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ORIGINAL ARTICLE

A study on *Sorghum bicolor* (L.) Moench response to split application of herbicides

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Abstract

Field experiments to evaluate the split application of mesotrione + s-metolachlor, mesotrione + terbuthylazine, dicamba + prosulfuron, terbuthylazine + mesotrione + s-metolachlor, and sulcotrione in the cultivation of sorghum var. Rona 1 were carried out in 2012 and 2013. The field tests were conducted at the field experimental station in Winna Góra, Poznań, Poland. Treatments with the herbicides were performed directly after sowing (PE) and at leaf stage 1–2 (AE1) or at leaf stage 3–4 (AE2) of sorghum. The treatments were carried out in a laid randomized block design with 4 replications. The results showed that the tested herbicides applied at split doses were effective in weed control. After the herbicide application weed density and weed biomass were significantly reduced compared to the infested control. The best results were achieved after the application of mesotrione tank mixture with s-metolachlor and terbuthylazine. Application of split doses of herbicides was also correlated with the density, biomass, and height of sorghum.

Key words: herbicides, mesotrione, s-metolachlor, sorghum, split doses, terbuthylazine, weed control

Introduction

Sorghum, the oldest cultivated crop in the world, is classified in Poland as a minor crop due to its small area of cultivation (about 20,000 ha) and lack of labeled herbicides. Interest in sorghum biomass as an important source of renewable energy is continually growing. In central Europe sorghum is cultivated mainly as a bioenergy and forage crop. Environmental and management conditions determine its productivity (Wight *et al*. 2012). Due to the increasing significance of sorghum in Poland more studies are being carried out in order to gain information about sorghum cultivation, including weed management practices (Kaczmarek *et al*. 2009; Skrzypczak *et al*. 2009; Księżak *et al*. 2012; Kaczmarek *et al*. 2013).

There are no registered sorghum varieties in Poland, however Polish farmers can successfully cultivate the varieties included in the European Union catalogue. Under European conditions, according to FAO (FAO 2014), grain sorghum is cultivated in 17 countries, on a total area of 390,000 ha. The largest cultivation area is found in Russia (about 150,000 ha) and in Ukraine (about 83,000 ha), with approximate sorghum yields of 15,000 and 26,981 kg · ha^{-1} respectively. There is no data for Poland. Sorghum plants can grow under low water conditions and plants are remarkably tolerant of high temperatures (Laidlaw *et al*. 2009).

Weed control with chemicals is an important factor since sorghum plants grow slowly in early stages, and if weeds are controlled within the first four weeks after crop emergence yield loss will be minimum (Moore *et al*. 2004). Weeds can compete with sorghum plants and can reduce the sorghum yield (Smith and Scot 2000; Magani 2008). Yield loss due to weeds depends on the duration of weed infestation, the nature and intensity of weeds, the crop cultivars, and environmental conditions (Knezevic *et al*. 2002; Tamado *et al*. 2002). Farmers who are interested in sorghum, should have access to scientific information in order to learn how to optimize chemical weed control management and improve the efficacy for minimizing the costs.

Sorghum is similar in appearance to corn and is used for many of the same purposes (Getachew *et al*. 2016). Therefore some of the herbicides registered for corn are also available for weed control in sorghum. But not all herbicides applied in corn are also safe for sorghum plants. In our previous studies (Kaczmarek *et al*. 2009) a herbicide containing foramsulfuron + iodosulfuron methyl sodium was not safe for sorghum cultivation. In this case, the study results did not verify the hypothesis that herbicide application in corn (Gołębiowska and Rola 2004; Idziak *et al*. 2006) and in sweet corn (Waligóra and Szpurka 2007) will also be effective for sorghum. Moreover, field tests should also include the sorghum variety factor because of the different responses to weed competition (Wu *et al*. 2010; Mishra *et al*. 2015).

The main goal of this study was to evaluate the herbicides applied in low doses for sorghum (var. Rona 1). The main reason for the field studies was the fact that there are still no registered herbicides for weed management for sorghum. It is still an undefined domain in weed management practices for sorghum, including novel methods/applications, environmental concerns and the variety of sorghum.

Materials and Methods

Fields experiments were carried out in 2012 and 2013 at the field experimental station in Winna Góra located about 60 km from Poznan, Poland (52°12' N; 17°27' E). The soil of the field in 2012 was sandy loam with pH 5.7 and 1.14% of organic carbon and in 2013 the soil was loamy sand with pH 4.8 and 0.88% of organic carbon. Soil size fractions in 2012 and 2013 were as follows: sand (2–0.05 mm) – 68.99% and 75.08%; silt (0.05–0.002 mm) – 27.85% and 21.03%; loam (< 0.002 mm) 3.16% and 2.89%.

The following split doses treatments were used in sorghum (pre-emergence and post-emergence): mesotrione + s-metolachlor (Camix 560 SE, 60 g · l^{-1} + 500 g · · l^{-1}), mesotrione + terbuthylazine (Calaris 400 SC, 70 g · l^{-1} + 330 g · l^{-1}), dicamba + prosulfuron (Casper 55 WG, 500 g · l^{-1} + 50 g · l^{-1}), terbuthylazine + mesotrione + s-metolachlor (Lumax 537.5 SE, 187.5 g · l^{-1} + + 37.5 g · l^{-1} + 312.5 g · l^{-1}), sulcotrione (Shado 300 SC, 300 g · l^{-1}). Doses of herbicides per ha are given in Tables 1 and 2. Herbicide application was conducted with a pressure plot sprayer of tank volume 4 l, working pressure of 2 bars, nozzle spacing of 50 cm, application rate of 200 l · ha^{-1}, mounting of sprayer beam of 50 cm and working velocity of 5 km · h^{-1}. A control object was included, where no chemical weed control was implemented (infested-control). The treatments were carried out in a randomized block design with 4 replications. In both years the plot size was 16.5 m^2 (width of 1.5 m, length of 11.5 m).

Mineral fertilization was performed before the sowing of sorghum seeds: N = 16–18 kg · ha^{-1}, P_2O_5 = = 64–72 kg · ha^{-1}, K_2O = 72–81 kg · ha^{-1}. In 2012, the sorghum seeds were sown on May 23 and in 2013 the seeds were sown on the same day, May 23. During both years fertilizer was applied based on the soil test recommendations. The total rainfall received during the growing season (May to October) was 335.5 mm and 346.3 mm in 2012 and 2013, respectively. The average temperature was 15.8°C and 16.2°C respectively. The crop was harvested at the end of October by cutting the plants near ground and then the fresh sorghum biomass (yield) was recorded.

The following data were collected during the vegetating season: the number of weeds, weed biomass, sorghum density, height, and yield (biomass). Weed control efficacy was based on the number and fresh weight of weeds per 1 m^2. Weeds were collected from an area of 0.25 × 0.5 m, 3–4 weeks after the last herbicide treatment. They were then separated according to species, counted, and weighed. Data were calculated per surface area of 1 m^2. Sorghum density was measured before harvest by counting sorghum plants in one of the middle rows of each plot. The mean height of sorghum plants was measured before harvest as the average height of 10 plants in the plot. Sorghum yield was determined by calculating the hand-harvested plants of one middle row from each plot. The average data of two years were subjected to one-way ANOVA with post-hoc Tukey HSD and the mean values of treatments were separated using XLSTAT software at $p < 0.05$.

Results

Effect on weed control

During the years of research the sorghum cultivation was infested by *Echinochloa crus-galli* (L.) P. Beauv., *Viola arvensis* Murray., *Geranium pusillum* L., *Chenopodium album* L., *Fallopia convolvulus* (L.) Á. Löve, *Polygonum aviculare* (L.), *Capsella bursa-pastoris* (L.), and *Tripleurospermum inodorum* (L.) Sch. Bip. *Echinochloa crus-galli*, the only representative of monocotyledonous weeds, was dominant in the composition of weed infestation. Data analysis showed a significant influence of the herbicide treatments. All the herbicides applied to the plants affected both weed number and weed biomass (Table 1).

After herbicide application the density of dicotyledonous weeds and their biomass were reduced compared to the natural infested control. The strongest effect on the dicotyledonous weed number occurred after the split application of mesotrione + terbuthylazine, and terbuthylazine + mesotrione + s-metolachlor. *Echinochloa crus-galli* was also well controlled in most cases. The best option for *E. crus-galli* control was mesotrione + s-metolachlor. Moreover, a positive correlation between application of dicamba + prosulfuron and *E. crus-galli* density was found.

Weed biomass was also affected by the herbicides (Table 1). Almost all substances, besides dicamba + + prosulfuron, reduced dicotyledonous weeds significantly (herbicide efficacy ranged from 83% to 97%). The highest reduction of weed biomass was recorded on the plots where mesotrione + terbuthylazine, and terbuthylazine + mesotrione + s-metolachlor were used. *Echinochloa crus-galli* biomass was suppressed by other dicotyledonous weeds on the control plots. As a result the monocotyledonous biomass was lower than some plots where herbicides were applied. The highest reduction of *E. crus-galli* biomass was achieved after the application of terbuthylazine + mesotrione + + s-metolachlor, whereas mesotrione + terbuthylazine and dicamba + prosulfuron were not effective in *E. crus-galli* control.

Effect on sorghum yield and plants

Herbicide treatments and their efficacy level influenced the density, height, and biomass of sorghum (Table 2). A positive correlation of the tested herbicides with the density of sorghum was observed for the three split applications: mesotrione + s-metolachlor, terbuthylazine + mesotrione + s-metolachlor, and sulcotrione. The same result was found for the sorghum biomass, where crop density recorded with these treatments was significantly higher than the density of crops in the control plots and in the plots where dicamba + prosulfuron were used.

The height of the plants was strongly correlated with the treatment. Plants collected from the control plots were significantly shorter than the plants collected from the herbicide-applied plots. But a negative effect on the height of sorghum also occurred for the dicamba + prosulfuron split application. The highest number of plants was harvested from the plots where terbuthylazine + mesotrione + s-metolachlor were tested.

There was a significant, negative correlation on sorghum biomass in two cases: in the infested plots and in the plots where dicamba + prosulfuron were used for weed control. Nevertheless, the biomass harvested from other treatments was significantly higher, and the best results were achieved from the plot where terbuthylazine + mesotrione + s-metolachlor were applied.

Correlation coefficients showed that the weed number and biomass significantly affected the sorghum (Table 3). The strongest negative correlation of weed density was found in relation to sorghum height and sorghum biomass. Taking the treatments into account, the application method (herbicides and control plots) was correlated with the height of the sorghum, which was greater than other sorghum traits (sorghum biomass and density).

Generally, it can be concluded that terbuthylazine + mesotrione + s-metolachlor were safe for sorghum plants and dicamba + prosulfuron caused sorghum height and biomass reduction. Split application of terbuthylazine + mesotrione + s-metolachlor can effectively control dicot- and monocotyledonous weeds.

Discussion

The results of the field experiments confirmed the usefulness of split application of the tested herbicides. Data from the studies show that the best choice for weed control was achieved after the application of three component herbicides: terbuthylazine + mesotrione + s-metolachlor. The tank mixture of mesotrione with s-metolachlor and mesotrione with terbuthylazine were also effective. All of the above mentioned active ingredients are well known in corn weed management, and they are still being tested in field experiments for different application methods (James *et al.* 2006; Whaley *et al.* 2009; Skrzypczak *et al.* 2011; Andr *et al.* 2014; Radivojevic *et al.* 2014). For example, mesotrione, chemically derived from a natural phytotoxin obtained from the *Callistemon citrinus* plant, is effective for pre- and post-emergence control of weeds in corn. The ED values for mesotrione showed that some species of weeds could be effectively controlled with reduced doses (Pannacci and Covarelli 2009).

Other studies confirmed that mesotrione applied in combination with terbuthylazine and s-metolachlor improved the efficacy for *E. crus-galli*, *Hibiscus trionum*, *Setaria glauca*, and *Sorghum halpense* (Radivojevic *et al.* 2014).

Moreover, Mendes *et al.* (2016) concluded that mesotrione applied alone or in a combination with s-metolachlor and terbuthylazine did not influence its sorption or desorption. Mesotrione sorption in this research was primarily affected by the clay mineral content and the soil pH.

Mesotrione, terbuthylazine, and s-metolachlor were also tested in our previous studies on sorghum cultivation as a single application during pre- or post-emergence of weeds (Kaczmarek *et al.* 2012, 2013). For example, in the field where mesotrione was applied post-emergence, in mixtures, sorghum biomass

Table 1. Effect of split herbicide doses on weed density and weed biomass in sorghum cultivation in the years 2013–2014 (average)

Treatments	Herbicide dose [l, kg · ha^{-1}]	Application time	Weed density		Weed biomass	
			no. m^2 dicot/monocot	correlation coefficient dicot/monocot	g · m^{-2} dicot/monocot	correlation coefficient dicot/monocot
Control	–	–	37 a/57 a	0.8072/0.7513	1654.8 a/1117.0 c	0.7403/–0.3772
Mesotrione + s-metolachlor/mesotrione + s-metolachlor	1.0+1.0	PE+AE1	6 b/9 b	–0.1677/–0.3698	146.7 b/1337.7 c	–0.2342/–0.2165
Mesotrione + terbuthylazine/mesotrione + terbuthylazine	0.75+0.75	PE+AE2	2 b/14 b	–0.2935/–0.2530	50.3 b/2064.9 ab	–0.2965/0.3130
Dicamba + prosulfuron/dicamba + prosulfuron	0.15+0.15	PE+AE2	10 b/33 ab	–0.0419/0.1907	871.5 ab/2648.9 a	0.2341/0.7383
Terbuthylazine + mesotrione + s-metolachlor/ terbuthylazine + mesotrione + s-metolachlor	1.5+1.5	PE+AE1	0 b/18 b	–0.3564/–0.1596	50.0 b/1112.6 c	–0.2966/–0.3804
Sulcotrione/sulcotrione	0.75+0.75	PE+AE2	13 b/18 b	0.0524/–0.1596	281.4 b/1529.2 bc	–0.1471/–0.0771

PE – pre-emergence; AE1– after emergence, at the 1–2 leaf stage of sorghum; AE2 – after emergence, at the 3–4 leaf stage of sorghum; dicot – dicotyledonous weeds; monocot – monocotyledonous weeds; different letters indicate significant differences between groups

Table 2. Effect of split herbicide doses on the density, height and the biomass of sorghum plants in the years 2013–2014 (average)

Treatments	Herbicide dose [l, kg · ha^{-1}]	Application time	Sorghum density		Sorghum height		Sorghum biomass	
			1 middle row	correlation coefficient	average for 1 plant	correlation coefficient	1 middle row	correlation coefficient
Control	–	–	41 a	–0.4375	148.2 a	–0.8159	5.18 b	–0.5852
Mesotrione + s-metolachlor/mesotrione + s-metolachlor	1.0+1.0	PE+AE1	61 b	0.3451	216.0 c	0.2692	27.89 a	0.2169
Mesotrione + terbuthylazine/mesotrione + terbuthylazine	0.75+0.75	PE+AE2	50 b	–0.0632	216.9 b	0.2833	28.97 a	0.2552
Dicamba + prosulfuron/dicamba +prosulfuron	0.15+0.15	PE+AE2	40 b	–0.4763	181.7 bc	–0.2793	8.41 b	–0.4710
Terbuthylazine + mesotrione + s-metolachlor/ terbuthylazine + mesotrione + s-metolachlor	1.5+1.5	PE+AE1	60 b	0.3257	222.1 d	0.3673	35.42 a	0.4830
Sulcotrione/sulcotrione	0.75+0.75	PE+AE2	60 b	0.3062	210.1 bc	0.1755	24.61 a	0.1011

Notes: see Table 1.

Table 3. Correlation matrix (Pearson) for the height, biomass and density of sorghum and for the number and biomass of weeds (average for years 2013–2014)

Variables	Treatments	Sorghum height	Sorghum biomass	Sorghum density	Dicot weeds number	Monocot weeds number	Dicot weeds biomass	Monocot weeds biomass
Treatments	1	0.5116	0.3822	0.3543	–0.4461	–0.3797	–0.4467	0.1565
Sorghum height	0.5116	1	0.8576	0.6499	–0.7729	–0.8093	–0.7927	–0.0303
Sorghum biomass	0.3822	0.8576	1	0.8214	–0.5625	–0.7029	–0.6910	–0.2859
Sorghum density	0.3543	0.6499	0.8214	1	–0.3569	–0.5563	–0.4497	–0.3590
Dicot weeds number	–0.4461	–0.7729	–0.5625	–0.3569	1	0.6802	0.6579	–0.1698
Monocot weeds number	–0.3797	–0.8093	–0.7029	–0.5563	0.6802	1	0.7948	0.0163
Dicot weeds biomass	–0.4467	–0.7927	–0.6910	–0.4497	0.6579	0.7948	1	0.1015
Monocot weeds biomass	0.1565	–0.0303	–0.2859	–0.3590	–0.1698	0.0163	0.1015	1

Dicot – dicotyledonous; Monocot – monocotyledonous

increased about 57–144% in comparison to the control plots. Its potential for use in different hybrids of sorghum was also verified by Takano *et al.* (2016). Experiments conducted in 2012 and 2013 confirmed the usefulness of the split application method in sorghum var. Rona 1. In most cases the tested herbicides led to the enhancement of sorghum biomass.

The highly efficient new technologies in herbicide production may allow for a reduction of the herbicide doses. Several researchers suggest the possibility of using lower herbicide doses without reducing the yield (Salonen 1992; Zhang *et al.* 2000; Domaradzki and Rola 2003). Reduced herbicide doses have been successfully used in Europe. Weed composition and their developmental stages are the main factors affecting an herbicide's effectiveness. Therefore species named as sensitive on the label of an herbicide can be successfully controlled with a herbicide dose lower than recommended (Kudsk 1989). Increased herbicide efficacy can be achieved by different strategies, for example by using herbicide mixtures and by repeated reduced amounts of herbicides (Wilson *et al.* 2005; Deveikyte and Seibutis 2006).

The efficacy of the split applications was tested and confirmed by studies on different crops (Kaps and Ondea 1994; Ferreira *et al.* 2000; Lockhart and Howatt 2004; Najafi *et al.* 2013; Idziak and Woźnica 2014). For example, in corn, a reduced dose of tembotrione and its mixture with flufenacet + isoxaflutole and adjuvants applied twice provided corn grain yield similar to the herbicides applied once at the labeled rates (Idziak and Woźnica 2014). In other experiments Idziak *et al.* (2013) tested split application of mesotrione in sorghum cultivation, with good results. Dose-splitting treatments were also verified by Mathiassen *et al.* (2007). Researchers found that the ratio of herbicide doses and the interval between the two applications did not affect the herbicide responses.

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