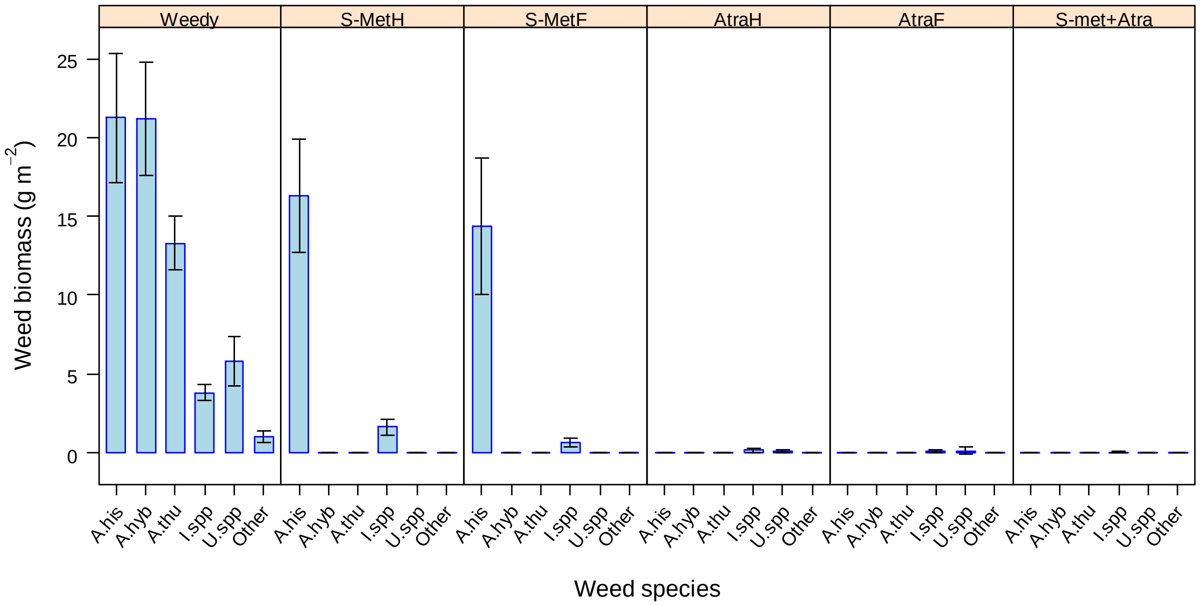

Fig. 5. Effect of pre-emergence herbicides on weed biomass in 2012–2013 season. Means and 95% confidence intervals are shown. *A. his–Acanthospermum hispidum*, *A. hyb–Amaranthus hybridus*, *A. thu–Amaranthus thunbergii*, *I.* spp–*Ipomoea species*, and *U.* spp–*Urochloa species*.

Weed biomass was strongly influenced by weed density, i.e. as the weed density increases, weed biomass also increases. For instance, linear regression between weed density and weed biomass in 2012–2013 season produced a strong positive relationship ($R^2 = 0.96$) between weed density and weed biomass (Fig. 6), indicating that 96% of the variation in weed biomass is due to an increase in weed density.

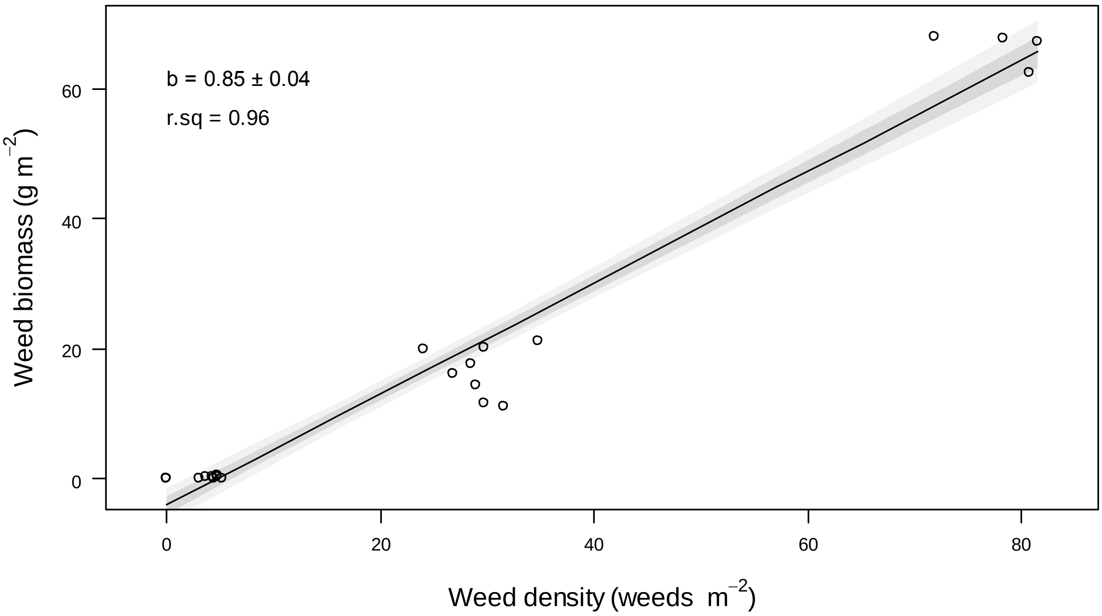

Fig. 6. Linear regression of weed biomass and weed density (2012–2013 season). Raw data (○), fitted regression line (–) and confidence bands (dark shading = 1 SE, light shading = 2 SE) are shown, and b = slope coefficient and r.sq = R^2.

3.3 Effect of herbicides on maize grain yield

In 2011–2012 season, maize did not grow to maturity due to low rainfall that resulted in moisture stress at the critical period of tasseling and silking. The rainfall amount recorded around these critical stages was 11.3, 3.3 and 3 mm for February, March and April, respectively. The total rainfall for the season (October to April) was deficient, about half (217.6 mm) the amount (482.20 mm) received in 2012–2013.

In 2012–2013 season, herbicide treatments had a significant effect ($p < 0.001$) on grain yield (Fig. 7). Atrazine application, at both rates, and tank mixture of *S*-metolachlor plus atrazine produced similar yields that were significantly greater than either the *S*-metolachlor treatment or the non-treated weedy plot; these latter two also produced similar yields. Atrazine at both low and high rate and *S*-metolachlor plus atrazine were effective in weed control and significantly increased grain yield in those plots by 80%, 93% and 86%, respectively. *S*-metolachlor at both rates was weak in controlling annual broadleaf weed species and consequently did not significantly influence grain yield.

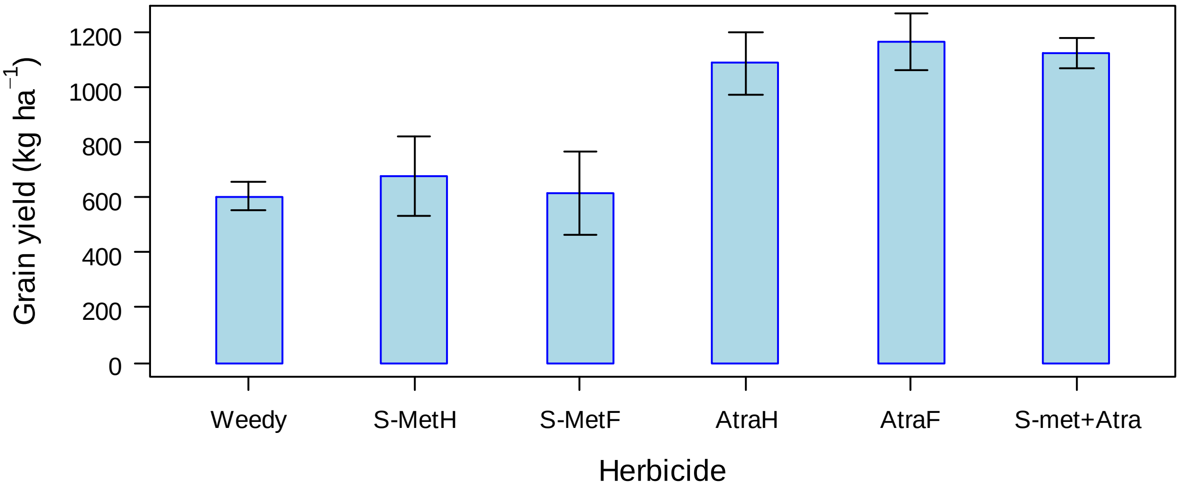

Fig. 7. Maize grain yield with a pre-emergence application of *S*-metolachlor, atrazine and tank mixture of *S*-metolachlor plus atrazine in the 2012–2013 season. Means and 95% confidence intervals are shown.

The relationship between grain yield and weed biomass accounts for 77% of the variation (Fig. 8). Grain yield under very low weed burdens was about 1,100 kg ha^{-1}. A small increase in the weed burden (10-20 g m^{-2}) reduced grain yield significantly to about 750 kg ha^{-1}. However, increasing weed burdens above about 20 g m^{-2} did not significantly reduce grain yield further.

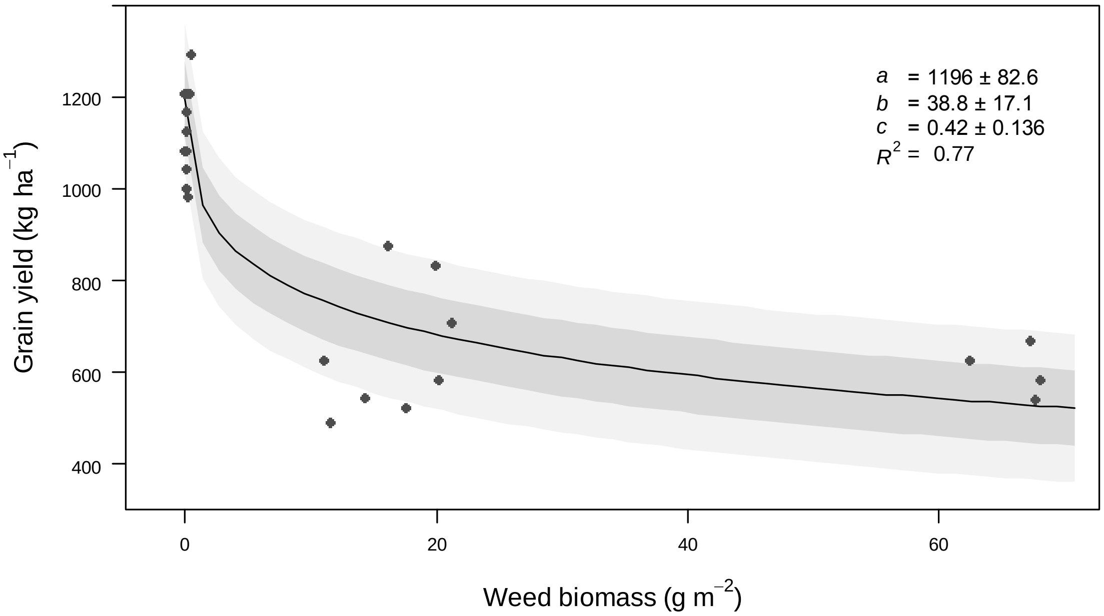

Fig. 8. Non-linear regression of grain yield and weed biomass (2012–2013 season). Raw data (●), fitted regression line (–) and confidence bands (dark shading = 1 SE, light shading = 2 SE) are shown, and *a*, *b* and *c* are the regression coefficients.

4. Discussion

4.1 Effect of herbicides on weed density

Broadleaf and grass weeds responded differently to the pre-emergence application of *S*-metolachlor or atrazine, and a tank mixture of these two herbicides. Both rates of *S*-metolachlor successfully controlled

Tragus berteronianus and *Urochloa* spp. (annual grass weeds) but were not effective against annual broadleaf weeds such as the dominant *Acanthospermum hispidum* and *Datura ferox*. However, both rates were effective against the small-seeded annual broadleaf weeds (*Amaranthus hybridus* L. and *Amaranthus thunbergii*). These results concurred with Soltani et al. (2004) who found that pre-emergence application of *S*-metolachlor successfully controlled annual grasses and failed to control broadleaf weeds. Control of *Amaranthus* spp. by *S*-metolachlor has been reported by Geier et al. (2006). In their study, pre-emergence application of *S*-metolachlor at 2,140 and 2,580 g a. i. ha^{-1} provided 85 to 100% of *Amaranthus palmeri* S. Wats (Palmer amaranth), a species not observed in this trial. *S*-metolachlor was previously reported to provide adequate control of annual grasses and some small-seeded annual broadleaf weed species (Webster 2006). Webster et al. (2006) in agreement reported ≥ 80% control of *Commelina benghalensis* L. (tropical spiderwort) with a pre-emergence application of *S*-metolachlor at 1.07 and 1.6 kg a.i. ha^{-1}.

Conversely, pre-emergence application of atrazine was found to be effective against most annual broadleaf weeds but low against annual grass weeds. Atrazine is known to inhibit germination and emergence of annual broadleaf weeds for the whole cropping season due to its residual activity (Muoni et al., 2014). Results from our study showed that either rate of atrazine was effective against annual broadleaf weeds but failed to control annual grass weeds. This finding is in agreement with the results from a study in eastern Ethiopia by Das et al. (2010) who observed that pre-emergence application of atrazine at 1.0 kg a.i. ha^{-1} was poor in controlling *Digitaria abyssinica* (A.Rich.) Stapf. a grass, but ultimately controlled five annual broadleaf weeds; *Plantago lanceolata* L., *Erucastrum arabicum* Fisch. & May, *Galinsoga parviflora* (L.) Cav., *Amaranthus viridis* L. and *Solanum nigrum* L. Atrazine was also reported to be poorly effective against crabgrass (*Digitaria sanguinalis*) and provided only 68% control in green foxtail, *Setaria viridis* (Geier, Stahlman, & Frihauf, 2009). Similarly, in Nigeria, atrazine applied pre-emergence at 3.0 and 3.5 kg a.i. ha^{-1} provided a minimum of 90% control in *Passiflora foetida*, *Commelina benghalensis* and *Pueraria phaseoloides* (Chikoye, Lum, Ekeleme, & Udensi, 2009). The effectiveness and affordability of atrazine have seen it promoted as the most widely used herbicide for broad-spectrum weed control (Bollman et al., 2006).

Sole application of either *S*-metolachlor or atrazine pre-emergent provides effective control against either grass or broadleaf weeds, respectively. A tank mixture of these herbicides is recommended to enhance control of both weed types (Richardson, Whaley, Wilson, & Hines, 2006). It may have the advantage of reducing the risk of herbicide resistance developing (Green & Owen, 2011).

The results demonstrated that a tank mixture of *S*-metolachlor and atrazine applied pre-emergence at 1,440 and 1,000 g a.i. ha^{-1} was highly effective against both grass and broadleaf weeds and provided season-long weed control. This observation is comparable to a study by Taylor-Lovell & Wax (2001) who found that a pre-mixture of 1,820 atrazine and 1,408 *S*-metolachlor g a.i. ha^{-1} effectively controlled the grass *Setaria faberi* and several broadleaf weeds. Likewise, 1,070 *S*-metolachlor mixed with 1,340 atrazine g a.i. ha^{-1} was effective against *S. faberi* and *A. palmeri* (Geier et al., 2006). In Nigeria, a pre-mixture of *S*-metolachlor with atrazine at 2.5 or 4 kg a.i. ha^{-1} was excellent against broadleaf weeds but failed to adequately control the grass *Panicum maximum* and the herb/forb *Euphorbia heterophylla*. However, some species of Panicum, e.g. *P. dichotomiflorum* are known to emerge late, and this may be after pre-emergence herbicides have deteriorated to levels too low to affect any control (Johnson, Defelice, & Holman, 1997). Poor control of *P. maximum* in that study was therefore partly attributed to late emergence after the herbicide application.

4.2 Effect of herbicides on weed biomass

Weed biomass of the different weed species was closely associated with weed density and was significantly influenced by the effectiveness of the tested herbicides. Pre-emergence application of *S*-

metolachlor did not control broadleaf weeds, which thrived on producing biomass. In stark contrast, grass weeds were not controlled by atrazine and grew to produce biomass. A tank mixture of *S*-metolachlor and atrazine provided complete control of both annual grass and broadleaf weeds resulting in season-long weed-free conditions. Das et al. (2010), in agreement with the current findings, reported no biomass for broadleaf weeds but reported 29.24 g m^{-2} for *Digitaria abyssinica* under sole application of atrazine, implying that atrazine failed to control this grass weed and allowed it to grow and produce biomass. In a study by Vyn et al. (2006), atrazine alone and a tank mixture of *S*-metolachlor and atrazine effectively controlled *Amaranthus tuberculatus* resulting in no weed biomass production and weed-free condition for the whole duration of the cropping season. The strategy of combining herbicides with different modes of action can potentially control a broader weed spectrum, offer improved control over single herbicide applications and thereby reduce selection pressure for resistant weeds populations (Green & Owen, 2011).

4.3 Effect of herbicides on maize grain yield

Effective control of broadleaf weeds by pre-emergence application of either rate of atrazine or a tank mixture of *S*-metolachlor and atrazine enhanced maize grain yield under these treatments. Poor control of broadleaf weeds at either rate of *S*-metolachlor failed to improve grain yield above what was recorded in the weedy plot. Broadleaf weeds in *S*-metolachlor treatments produce more biomass (85–94 g m^{-2}) than grass weeds in atrazine (15–16 g m^{-2}). Massive broadleaf weed biomass significantly reduced grain yield in *S*-metolachlor treatments and weedy plot. In a similar study in Nigeria, a pre-mixture of *S*-metolachlor with atrazine applied pre-emergence at 2.5 kg a.i. ha^{-1} controlled sedges and broadleaf weeds resulting in an increase of 12–22% in maize grain yield (Chikoye et al., 2009). Several studies in the U.S.A (Whaley et al., 2009; Taylor-Lovell & Wax, 2001; Johson et al., 1997) and Canada (Vyn, Swanton, Weaver, & Sikkema, 2006), show findings in agreement with the present results by demonstrating that a pre-mixture of *S*-metolachlor with atrazine provided broad-spectrum weed species control and a resultant increase in maize grain yield.

5. Conclusion

The use of pre-emergence herbicides has the potential to control weeds and improve crop yield effectively. However, sole pre-emergence application of atrazine or *S*-metolachlor was only able to control one type of weeds and allowed the other to proliferate and compete with the crop for resources. The results indicated that broad-spectrum weed control was achieved by the pre-emergence application of tank mixture of atrazine at 1,000 and *S*-metolachlor at 1,440 g a.i. ha^{-1}. This tank mixture is recommended to provide comprehensive spectrum weed control in Botswana, and that a mixture of herbicides with different modes of action may reduce the likelihood of herbicide resistance developing.

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Disclosure of conflict of interest

The authors declare no conflict of interest.

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