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Evaluation of chemical weed control strategies in biomass sorghum

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Abstract

Two field experimental trials were carried out in central Italy, in 2005 and 2006, on biomass sorghum [*Sorghum bicolor* (L.) Moench] in order to assess weed control efficacy and selectivity to the crop of some pre- and post-emergence herbicides applied at different doses and in different mixtures. All herbicides showed good selectivity to the crop, although post-emergence treatments showed higher transitory phytotoxicity effects than pre-emergence treatments, especially when high temperatures occurred after treatments, decreasing the selectivity of leaf herbicides (i.e. MCPA, 2,4-D, bromoxynil and dicamba). Considering pre-emergence applications, terbuthylazine alone against broadleaves or in mixtures at low doses with s-metolachlor against mixed infestations (grasses + broadleaves), seemed to be the best options to obtain a good selectivity to the sorghum and a high weed control level. Aclonifen showed some limits in terms of weed spectrum and could be recommended only against simplified broadleaf weed infestations without the presence of less susceptible weeds, like *Amaranthus retroflexus*, *Portulaca oleracea* and *Solanum nigrum*. Propachlor seemed not to be advisable due to the low efficacy against all the major broadleaf warm-season weed species in the Mediterranean areas. Considering post-emergence applications, all treatments gave quite similar results in terms of weed control, although, the mixture of terbuthylazine + bromoxynil seemed to be the best option due to bromoxinil's higher efficacy than other foliar herbicides, such as MCPA, 2,4-D and dicamba, which can increase the efficacy of terbuthylazine alone especially under dry weather conditions. There were no significant differences in sorghum biomass between herbicide treatments, although, the more selective pre-emergence treatments showed, on average, a higher biomass yield value than the less selective post-emergence treatments. For these reasons, biomass values seemed to be more related to herbicide selectivity than to herbicide efficacy, especially in cases of scarce competitiveness of weed flora.

Keywords: biomass crop, herbicides, *Sorghum bicolor*, weed management

Introduction

Sorghum [*Sorghum bicolor* (L.) Moench] is a widely adapted crop with high potential for bioenergy production (Regassa and Wortmann 2014). Cellulose, hemicellulose and lignin, the main chemical components of sorghum biomass, are the most abundant renewable resources on earth and can be used as alternatives to petroleum and other fossil resources (Habyarimana *et al.* 2004). Bioenergy sorghum is also of interest due to its relatively low input requirements, drought tolerance, and ability to maintain high biomass yields under a wide range of soil and environmental conditions (Miller and Mcbee 1993). For these reasons, this crop is well adapted to semi-arid regions and could be grown in place of maize in non-irrigated cropping systems (Bonciarelli *et al.* 2016; Pannacci and Bartolini 2016).

However, sorghum is a poor competitor against weeds due to slow growth and poor vigour for the first three-four weeks after emergence, although it eventually establishes a dense canopy (Peerzada *et al.* 2017).

After this crop stage, the competitiveness of sorghum increases thanks to high plant density and height, reducing subsequent weed emergence and growth. In sweet sorghum, the critical period of weed control was from 14 to 58 days after emergence (Silva *et al.* 2014).

Due to these growth habits, severe, uncontrolled weed infestations at early stages of sorghum, can cause poor crop establishment or complete crop failure (Everaarts 1993). Due to its high optimum temperature (21°C) for seed germination and emergence, sorghum is very often infested by warm-season grass and broadleaved weeds (Vencill and Banks 1994; Knezevic *et al.* 1997). Grass weeds are considered to be the most common and troublesome weeds in grain sorghum, particularly those species from the genus *Echinochloa*, *Panicum*, *Digitaria*, and *Sorghum* (Limon-Ortega *et al.* 1998; Peerzada *et al.* 2017). Furthermore, *Amaranthus* spp. are among the ten most common and ten most troublesome weeds in sorghum in the USA (Traore *et al.* 2003). The presence of these weed species, the increasing of herbicide-resistant weeds and crop rotational restrictions along with limited registered herbicides available to farmers have created a challenging environment for the control of weeds in sorghum (Peerzada *et al.* 2017). The main problems are: 1) scarce availability of herbicides registered both for pre- and post-emergence applications; 2) restrictions on the use of terbuthylazine; 3) low efficacy of pre-emergence herbicides with inadequate rainfall conditions; 4) unavailability of selective post-emergence grass herbicides. The increasing interest of farmers on biomass sorghum grown for renewable energy production should be supported with scientific information on how to optimize chemical weed control strategies and improve the efficacy minimising application costs (Hallam *et al.* 2001).

In this context, a good approach to increase scientific information for farmers, is to improve chemical weed control strategies by investigating the efficacy of herbicides used at different times, at different doses and in different mixtures (Covarelli *et al.* 2010; Jursík *et al.* 2015, 2017; Pannacci 2016).

The objective of this research was to investigate weed control efficacy and phytotoxicity to the biomass sorghum of some herbicides applied alone and in mixtures, at different doses and times.

Materials and Methods

Two field experiments on biomass sorghum were carried out in 2005 and 2006 in central Italy (Experimental Station of Papiano, 42°57'N, 12°22'E, 165 m a.s.l.) on a clay-loam soil (25% sand, 30% clay and 45% silt, pH 8.2, 0.9% organic matter).

The experiment was designed as a randomized block with four replicates and plot size of 17.5 m^2 (2.5 m width). Each plot had five rows; three central rows for measurements and two border rows on the perimeter of each plot to reduce potential border effects. The main agronomic practices are shown in Table 1.

The trials were carried out in accordance with recommended management practices, as concerns soil tillage and seedbed preparation.

In each trial, some herbicides were used in pre- or post-emergence applications at different doses and in different mixtures in order to assess weed control ability and selectivity to the crop (Table 2).

Herbicides under investigation were: aclonifen (Challenge, 600 g a.i. · l^{-1}, Bayer CropScience), terbuthylazine (Click 50 FL, 500 g a.i. · l^{-1}, Sipcam S.p.A.), propachlor (Ramrod Flow, 480 g a.i. · l^{-1}, Sipcam S.p.A.), terbuthylazine + s-metolachlor (Primagram Gold, 187.5 g a.i. · l^{-1} + 312.5 g a.i. · l^{-1}, Syngenta Crop Protection), MCPA + 2,4-D (Bi-Fen, 337 g a.i. · l^{-1} + + 331 g a.i. · l^{-1}, Sariaf Gowan S.p.A.), bromoxynil (Emblem, 20% a.i., Nufarm Italia), dicamba (Mondak 21S, 243.8 g a.i. · l^{-1}, Syngenta Crop Protection). Herbicide treatments were applied with a backpack plot sprayer fitted with four flat fan nozzles (Albuz APG 110 – Yellow) and calibrated to deliver 300 l · ha^{-1} aqueous solution at 200 kPa. Untreated plots were always added as controls.

In both trials, one irrigation (150 m^3 · ha^{-1}) was carried out one day after pre-emergence treatments in order to improve crop emergence and pre-emergence herbicide activity. Early post-emergence and post-emergence treatments were always performed with the crop at the 2–3 and 4–5 leaf stages, respectively.

The herbicide's phytotoxicity to the sorghum was rated visually 25 and 40 days after emergence (DAE)

Table 1. Agronomic practices in the field experiments

Agronomic practices	2005	2006
Preceding crop	wheat	wheat
Sowing date	17 May	15 May
Hybrid biomass sorghum	H133*	H133*
Density (plants · m^{-2})	30	30
Spacing between rows (m)	0.5	0.5
Fertilization (kg · ha^{-1}):		
P_2O_5 (pre-sowing time application)	75	75
N (sowing time application)	75	75
Emergence date	25 May	19 May
Pre-emergence treatments date	20 May	18 May
Early post-emergence treatments date	03 June	30 May
Post-emergence treatments date	15 June	20 June
Harvest	13 October	17 July

*Syngenta seeds NK

Table 2. Experimental treatments on biomass sorghum in 2005 and 2006

Code	Treatment	Dose [g a.i. · ha^{-1}]	Application time
A	aclonifen	900	pre-emergence
B	terbuthylazine	750	pre-emergence
C	propachlor	3360	pre-emergence
D	terbuthylazine + + propachlor	750 + 3360	pre-emergence
E	terbuthylazine + + s-metolachlor	328 + 547	pre-emergence
F	terbuthylazine + + s-metolachlor	188 + 313	early post-emergence
G	terbuthylazine	750	early post-emergence
H	terbuthylazine + + MCPA + 2,4-D	750 + 169 + 166	early post-emergence
I	terbuthylazine + + bromoxynil	750 + 450	early post-emergence
L	terbuthylazine + + dicamba	750 + 183	early post-emergence
M	bromoxynil + + dicamba	450 + 183	post-emergence
N	untreated control	–	–

on the EWRC 0–10 scale (0 – no visible injury; 10 – plant death) (EWRC, 1964). Weed ground cover (%) was rated visually 50 DAE by using the Braun-Blanquet cover-abundance scale (Maarel 1979). In 2006, weeds on three squares (0.25 m^2) per plot were collected, counted, weighed, oven dried at 105°C to determine moisture content and dry weight. Data on weed ground cover, weed density and weed dry weight were used to calculate weed control efficacy (WCE) of different treatments relative to the untreated control, according to Chinnusamy *et al.* (2013):

$$WCE = \frac{W_U - W_T}{W_U} \times 100\ [\%],$$

where: W_U – weed ground cover/density/dry weight in untreated plots, W_T – weed ground cover/density/dry weight in treated plots.

The sorghum biomass yield (fresh and dry weights) was determined by hand-harvesting the central part of each plot (7.5 m^2). In 2006, the sorghum biomass was harvested earlier than the end of the crop cycle (see Table 1), due to the lodging of the crop which occurred on July 7 during a rain storm with gusts of wind at a speed of 9 m · s^{-1}.

Meteorological data (daily maximum and minimum temperature and rainfall) were collected from a nearby station. Ten days averages were calculated and compared with multiannual averages (Fig. 1).

Treatment means of sorghum biomass dry weight were correlated to treatment means of total weed ground cover and herbicide phytotoxicity to the sorghum in order to assess Pearson's *r* correlation coefficients (Kozak *et al.* 2012).

All data were subjected to ANOVA and treatment means were separated according to Fisher's protected LSD at p = 0.05 level. ANOVA and its assumption check were performed with the EXCEL® Add-in macro DSAASTAT (Onofri and Pannacci 2014).

Results

Weed control efficacy of herbicide treatments

The two experiments were characterised by a different weed flora composition. A combined analysis of data showed that the interactions "years × treatments" were significant ($p < 0.001$); therefore, the results were shown and discussed separately for each year.

In 2005, weed flora in the untreated control was mainly composed of *Amaranthus retroflexus* L. (AMARE, 51% of ground cover), *Polygonum persicaria* L. (POLPE, 29% of ground cover), *Portulaca oleracea* L. (POROL, 23% of ground cover), *Chenopodium album* L. (CHEAL, 22%), and other sporadic weed species (3%) [*Echinochloa crus-galli* (L.) Beauv., *Solanum nigrum* L., *Ammi majus* L.], with 128% of total ground cover in the untreated control. This flora was characterised by high weed density but with low plant size.

Considering pre-emergence applications, terbuthylazine (750 g a.i. · ha^{-1}) alone or in mixtures with propachlor and at a low dose (328 g a.i. · ha^{-1}) with s-metolachlor, gave the best total weed control with values, not significantly different, that ranged from 98 to 100% due to a high efficacy against the above-mentioned broadleaved species. Aclonifen and propachlor alone showed lower weed control efficacy (75 and 70% respectively), due to the scarce efficacy of aclonifen against *A. retroflexus* and *P. persicaria* and of propachlor against all the broadleaved species (Table 3).

Considering post-emergence applications all treatments gave total weed control higher than 90% with values not significantly different than the best pre-emergence treatments, except for the mixture terbuthylazine + MCPA + 2,4-D, that showed a total weed control significantly lower, with a value of 80%, due to a significant reduction of efficacy against all the weeds (Table 3).

In 2006, low temperatures and low rainfall at the beginning of the crop cycle (Fig. 1B) resulted in a lower

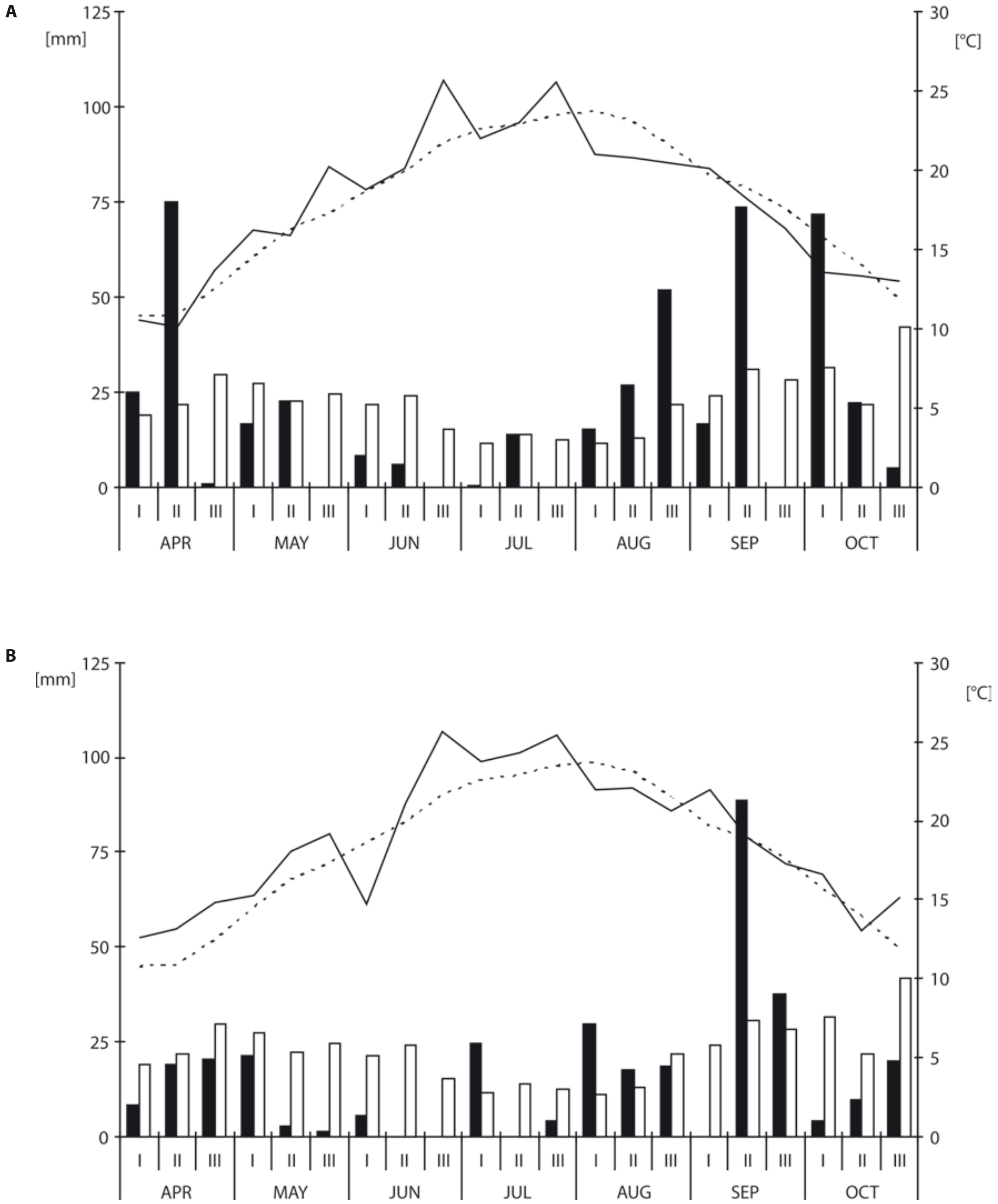

Fig 1. Average 10 days values of rainfall (mm; bold bar) and temperature (°C; solid line) recorded during the experimental trial in 2005 (A) and 2006 (B), compared to multi-annual (from 1921) averages (rainfall: mm, empty bar; temperature: °C, sketched line)

weed infestation level than in 2005. In particular, weed flora in the untreated control was mainly composed of *P. oleracea* (50% of ground cover, 20 plants · m^{-2}, 41 g d.m. · m^{-2}) and other sporadic weed species (8% of ground cover, 9 plants · m^{-2}, 18 g d.m. · m^{-2}) [*A. retroflexus, E. crus-galli*, *S. nigrum*, *C. album, Fallopia convolvulus* (L.) Á. Löve, *Polygonum aviculare* L., *Lolium multiflorum* Lam.].

As in 2005, pre-emergence treatments based on terbuthylazine showed the highest weed control against the total infestation in terms of ground cover, density and dry weight, with values of efficacy that ranged from 83 to 100% (Table 4).

Propachlor alone gave the lowest weed control efficacy with values always under 50% due to scarce efficacy against *P. oleracea* and the main species of sporadic weeds. On the contrary, aclonifen gave good total weed control, with values of efficacy between 81 and 88% and not significantly different to those obtained with treatments based on terbuthylazine.

Table 3. Efficacy of herbicide treatments on ground cover of weed flora* (2005)

Treatment	Dose [g a.i. · ha^{-1}]	Application time	Weed control efficacy [%]					
			AMARE	POLPE	POROL	CHEAL	other	total
Aclonifen	900	pre-emergence	57 c	93 ab	76 b	94 ab	71	75 bc
Terbuthylazine	750	pre-emergence	99 a	100 a	100 a	100 a	51	98 a
Propachlor	3360	pre-emergence	67 c	76 c	78 b	63 c	73	70 c
Terbuthylazine + + propachlor	750 + 3360	pre-emergence	100 a	100 a	100 a	100 a	100	100 a
Terbuthylazine + + s-metolachlor	328 + 547	pre-emergence	100 a	100 a	100 a	100 a	96	100 a
Terbuthylazine + + s-metolachlor	188 + 313	early post-emergence	99 a	100 a	94 a	100 a	74	98 a
Terbuthylazine	750	early post-emergence	97 a	100 a	92 a	100 a	71	96 a
Terbuthylazine + + MCPA + 2,4-D	750 + 169 + + 166	early post-emergence	82 b	87 b	76 b	81 b	25	80 b
Terbuthylazine + + bromoxynil	750 + 450	early post-emergence	99 a	100 a	97 a	97 ab	74	98 a
Terbuthylazine + + dicamba	750 + 183	early post-emergence	96 a	98 a	97 a	81 b	74	94 a
Bromoxynil + + dicamba	450 + 183	post-emergence	100 a	100 a	100 a	100 a	96	100 a
S.E.M. (df = 30)			4.7	3.5	4.4	6.3	18.9	3.1
LSD (p = 0.05)			13.6	10.0	12.6	18.1	ns	9.0

*weed species: *Amaranthus retroflexus* L. (AMARE), *Polygonum persicaria* L. (POLPE), *Portulaca oleracea* L. (POROL), *Chenopodium album* L. (CHEAL), other: *Echinochloa crus-galli* (L.) Beauv., *Solanum nigrum* L., *Ammi majus* L.

ns – not significant

In each column values followed by the same letter are not significantly different according to the Fisher's protected LSD test (p = 0.05)

Table 4. Efficacy of herbicide treatments on ground cover, density and dry weight of weed flora (2006)

Treatment	Dose [g a.i. · ha^{-1}]	Application time	Weed control efficacy [%]		
			ground cover	density	dry weight
Aclonifen	900	pre-emergence	87 ab	81 abc	88 abc
Terbuthylazine	750	pre-emergence	99 a	95 a	100 a
Propachlor	3360	pre-emergence	50 c	47 d	35 e
Terbuthylazine + propachlor	750 + 3360	pre-emergence	100 a	98 a	100 a
Terbuthylazine + s-metolachlor	328 + 547	pre-emergence	99 a	83 ab	93 ab
Terbuthylazine + s-metolachlor	188 + 313	early post-emergence	60 c	45 d	68 bcd
Terbuthylazine	750	early post-emergence	70 bc	60 bcd	61 cde
Terbuthylazine + MCPA + 2,4-D	750 + 169 + 166	early post-emergence	57 c	52 d	69 bcd
Terbuthylazine + bromoxynil	750 + 450	early post-emergence	93 ab	88 a	92 ab
Terbuthylazine + dicamba	750 + 183	early post-emergence	52 c	55 cd	55 de
Bromoxynil + dicamba	450 + 183	post-emergence	75 abc	59 bcd	76 abcd
S.E.M. (df = 30)			9.0	9.1	9.5
LSD (p = 0.05)			25.9	26.1	27.5

In each column values followed by the same letter are not significantly different according to the Fisher's protected LSD test (p = 0.05)

In comparison to pre-emergence treatments, post-emergence treatments showed a significantly lower efficacy due to low activity against *P. oleracea*, although the use of bromoxynil in a mixture with terbuthylazine provided the best post-emergence weed control (Table 4).

Phytotoxicity to sorghum

Phytotoxicity data showed that all the treatments can be considered relatively safe to the crop with values never over 2, in a scale from 0 to 10 (Table 5).

In 2005, all treatments at 25 DAE showed comparable phytotoxicity, but with values significantly higher than the untreated control. However, 40 DAE, all the treatments reduced the phytotoxicity in comparison to the previous values, although only aclonifen and terbuthylazine at low doses (328 g a.i. · ha^{-1} and 188 g a.i. · ha^{-1}) in mixtures with s-metolachlor, showed values not significantly different from the untreated control.

In 2006, phytotoxic symptoms were not observed in pre-emergence treatments and very low transitory phytotoxic effects appeared in post-emergence applications (Table 5). In particular, only terbuthylazine at the highest dose (750 g a.i. · ha^{-1}) in a mixture with foliar herbicides (MCPA + 2,4-D, bromoxynil and dicamba), at 25 DAE, showed phytotoxicity values significantly higher than the untreated control. Forty DAE the phytotoxic symptoms had almost disappeared and there were no significant differences between treatments and the untreated control (Table 5).

Sorghum biomass yield

In 2006, dry weight biomass levels were lower than in 2005, due to the above-mentioned early harvest. However, the data collected in 2006 were taken into consideration in order to evaluate the treatment effects on dry weight up to the lodging of the crop.

In both years, there were no significant differences between treatments of the dry weight of sorghum biomass, even though the lowest biomass was always observed in the untreated control (Table 6, Fig. 2).

In particular, the correlation between sorghum biomass dry weight and total weed ground cover was poor with values of $r = -0.159$ and -0.414, respectively in 2005 and 2006 (Table 6). The correlation between herbicide phytotoxicity (average between 25 and 40 DAE values) and sorghum dry weight was quite high ($r = -0.538$ and -0.622, respectively in 2005 and 2006). Furthermore, crop yield indices, expressed as the average of the two years and grouped according to application time (pre- or post-emergence), showed that the pre-emergence treatments gave, on average, a biomass yield greater than the overall mean of trials and greater than post-emergence treatments (Fig. 2).

Discussion

The results of this research showed that of the pre-emergence applications, terbuthylazine alone against broadleaves or in mixtures at a low dose with s-metolachlor against mixed infestations (grasses + broadleaves), seemed to be the best options to obtain a good selectivity to the sorghum and a high weed control level. In particular, the mixture terbuthylazine + + s-metolachlor, largely adopted in maize as the main pre-emergence strategy due to its high weed efficacy

Table 5. Phytotoxicity of herbicide treatments to sorghum

Treatment	Dose [g a.i. · ha^{-1}]	Application time	Phytotoxicity [scale 0–10]			
			2005		2006	
			25 DAE	40 DAE	25 DAE	40 DAE
Aclonifen	900	pre-emergence	1.4 ab	0.5 bc	0 c	0
Terbuthylazine	750	pre-emergence	1.1 b	1.0 ab	0 c	0
Propachlor	3360	pre-emergence	1.3 ab	0.9 ab	0 c	0
Terbuthylazine + propachlor	750 + 3360	pre-emergence	1.4 ab	0.8 ab	0 c	0
Terbuthylazine + s-metolachlor	328 + 547	pre-emergence	1.9 ab	0.5 bc	0 c	0
Terbuthylazine + s-metolachlor	188 + 313	early post-emergence	2.0 ab	0.5 bc	0.1 bc	0
Terbuthylazine	750	early post-emergence	1.8 ab	0.6 b	0.1 bc	0
Terbuthylazine + MCPA + 2,4-D	750 + 169 + 166	early post-emergence	2.0 ab	0.9 ab	0.3 ab	0.1
Terbuthylazine + bromoxynil	750 + 450	early post-emergence	2.1 a	1.0 ab	0.3 ab	0.1
Terbuthylazine + dicamba	750 + 183	early post-emergence	1.9 ab	1.0 ab	0.4 a	0.1
Bromoxynil + dicamba	450 + 183	post-emergence	2.0 ab	1.3 a	–	0.3
Untreated control	–	–	0 c	0 c	0 c	0
S.E.M. (df)			0.35 (33)	0.21 (33)	0.09 (30)	0.09 (33)
LSD (p = 0.05)			0.99	0.61	0.25	ns

DAE – days after emergence. In each column values followed by the same letter are not significantly different according to the Fisher's protected LSD test (p = 0.05)
ns – not significant

Table 6. Effects of herbicide treatments on sorghum biomass yield

Treatment	Dose [g a.i. · ha⁻¹]	Application time	2005		2006	
			Moisture content [%]	Dry weight [t · ha⁻¹]	Moisture content [%]	Dry weight [t · ha⁻¹]
Aclonifen	900	pre-emergence	65.2	23.93	85.2	10.66
Terbuthylazine	750	pre-emergence	67.7	18.91	85.9	9.94
Propachlor	3360	pre-emergence	68.4	22.18	85.2	12.41
Terbuthylazine + propachlor	750 + 3360	pre-emergence	70.0	19.85	85.7	10.81
Terbuthylazine + s-metolachlor	328 + 547	pre-emergence	68.9	19.80	86.6	12.07
Terbuthylazine + s-metolachlor	188 + 313	early post-emergence	69.1	19.67	85.8	10.93
Terbuthylazine	750	early post-emergence	69.2	19.46	85.6	11.07
Terbuthylazine + MCPA + 2,4D	750 + 169 + 166	early post-emergence	66.7	19.70	86.1	9.27
Terbuthylazine + bromoxynil	750 + 450	early post-emergence	69.9	19.69	85.9	11.49
Terbuthylazine + dicamba	750 + 183	early post-emergence	69.4	18.38	86.2	9.30
Bromoxynil + dicamba	450 + 183	post-emergence	68.5	20.47	85.3	9.60
Untreated control	–	–	68.9	17.63	85.9	9.11
S.E.M. (df = 33)			1.02	1.392	0.38	1.436
LSD (p = 0.05)			ns	ns	ns	ns

ns – not significant

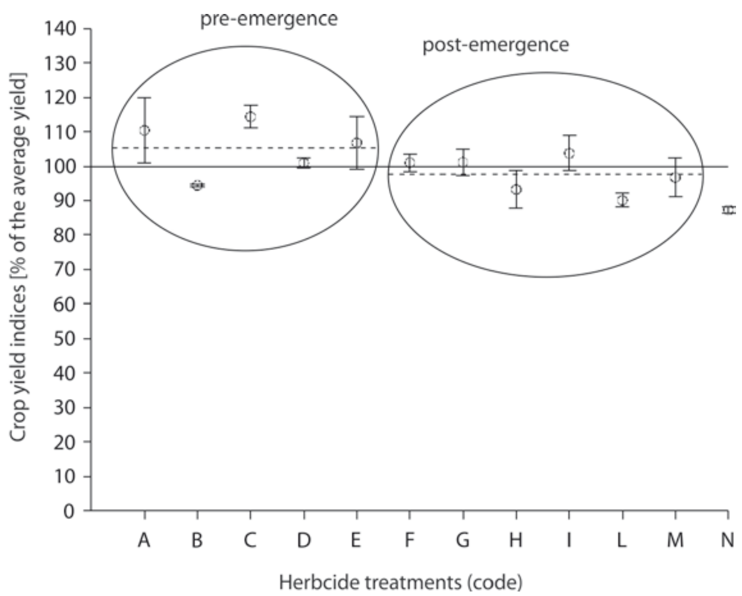

Fig. 2. Crop yield indices (overall mean of trials carried out in 2005 and 2006 = 100) of treatments (see Table 2 for corresponding treatments code). This circles show the average indices of the two years, the horizontal bars show the inter-annual variation. Indices were grouped based on common application time (pre or post-emergence) inside to each ellipse. The major axis of each ellipse (dashed lines) show the average values of the inside indices

(Pannacci and Tei 2014; Pannacci and Onofri 2016), could be favourably adopted also in sorghum due to its high efficacy against weeds and low phytotoxicity to the crop, as recently observed also by Kaczmarek (2017). Furthermore, the use of this herbicide mixture makes it possible to apply a low dose of terbuthylazine thus respecting the restrictions on the use of this active ingredient, recently implemented by the EU (Regulation 2011). Aclonifen showed some limits in terms of weed spectrum. Indeed, this active ingredient could be suggested only against simplified broadleaved weed infestations without the presence of less susceptible weeds, like *A. retroflexus*, *P. oleracea* and *S. nigrum*, as already observed by Pannacci *et al.* (2007) in the same area. Propachlor either alone or in mixture with terbuthylazine does not seem to be advisable due to the low efficacy against all the major warm-season broadleaved weed species in the Mediterranean areas.

Considering post-emergence applications, all treatments gave quite similar weed control results. In particular, the efficacy of early post-emergence treatments based on terbuthylazine in comparison to pre-emergence treatments based on terbuthylazine was lower in 2006 than in 2005. This can be due to the weather conditions with less rainfall after early post-emergence (June) in 2006 than in 2005 (Fig. 1) that reduced soil moisture and as a consequence the activity and the efficacy of terbuthylazine against weeds, as was already found by Pannacci and Tei (2014) and by Pannacci and Onofri (2016) in maize. In fact, all pre-emergent herbicides need at least some soil moisture or ideally rainfall following application to become 'activated' and available to weed seeds; until this occurs, uptake may be limited and weed control may be poor (Haskins 2012). Among the post-emergence treatments, the mixture of terbuthylazine + bromoxynil seemed to be the best option due to the higher efficacy of bromoxinil than the other foliar herbicides, such as MCPA, 2,4-D and dicamba, that can increase the efficacy of terbuthylazine alone especially under dry weather conditions.

All herbicides showed a good selectivity to the crop, although, post-emergence treatments showed higher transitory phytotoxicity effects than pre-emergence treatments. However, sorghum recovered quickly with phytotoxic symptoms that disappeared 5 or 6 weeks after sorghum emergence. The positive results on the efficacy and selectivity of terbuthylazine at different doses and in mixtures with pre and post-emergence herbicides showed that this active ingredient should always be considered in chemical weed control strategies in sorghum, as already observed in central Italy by Covarelli *et al.* (1993). Furthermore, sorghum biomass yield did not show significant differences between herbicide treatments, although, biomass yield values seemed to be more related to herbicide selectivity than to herbicide efficacy, especially in cases of scarce competitiveness of weed flora. On average, the more selective pre-emergence treatments showed higher biomass yield value than the less selective post-emergence treatments. Therefore, pre-emergence treatment had the advantage of being very selective and avoided weed/crop competition in the first part of the growth cycle of sorghum, thereby favouring sorghum growth and reducing biomass yield losses. Post-emergence treatments should be advised only if the pre-emergence treatments were not carried out, to manage scarce infestation and the presence of perennial weeds or in peat soil, for which pre-emergence herbicides are not effective.

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