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Grain Sorghum Response and Palmer Amaranth Control with Postemergence Application of Fluthiacet-methyl

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Abstract

Palmer amaranth is a problematic weed in grain sorghum production in central United States. Due to limited herbicide options available and ever increasing herbicide resistant weed species, there is a demand for new mode-of-action herbicides for use in grain sorghum. Fluthiacet-methyl is a relatively new active ingredient that inhibits protoporphyrinogen oxidase enzyme in target plants. Field studies were conducted at three sites in the central United States in 2010 and 2011 to evaluate crop response and Palmer amaranth control with postemergence application of fluthiacet-methyl in grain sorghum. Treatments included fluthiacet-methyl at 4.8 and 7.2 g ai ha^{-1} alone and tank mixed with 2,4-D amine at 260 g ae ha^{-1} or atrazine at 840 g ai ha^{-1}. Carfentrazone at 8.8 g ai ha^{-1}, atrazine at 840 g ha^{-1}, and a non-treated control were also included. Fluthiacet-methyl treatments caused 9 to 38% crop injury at 4 ± 1 days after treatment. Tank mixing atrazine with fluthiacet-methyl seldom affected crop injury, while mixing 2,4-D with fluthiacet-methyl often reduced crop injury. Generally, injury caused by fluthiacet-methyl alone or in combination with atrazine or 2,4-D disappeared within 3 weeks after treatment. Grain yields were reduced in one trial, when 2,4-D mixed with 4.8 or 7.2 g ha^{-1} of fluthiacet-methyl caused 18 and 13% plant lodging and 24 and 14% grain yield loss, respectively. Across site-years, fluthiacet-methyl alone at 4.8 or 7.2 g ha^{-1} gave 55 to 95% control of Palmer amaranth. Greater Palmer amaranth control (≥75%) with fluthiacet-methyl alone was achieved when weeds were small or density was low at the time of spraying. Tank mixing atrazine with fluthiacet-methyl increased Palmer amaranth control and sorghum yields considerably. Tank mixing 2,4-D with fluthiacet-methyl also increased Palmer amaranth control, but to lesser extent and less consistently than atrazine. Results indicated that fluthiacet-methyl has potential for use in grain sorghum to combat weeds resistant to ALS-inhibitors,

triazines, and synthetic auxin herbicides. Tank mixing atrazine or 2,4-D with fluthiacet-methyl is desirable for effective Palmer amaranth control.

Key words: grain sorghum; fluthiacet-methyl; crop injury; postemergence; PPO-inhibitor; weed control.

1. Introduction

Grain sorghum [*Sorghum bicolor* (L.) Moench] is the third most important grain crop grown in the United States after corn and wheat. Sorghum grain is primarily used for animal feed in the USA. Nearly 2.0 million ha of grain sorghum was harvested in the United States in 2011, yielding 6.3 billion kg of grain (USDA-NASS 2012). The major sorghum growing states in the United States are Kansas, Texas, Colorado, Oklahoma, South Dakota and Arkansas; 80% of total production comes from Kansas and Texas (USDA-NASS 2012). Grain sorghum is more drought tolerant than corn (*Zea mays* L.) and, therefore, is better adapted to semi-arid regions of the central and southern Great Plains (Stahlman and Wicks 2000) where periods of drought are common. Though sorghum is better adapted to drought conditions, productivity can be reduced greatly by weed interference.

Due to limited soil moisture availability, most rainfed sorghum grown in central and southern Great Plains is planted in widely spaced rows (76 cm) leaving inter-row spaces open to weed establishment. Thus, wide row spacing initially provides weeds a competitive advantage over sorghum. Sorghum is a relatively slow growing crop in the first few weeks after emergence, giving further advantage to weeds (Ferrell et al. 2012, Warrick 2014). Weeds can reduce sorghum grain yields by 30 to 50% and losses can be much higher under moisture stress conditions (Stahlman and Wicks 2000). Some of the most common broadleaf weeds found in sorghum are pigweeds (*Amaranthus* spp.), Kochia [*Kochia scoparia* (L.) Schrad], puncturevine (*Tribulous terrestris* L.), velvetleaf (*Abutilon theophrasti* Medik.) and common cocklebur (*Xanthium strumarium* L.) (Stahlman and Wicks 2000). Among *Amaranthus* species, Palmer amaranth *(Amaranthus palmeri* (S.) Wats.) is extremely competitive with crops due to its aggressive growth habit and prolific seed production ability. Past research reported that an increase in Palmer amaranth density from 0.5 to 8 plants m^{-1} of a corn row reduced corn yields by 11 to 91% (Massinga et al. 2001) and a density of 0.33 to 10 plants m^{-1} reduced soybean [Glycine max (L.) Merr.] yields by 17 to 68% (Klingaman and Oliver 1994). Similarly, a loss of 392 kg ha^{-1} sorghum grain yield with 1 kg increase of Palmer amaranth dry matter per 15 cm row has been reported in Oklahoma (Moore and Murray 2000). Hence, effective Palmer amaranth control is crucial for successful crop production.

Weeds in sorghum are generally controlled with preplant, preemergence (PRE) and/or postemergence (POST) herbicides from the triazine, cloroacetamide, acetolactate synthase (ALS)-inhibitor, and synthetic auxin herbicide groups (Stahlman and Wicks 2000). Atrazine is the most widely used herbicide in sorghum. Repeated use of atrazine in corn and sorghum has resulted in selection of triazine resistant weed biotypes. Triazine-resistant Palmer amaranth, common waterhemp (*Amaranthus rudis* Sauer) and redroot pigweed (*Amaranthus retroflexus* L.) have been reported in grain sorghum in the United States (Heap 2013). Additionally, resistance to ALS-inhibitor herbicides has been documented in Palmer amaranth and common waterhemp (Heap 2014). Rotating herbicides with different modes of action is recommended to prevent evolved herbicide resistance in weeds (Prather et al. 2000). However, there are fewer options to rotate herbicide modes-of-action in grain sorghum than in corn or soybeans (Thompson et al. 2013). Hence, there is a need for new mode-of-action herbicides for use in sorghum.

Fluthiacet-methyl is a relatively new active ingredient belonging to the isourazole family of herbicides. Fluthiacet-methyl inhibits the protoporphyrinogen oxidase (PPO or Protox) enzyme (Shimizu et al. 1995) that is responsible for chlorophyll and heme biosynthesis. Fluthiacet-methyl inhibits PPO activity after conversion (isomerization) to the corresponding urazole by glutathione *S*-transferase (Shimizu et al. 1995). Inhibition of PPO leads to accumulation of protoporphyrin IX (PPIX), which creates free radical oxygen in the cell and destroys cell membranes resulting in leakage of cell contents. Exposure of susceptible plants to fluthiacet-methyl results in yellowing of leaves, tissue necrosis and ultimate growth reduction and plant death. Currently, fluthiacet-methyl is registered for postemergence use in corn, sweet corn, popcorn, and soybeans (Anonymous 2011). Literature on crop response to fluthiacet-methyl and its weed control efficacy is very limited. Hence, a study was conducted to determine if fluthiacet-methyl has potential for use in grain sorghum. The objective of the study was to evaluate fluthiacet-methyl alone and in tank mixture with 2,4-D or atrazine for crop safety and Palmer amaranth control efficacy in grain sorghum.

2. Material and Methods

Field experiments were conducted during the 2010 and 2011 growing seasons at Hays, KS (38.85N, 99.34W), Amarillo, TX (35.18N, 102.08W), and Springfield, NE (41.05N, 96.14W) in the central United States. All sites were rainfed and did not receive supplemental irrigation. Soil characteristics are shown in Table 1. Soil pH was measured in a 1:1 mixture of soil and water (Robertson et al. 1999) and soil organic matter was measured by the Walkley–Black method (Combs and Nathan 1998). The experimental design was a randomized complete block with four treatment replications. Experimental treatments included two rates of fluthiacet-methyl (4.8 and 7.2 g ai ha^{-1}) (Cadet®, FMC Corporation, 1735 Market Street, Philadelphia, PA 19103, USA) applied alone and tank-mixed with 2,4-D amine at 260 g ae ha^{-1} (2,4-D Amine 4®, Winfield Solutions, LLC, P.O. Box 64589, St. Paul, MN 55164, USA) or atrazine at 840 g ai ha^{-1} (AAtrex®4L, Syngenta Crop Protection, Inc. P. O. Box 18300, Greensboro, NC 27419, USA). Carfentrazone at 8.8 g ai ha^{-1} (Aim®EC, FMC Corporation, 1735 Market Street, Philadelphia, PA 19103, USA), atrazine at 840 g ha^{-1}, and a non-treated control were also included. All herbicide treatments included a non-ionic surfactant at 0.25% v/v. The treatment fluthiacet-methyl at 7.2 g ha^{-1} plus 2,4-D at 260 g ha^{-1} at Amarillo in 2010 was lost, and hence no data is available for that particular treatment and location in 2010.

Sorghum was planted in 3-m-wide and 9-m-long no-till or conventionally tilled plots with a row spacing of 76 cm. Grain sorghum hybrids used were medium or medium-early maturing hybrids which were appropriate for dryland conditions (Table 1). Herbicides were broadcast using backpack or tractor-mounted plot sprayers calibrated to deliver 95 to 140 L ha^{-1} at 207 to 220 kPa when sorghum was 13 to 30 cm tall. Palmer amaranth was the predominant weed in all experimental locations. Depending on location, Palmer amaranth was 1 to 7 cm tall with a density of 10 to 65 plants m^{-2} at the time of POST herbicide application (Table 1).

Palmer amaranth control was rated based on composite visual estimations of density reduction, growth inhibition, and foliar injury on a scale of 0 (no effect) to 100 (plant death). Weed control ratings were determined 3 to 6 wk after treatment across sites and years. At Hays in 2010, Palmer amaranth density was too low for reliable efficacy evaluation, thus weed control ratings were not taken. Crop response also was rated visually on a scale of 0 to 100. Observed crop response symptoms in sorghum were foliar bleaching and stunting. Crop injury was assessed 4 ± 1 days after treatment (DAT). Sorghum grain was harvested mechanically from the center two rows of each plot, weighed, and grain yield was adjusted to 14% moisture content.

Data were analyzed using the general linear model procedure of the Statistical Analysis System (Statistical Analysis Systems Institute, Cary, NC, USA) and means were separated at the 5% significance level using Fisher's protected LSD. Percent weed control and sorghum injury data were arcsine transformed before analysis, but original values are presented in this paper. The control treatment was omitted from weed control and crop injury analyses, but included in the analysis of sorghum grain yield. Data are presented by year for each site because of significant ($P \leq 0.05$) treatment-by-site-by-year interactions.

3. Results and Discussion

3.1. Crop injury

Fluthiacet-methyl alone at 4.8 g ha^{-1} caused 9 to 30% sorghum injury at 4 ± 1 DAT (Table 2). Increasing fluthiacet-methyl rate from 4.8 to 7.2 g ha^{-1} increased crop injury in four of six trials. The rate of 7.2 g ha^{-1} caused 16 to 38% sorghum injury. Tank mixing 2,4-D at 260 g ha^{-1} with either rate of fluthiacet-methyl reduced crop injury compared to fluthiacet-methyl alone in 5 of 11 site-year observations, but increased injury in three instances and had no effect in three instances. At Hays, fluthiacet-methyl at 4.8 or 7.2 g ha^{-1} plus 2,4-D caused greater sorghum injury compared to fluthiacet-methyl alone in 2010, but 2,4-D did not affect injury in 2011. Conversely, tank mixing 2,4-D with fluthiacet-methyl at 4.8 g ha^{-1} in 2010 and with fluthiacet-methyl at either rate in 2011 reduced crop injury at Amarillo. At Springfield, mixing 2,4-D with fluthiacet-methyl at 4.8 g ha^{-1} increased crop injury in 2010, but decreased injury in 2011.

However, 2,4-D had no effect on crop injury in either year when mixed with 7.2 g ha^{-1} of fluthiacet-methyl. In comparison, atrazine at 840 g ha^{-1} seldom increased crop injury when mixed with fluthiacet-methyl at 4.8 g ha^{-1}, and never did with 7.2 g ha^{-1} rate. Carfentrazone, another PPO inhibitor, caused 16 to 40% injury, which was similar to that of fluthiacet-methyl at 7.2 g ha^{-1}. The least injury (0 to 5%) was caused by atrazine alone at 840 g ha^{-1} compared to all other herbicide treatments.

Despite the level of foliar injury which was as much as 38%, sorghum plants treated with fluthiacet-methyl alone or tank mixed with atrazine recovered completely; foliar symptoms disappeared within 3 wk after treatment. However, 13 to 18% sorghum lodging was observed at the time of harvest in plots treated with mixtures of fluthiacet-methyl and 2,4-D at Hays in 2010 (data not shown). Auxinic herbicides can cause brittleness in sorghum stalks and retard or distort brace root development that often results in lodging (Stahlman and Wicks 2000).

3.2. Palmer amaranth control

Palmer amaranth control with fluthiacet-methyl varied considerably among sites and years (Table 3). Differences in Palmer amaranth size and populations could be the reasons for variation in control among sites and years (Table 1). Fluthiacet-methyl at 4.8 g ha^{-1} gave 55 to 95% control of Palmer amaranth. Greater control (≥75%) was achieved when Palmer amaranth plant size was small or density was low at the time of spraying (Table 1). Highest Palmer amaranth control (95%) was achieved at Springfield in 2011, which could be due to smaller weeds at low density. Increasing the rate of fluthiacet-methyl from 4.8 to 7.2 g ha^{-1} did not increase Palmer amaranth control at any site. Tank mixing 2,4-D at 260 g ha^{-1} with fluthiacet-methyl at either rate increased Palmer amaranth control compared to fluthiacet-methyl alone at Amarillo in 2011 and Springfield in both years. Also, at Hays in 2011, the 7.2 g ha^{-1} rate of fluthiacet-methyl plus 2,4-D provided greater Palmer amaranth control compared to fluthiacet-methyl alone.

Tank mixing fluthiacet-methyl at either rate with atrazine at 840 g ha^{-1} increased Palmer amaranth control considerably compared to fluthiacet-methyl alone at all sites in both years (Table 3). Across site-years, fluthiacet-methyl at 4.8 g ha^{-1} plus atrazine controlled Palmer amaranth 78 to 100%. Increasing fluthiacet-methyl rate in the tank-mix from 4.8 to 7.2 g ha^{-1}

did not increase control. Carfentrazone at 8.8 g ha^{-1} provided 55 to 96% Palmer amaranth control, which was similar to that of fluthiacet-methyl at either rate. Similarly, Norsworthy et al. (2008) reported 60 to 84% Palmer amaranth control with carfentrazone at a much higher rate (34 g ha^{-1}). Palmer amaranth control with atrazine alone at 840 g ha^{-1} varied substantially from 20 to 100%; least at Amarillo in 2010 and highest at Springfield in 2011. Poor control of Palmer amaranth with atrazine alone at Amarillo in 2010 might have been due to the presence of triazine-resistant biotypes in the population.

3.3. Grain yields

Sorghum grain yields varied considerably between sites and years (Table 4). Foliar injury caused by fluthiacet-methyl at 4.8 or 7.2 g ha^{-1} did not adversely impact grain yields. Sorghum treated with fluthiacet-methyl alone at either rate at Hays in both years, Amarillo in 2011, and the 4.8 g ha^{-1} rate at Springfield in 2010 yielded similar to the non-treated control for each site-year. However, yields were increased substantially with both rates at Amarillo in 2010, Springfield in 2011, and with the 7.2 g ha^{-1} rate at Springfield in 2010. Tank mixing 2,4-D with fluthiacet-methyl seldom increased grain yields. Furthermore, at Hays in 2010, tank mixing 2,4-D at 260 g ha^{-1} with fluthiacet-methyl at 4.8 or 7.2 g ha^{-1} reduced sorghum grain yields by 24 and 14%, respectively, compared to fluthiacet-methyl alone. These yield losses are attributed to 18 and 13% sorghum lodging caused by mixing 2,4-D with fluthiacet-methyl. Overall, the highest grain yields were achieved from sorghum treated with mixtures of fluthiacet-methyl at either rate plus atrazine at 840 g ha^{-1}. This reflects the highest Palmer amaranth control achieved with fluthiacet-methyl plus atrazine (Table 3). Moore and Murray (2000) reported that one Palmer amaranth plant per 15 cm sorghum row can reduce grain yields by almost 100 kg ha^{-1}. Hence, effective Palmer amaranth control is essential to achieve high sorghum yields. On average, across site-years, sorghum treated with fluthiacet-methyl plus atrazine yielded 18% more grain than sorghum treated with fluthiacet-methyl alone and 64% more grain than the non-treated control. A majority of times, sorghum treated with carfentrazone at 8.8 g ha^{-1} or atrazine at 840 g ha^{-1} yielded similar to fluthiacet-methyl at either rate.

Conclusions

Results of this study showed that fluthiacet-methyl treatments caused 9 to 38% sorghum injury. Tank mixing atrazine with fluthiacet-methyl seldom increased crop injury. The injury caused by fluthiacet-methyl alone or in combination with atrazine disappeared with new growth within 3 wk after treatment and grain yields were not reduced. Though tank mixing 2,4-D with fluthiacet-methyl reduced crop injury in 5 of 11 site-years, in one instance, 2,4-D in the tank mixture caused 13 to 18% plant lodging and 14 to 24% grain yield loss. Thus, there is greater crop risk associated with 2,4-D compared to atrazine when mixed with fluthiacet-methyl. Across sites, fluthiacet-methyl alone controlled Palmer amaranth by 55 to 95%. Greater weed control was achieved when Palmer amaranth density was less and plant size was small at the time of spraying. Tank mixing atrazine with fluthiacet-methyl significantly increased the control. Tank mixing with 2,4-D also increased Palmer amaranth control, but less effectively and less consistently than atrazine. An average of 39% grain yield advantage was achieved with fluthiacet-methyl treatments compared to untreated control.

Results indicated that fluthiacet-methyl has potential for use in grain sorghum. Hence, with a unique mode of action, fluthiacet-methyl can be an alternative herbicide for sorghum growers to combat weeds resistant to ALS-inhibitors, triazines, and synthetic auxin herbicides. Satisfactory Palmer amaranth control can be achieved with fluthiacet-methyl alone when the weeds are small, but in general tank mixing with 2,4-D or preferably atrazine is desirable for effective Palmer amaranth control.

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Table 1. Soil characteristics, planting and spraying information, 2010 and 2011.

	Hays, KS		Amarillo, TX		Springfield, NE	
	2010	2011	2010	2011	2010	2011
Soil type	Crete silty clay loam	Crete silty clay loam	Pullman silty clay loam	Pullman silty clay loam	Marshall silt loam	Marshall silt loam
Soil pH	6.5	6.5	7.6	7.7	6.5	6.5
Organic matter (%)	1.8	1.7	1.3	1.8	2.2	2.2
Sorghum hybrid	DKS 37-07	DKS 37-07	DKS 37-07	DKS 44-20	NC+ 371	NC+ 371
Seed rate (Seeds ha^{-1})	107,000	114,000	130,000	130,000	147,000	110,000
Planting date	06/23/2010	05/31/2011	06/15/2010	05/26/2011	05/04/2010	05/07/2011
POST spray information						
Spraying date	07/15/2010	06/17/2011	07/07/2010	06/21/2011	06/03/2010	06/05/2011
Sorghum height (cm)	17	13	30	20	15	18
Palmer amaranth height (cm)	-[a]	6	5	1	7	2.5
Palmer amaranth density m^{-2}	-	35	65	55	10	10
Air temperature (^{o}C)	23	31	27	26	29	32
Relative humidity (%)	81	39	38	30	60	50
Cloud cover (%)	90	70	60	0	60	-[b]

[a] Palmer amaranth was not present at Hays, KS in 2010.

[b] Information not available.

Table 2. Grain sorghum injury 4 ± 1 days after treatment caused by POST application of fluthiacet-methyl alone and tank-mixed with 2,4-D or atrazine at three sites in 2010 and 2011.

		Hays, KS		Amarillo, TX		Springfield, NE	
Treatment[a]	Rate	2010	2011	2010	2011	2010	2011
	$g\ ha^{-1}$	----------------	----------------	----------------	%	----------------	----------------
Fluthiacet-methyl	4.8	20	28	30	22	9	29
Fluthiacet-methyl	7.2	21	38	35	33	16	28
Fluthiacet-methyl + 2,4-D	4.8 + 260	24	31	22	15	14	21
Fluthiacet-methyl + 2,4-D	7.2 + 260	25	34	-[b]	23	15	24
Fluthiacet-methyl + atrazine	4.8 + 840	20	29	32	28	15	24
Fluthiacet-methyl + atrazine	7.2 + 840	23	38	35	35	13	30
Carfentrazone	8.8	26	29	32	33	16	40
Atrazine	840	0	5	0	0	1	3
LSD (0.05)		2	4	5	4	4	5

[a]All treatments include non-ionic surfactant at 0.25% v/v.

[b]Treatment was lost at Amarillo in 2010.

Table 3. Palmer amaranth control with POST-applied fluthiacet-methyl alone and tank-mixed with 2,4-D or atrazine at three sites in 2010 and 2011.

		Hays, KS	Amarillo, TX		Springfield, NE	
Treatment[a]	Rate	2011	2010	2011	2010	2011
	g ha^{-1}	----------	----------	%	----------	----------
Fluthiacet-methyl	4.8	55	57	80	75	95
Fluthiacet-methyl	7.2	58	67	78	79	93
Fluthiacet-methyl + 2,4-D	4.8 + 260	58	68	87	89	99
Fluthiacet-methyl + 2,4-D	7.2 + 260	76	-[b]	85	90	100
Fluthiacet-methyl + atrazine	4.8 + 840	78	85	97	90	100
Fluthiacet-methyl + atrazine	7.2 + 840	75	90	95	89	100
Carfentrazone	8.8	55	67	78	72	96
Atrazine	840	58	20	93	79	100
LSD (0.05)		13	9	7	9	3

[a]All treatments include non-ionic surfactant at 0.25% v/v.

[b]Treatment was lost at Amarillo in 2010.

Table 4. Sorghum grain yields as influenced by POST-applied fluthiacet-methyl alone and tank-mixed with 2,4-D or atrazine at three sites in 2010 and 2011 .

		Hays, KS		Amarillo, TX		Springfield, NE	
Treatment[a]	Rate	2010	2011	2010	2011	2010	2011
	$g\ ha^{-1}$	$kg\ ha^{-1}$					
Fluthiacet-methyl	4.8	6700	2280	1880	2730	4380	5460
Fluthiacet-methyl	7.2	6450	2220	2130	2860	5610	6550
Fluthiacet-methyl + 2,4-D	4.8 + 260	5120	2560	2900	2880	4530	9000
Fluthiacet-methyl + 2,4-D	7.2 + 260	5580	2600	-[b]	2180	5560	8380
Fluthiacet-methyl + atrazine	4.8 + 840	6410	3560	3800	2260	5800	7760
Fluthiacet-methyl + atrazine	7.2 + 840	6520	2840	2830	2980	5450	7890
Carfentrazone	8.8	6700	3390	1800	2790	5015	5520
Atrazine	840	6320	3250	1380	2540	4880	6610
Non-treated control	-	6440	1530	710	2930	3710	2410
LSD (0.05)		640	880	387	NS	1060	1750

[a]All herbicide treatments include non-ionic surfactant at 0.25% v/v.

[b]Treatment was lost at Amarillo in 2010.