POSTEMERGENCE WEED MANAGEMENT IN ACETOLACTATE SYNTHASE (ALS) RESISTANT GRAIN SORGHUM

by

DAVID SHANE HENNIGH

B.S., Kansas State University, 2000
M.S., Kansas State University, 2004

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Agronomy
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Abstract

Field experiments were conducted to evaluate the efficacy of nicosulfuron and nicosulfuron + rimsulfuron applied alone or in combination with various broadleaf herbicides in acetolactate synthase (ALS)-resistant grain sorghum. Herbicides were applied when weeds were 5 to 15 cm in height. Overall weed control was greater when nicosulfuron + rimsulfuron were applied with other herbicides than when it was applied alone. Results indicated that postemergence (POST) application of nicosulfuron and nicosulfuron + rimsulfuron is effective at controlling grasses including barnyardgrass, green foxtail, and giant foxtail. The research also showed that broadleaf weed control was more effective when nicosulfuron + rimsulfuron were applied with other broadleaf herbicides.

A field study was conducted to evaluate the differential response of ALS-resistant grain sorghum to POST applications of nicosulfuron + rimsulfuron at three growth stages. Grain sorghum was treated with nicosulfuron + rimsulfuron at the 3- to 5-leaf, 7- to 9-leaf, or 11- to 13-leaf collar stage. Nicosulfuron + rimsulfuron injured grain sorghum when applied at the 3- to 5-leaf, and 7- to 9-leaf collar stage, however, sorghum yields and plant height were only reduced for the 3- to 5-leaf collar stage. Results indicated that nicosulfuron + rimsulfuron application at the 3- to 5-leaf collar stage injured ALS-resistant grain sorghum, but application at 7- to 9-leaf and 11- to 13-leaf collar stages did not result in grain yield reduction.

Greenhouse experiments were conducted to evaluate the efficacy, absorption, and translocation of nicosulfuron, rimsulfuron, and nicosulfuron + rimsulfuron. Barnyardgrass, green foxtail, longspine sandbur, and large crabgrass were treated at 5 to 10 cm in height. Barnyardgrass GR_{50} was the lowest and was the most susceptible to all herbicides whereas, large crabgrass had the highest GR_{50} for all herbicides and was the most tolerant. Barnyardgrass and

large crabgrass were treated with 14C-nicosulfuron, 14C-rimsulfuron, or both and radioactivity was recovered at 7 DAT. Barnyardgrass absorption and translocation of nicosulfuron, rimsulfuron and nicosulfuron + rimsulfuron was higher than large crabgrass. Results may indicate that greater absorption and translocation of the herbicides may attribute to the differential response of the species to nicosulfuron, rimsulfuron, and nicosulfuron + rimsulfuron.

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CHAPTER 1 - Efficacy of Postemergence Herbicide Tankmixes in Acetolactate Synthase Resistant Grain Sorghum

ABSTRACT

Postemergence (POST) herbicide treatments to control grasses in grain sorghum are limited. Acetolactate synthase (ALS)-inhibiting herbicides are very effective in controlling many grass species in many crops; unfortunately, use of ALS-inhibiting herbicides is not an option in conventional grain sorghum because of its susceptibility to these herbicides. With the development of ALS-resistant grain sorghum, several POST ALS-inhibiting herbicides can be used to control weeds in grain sorghum. Field experiments were conducted in 2007 and 2008 to evaluate the efficacy of nicosulfuron + rimsulfuron applied alone or in combination with bromoxynil, carfentrazone-ethyl, halosulfuron + dicamba, prosulfuron, 2,4-D, and metsulfuron methyl + 2,4-D. These treatments were applied with and without atrazine. Herbicides were applied when weeds were 5 to 15 cm in height. Overall weed control was greater when nicosulfuron + rimsulfuron were applied with other herbicides than when they were applied alone. Grass weed control was greater than 90 and 80% with all herbicide treatments except nicosulfuron + rimsulfuron + atrazine and nicosulfuron + rimsulfuron + carfentrazone-ethyl + atrazine 2 and 4 weeks after treatment (WAT), respectively. Broadleaf weed control was greater than 70% in all treatments except nicosulfuron + rimsulfuron and nicosulfuron + rimsulfuron + bromoxynil. In general, adding atrazine to the herbicide mix decreased control of grass species by up to 13% at 28 DAT. Weed populations and biomass were lower when nicosulfuron + rimsulfuron were applied with various broadleaf herbicides than when they were applied alone. Grain sorghum yield was greater in all herbicide treatments than in the weedy check, with the greatest grain yield from nicosulfuron + rimsulfuron + prosulfuron. This research showed that postemergence application of nicosulfuron + rimsulfuron is effective at controlling grasses including barnyardgrass, green foxtail, and giant foxtail. The research also showed that broadleaf weed control was more effective when nicosulfuron + rimsulfuron were applied with other broadleaf herbicides.

Nomenclature: Atrazine; bromoxynil; carfentrazone-ethyl; dicamba; halosulfuron; mesotrione; nicosulfuron; rimsulfuron; prosulfuron; S-metolachlor; 2,4-D; barnyardgrass, *Echinochloa crus-galli* (L.) P. Beauv; giant foxtail, *Setaria faberi* Herrm.; grain sorghum, *Sorghum bicolor* (L.) Moench; green foxtail, *Setaria virdis* (L.) Beauv.

Key words: ALS-inhibiting herbicides, sulfonylurea, herbicide-resistant crops.

INTRODUCTION

Grain sorghum is an important crop in the central and southern Great Plains of the United States. In 2008, almost 3.4 million ha were planted in the United States, with 35% of these planted in Kansas (NASS 2008a, 2008b). Because of its drought tolerance, grain sorghum can be cultivated in areas that are often too hot and dry for other crops to be grown (Bennett et al. 1990; Stahlman and Wicks 2000).

Weeds adversely affect grain sorghum production in many areas by competing for light, nutrients, and water (Burnside and Wicks 1969; Feltner et al. 1969a, 1969b; Smith et al. 1990). Research has shown that grain sorghum’s poor competition with most weeds in the early growth stages may cause major yield reduction (Feltner et al. 1969a; Graham et al. 1988; Knezevic et al. 1997). Sorghum yield losses from weed competition often exceed those of most other major row crops and range from 30 to 50%, but losses can be much higher under adverse conditions (Stahlman and Wicks 2000). In addition, weeds may decrease grain quality, increase insect and disease pressure, and increase harvest difficulty (Zimdahl 1999).

Effective tillage and cultural practices are important weed management practices in grain sorghum production; however, herbicides are the most important component of weed management, especially in grain sorghum grown under no-till cropping systems (Bridges 1994). Grain sorghum producers usually use preemergence (PRE) herbicides, such as atrazine alone or in combination with alachlor, dimethamide, or metolachlor, followed by POST herbicide treatments of bromoxynil, 2,4-D, dicamba, prosulfuron, fluroxypyr, carfentrazone, or halosulfuron (Regehr et al. 2008). Broadleaf weed species historically have been predominate in grain sorghum, but annual grass species are increasing in importance in some production areas

(Stahlman and Wicks 2000). The main options for annual grass control in grain sorghum are PRE herbicides such as metolachlor, dimethamide, or alachlor. However, because grain sorghum typically is grown in dry conditions, the lack of soil moisture may decrease the efficacy of PRE herbicide treatments, especially on grasses, because these herbicides need moisture for activation (Tapia et al. 1997). These annual grass escapes need to be cultivated or treated with POST herbicides, but there is no effective broad-spectrum POST grass control currently available for grain sorghum (Regehr et al. 2008).

Acetolactate synthase (ALS)-inhibiting herbicides are among the most widely used herbicides in many cropping systems. ALS is the first common enzyme in the biosynthetic pathway of the branched-chain amino acids, valine, leucine, and isoleucine (Durner et al. 1990). ALS-inhibiting herbicides are the target site for more than 50 commercial herbicides (Heap 2008). ALS-inhibiting herbicides include five different groups of chemistry: sulfonylureas, imidazolinones, triazolopyrimidines, pyrimidinylthio-benzoates, and sulfonylamino-carbonyltriazolinones (Westwood et al. 2007).

Preemergence and POST ALS-inhibiting herbicides are used effectively to control weeds in corn (*Zea mays* L.) and other crops. Unfortunately, sorghum is susceptible to grass control ALS-inhibiting herbicides such as nicosulfuron and rimsulfuron, which makes it impossible to use these herbicides in sorghum. However, by transferring a major resistance gene from a wild sorghum relative, researchers at Kansas State University developed a grain sorghum that is resistant to several ALS-inhibiting herbicides (Tuinstra and Al-Khatib 2007; Tuinstra et al. 2009).

Nicosulfuron and rimsulfuron are used extensively as POST herbicides to control weeds in corn. Previous research has shown that nicosulfuron and rimsulfuron provide excellent control of many grassy weeds and also certain broadleaf weed species. Damalas and Eleftherohorinos (2001) reported that rimsulfuron provided more than 95% control of johnsongrass (*Sorghum halepense* L. Pers.). In other research, nicosulfuron provided greater than 80% control of giant foxtail and velvetleaf (*Abutilon theohrasti* Medicus) (Dobbels and Kapusta 1993). In addition, a combination of nicosulfuron and rimsulfuron controlled more than 80% of several grasses including barnyardgrass, green foxtail, yellow foxtail (*Setaria glauca* L. Beauv), and witchgrass (*Panicum capillare* L.) (Schuster et al. 2008; Swanton et al. 1996). Because of their effectiveness at controlling weedy grass species, rimsulfuron and nicosulfuron were used on 18% of the corn hectares in the United States in 2005 (USDA 2006). The objective of this study was to evaluate the efficacy of nicosulfuron + rimsulfuron applied alone or in combination with various broadleaf herbicides in ALS-resistant grain sorghum.

MATERIALS AND METHODS

Field experiments were conducted at the Kansas State University Agronomy Department fields at Ashland Bottoms south of Manhattan, KS, in 2007 and 2008. In 2007, the soil was a Reading silt loam (fine-silty, mixed, superactive, mesic Pachic Argiudolls) with a pH of 6.3 and 2.4% organic matter. In 2008, the soil was a Wymore silty clay loam (fine, montmorillonitic, mesic, Aquic Argiudolls) with a pH of 6.2 and 2.2% organic matter. The site was under dryland production in both years.

A genetic line of ALS-resistant grain sorghum ‘06MN8419’ was planted in 0.76-m rows at 136,000 seeds/ha on June 11 in 2007 and 2008. Plots were 3.1 m wide by 7.6 m long. Barnyardgrass, green foxtail, giant foxtail, velvetleaf, and ivyleaf morningglory (*Ipomoea* *hederacea* (L.) Jacq.) seeds were sown perpendicular to the grain sorghum rows immediately after grain sorghum planting in both years. These weeds were chosen because they are commonly found in grain sorghum fields in central and western Kansas. Natural infestations of large crabgrass (*Digitaria sanguinalis* L. Scop.), yellow foxtail, Palmer amaranth (*Amaranthus palmeri* S. Watts.), and common waterhemp (*Amaranthus rudis* Sauer) were also present within the fields. Palmer amaranth was the most prominent of these species in both years. Herbicides were applied with a CO_2 pressurized backpack sprayer equipped with TeeJet[1] XR8002 flat fan nozzle tips calibrated to deliver 187 L/ha at a pressure of 138 kPa.

Herbicides treatments were POST application of nicosulfuron + rimsulfuron at 26 + 13 g ai/ha alone and in combination with bromoxynil, carfentrazone-ethyl, dicamba, halosulfuron + dicamba, prosulfuron, 2,4-D, and metsulfuron methyl + 2,4-D. These herbicide treatments were applied with and without atrazine. Atrazine, bromoxynil, carfentrazone-ethyl, dicamba, halosulfuron + dicamba, prosulfuron, 2,4-D, and metsulfuron methyl + 2,4-D rates were 561, 280, 8.3, 280, 34 + 56, 22.4, 421, and 2.2 + 280 g ai/ha, respectively. A non-treated control plot and standard PRE treatment of S-metolachlor + atrazine + mesotrione at 1884 + 188 + 706 g ai/ha were included for comparison. The PRE herbicide treatment was applied immediately after planting, and POST herbicide treatments were applied when weeds were 5 to 15 cm in height. All POST herbicides treatments included nonionic surfactant[2] at 0.25% vol/vol and ammonium sulfate at 2.2 kg/ha as recommended on the herbicide label.

Visual ratings of sorghum injury and weed control were conducted 2, 4, and 6 WAT based on a scale of 0 to 100%, where 0% = no control or injury and 100% = mortality. Barnyardgrass, green foxtail, giant foxtail, velvetleaf, and ivyleaf morningglory populations were determined at 6 WAT by counting the number of plants in 1 m^2. To determine weed dry weights, barnyardgrass, green foxtail, giant foxtail, velvetleaf, and ivyleaf morningglory were harvested from a 1-m^2 area, dried at 70 C for 96 h, and weighed. Grain sorghum was mechanically harvested from the middle two rows of each plot to measure yield. Moisture content and test weight were determined with a grain analyzer[3], and yield was adjusted to 14% moisture.

The experiments were organized in a randomized complete block design. Treatments were replicated four times. Data were tested for homogeneity of variances and normality of distribution (Ramsey and Schafer 1997). All data were subjected to ANOVA using PROC MIXED in SAS[4], and means were separated using Fisher's protected LSD at $P \leq 0.05$. Mean separation tests revealed that the ranking of treatment means within experiments was similar between years; thus, the data were analyzed across years with treatments designated as a fixed effect and years and the interaction between years and treatments designated as random effects (Kuehl 2000). Correlation analysis between visual weed ratings and grain sorghum yield was performed using PROC CORR in SAS.

RESULTS AND DISCUSSION

Data were averaged across years because no treatment by year interaction occurred for response variables, including visual control ratings, weed populations, dry weights, and grain sorghum yield.

Nicosulfuron and rimsulfuron slightly injured grain sorghum 1 and 2 WAT in 2007 and 2008 (data not shown). Injury symptoms in the form of stunting, interveinal chlorosis, and chlorotic banding were observed at 1 and 2 WAT. Growth resumed at 2 to 3 WAT, and leaves regained their normal color. By 21 DAT, injury symptoms were no longer visible. Symptoms caused by nicosulfuron + rimsulfuron were similar to sulfonylurea herbicide symptoms observed on other crops (Al-Khatib and Peterson 1999; Al-Khatib and Tamhane 1999).

Overall grass control at 2 WAT was greater than 93% for all herbicide treatments except nicosulfuron + rimsulfuron + atrazine (Table 1.1). In addition, all POST treatments provided 90% or greater control of barnyardgrass, green foxtail, and giant foxtail at 2 WAT, except the application of nicosulfuron + rimsulfuron + dicamba + atrazine, which controlled 86% or more of all three grasses (Table 1.1). At 4 WAT, barnyardgrass, green foxtail, and giant foxtail control was greater than 85% for all herbicide treatments except for the treatments of nicosulfuron + rimsulfuron + carfentrazone-ethyl + atrazine and nicosulfuron + rimsulfuron + metsulfuron methyl + 2,4-D + atrazine. Nicosulfuron + rimsulfuron + halosulfuron + dicamba, nicosulfuron + rimsulfuron + prosulfuron, and S-metolachlor + atrazine + mesotrione provided the greatest grass control across all ratings (Table 1.1). The high S-metolachlor + atrazine + mesotrione activity in this study may be a result of greater herbicide activation due to timely rainfall after herbicide application (Anonymous 2009; Carey and DeFelice 1991; Moomaw and Martin 1985).

Barnyardgrass, green foxtail, and giant foxtail control was greater when nicosulfuron + rimsulfuron was applied without atrazine (Table 1.1). At 2 WAT, overall grass control was 97 and 89% when nicosulfuron + rimsulfuron were applied alone or with the high rate of atrazine, respectively (Table 1.1). In addition, grass control with nicosulfuron + rimsulfuron applied in combination with various broadleaf herbicides was not different from that with nicosulfuron + rimsulfuron applied alone (Table 1.1). Barnyardgrass, green foxtail, and giant foxtail control was 95, 87 and 94% or greater, respectively, at 4 WAT when nicosulfuron + rimsulfuron was applied with either bromoxynil, carfentrazone-ethyl, dicamba, halosulfuron + dicamba, prosulfuron, 2,4-D, or metsulfuron methyl + 2,4-D. However, addition of atrazine to nicosulfuron +

rimsulfuron + dicamba reduced barnyardgrass, green foxtail, and giant foxtail control at 2 WAT by 9, 10, and 8%, respectively, compared with nicosulfuron + rimsulfuron + dicamba applied alone. The reduction in grass control when atrazine was added to the tank mix was not surprising. Research has shown that tank mixes of atrazine with sulfonylurea herbicides may reduce the herbicides' efficacy on green foxtail, yellow foxtail (Schuster et al. 2007, 2008), and johnsongrass (Damalas and Eleftherohorinos 2001). This reduction in efficacy was attributed to reduced sulfonylurea herbicide absorption and translocation (Schuster et al. 2007).

In general, broadleaf weed control was greater when nicosulfuron + rimsulfuron were applied with various broadleaf herbicides than when they were applied alone (Table 1.2). Overall broadleaf weed control was greater than 90% for all herbicide treatments at 4 WAT, except when nicosulfuron + rimsulfuron were applied alone or in combination with bromoxynil or atrazine. Velvetleaf and ivyleaf morningglory control was greater than 85% for all herbicide treatments at 2 WAT, except when nicosulfuron + rimsulfuron were applied alone or in combination with 561 g/ha of atrazine (Table 1.2). At 4 WAT, all treatments provided at least 95% control of velvetleaf and ivyleaf morningglory, except when nicosulfuron + rimsulfuron were applied alone or in combination with atrazine, bromoxynil, bromoxynil + atrazine, and prosulfuron + atrazine. Nicosulfuron + rimsulfuron applied in combination with halosulfuron + dicamba, carfentrazone-ethyl + atrazine, or metsulfuron methyl + 2,4-D controlled 100% of velvetleaf and ivyleaf morningglory at 4 WAT (Table 1.2). The PRE treatment of S-metolachlor + atrazine + mesotrione provided perfect control of velvetleaf and ivyleaf morningglory at 2 and 4 WAT. The excellent weed control provided by the PRE treatment is likely due to timely rainfall after application (Anonymous 2009).

In general, grass and broadleaf weed control from the POST treatments were lower at 6 WAT compared with ratings at 2 and 4 WAT (Tables 1.1 and 1.2). The decreased weed control at 6 WAT is due to new weeds that emerged after residual activity of the POST herbicide diminished. The longest half-life of these POST herbicides is 30 d except atrazine (Vencill 2002).

All POST herbicide treatments significantly reduced barnyardgrass, green foxtail, giant foxtail, velvetleaf, and ivyleaf morningglory populations compared with the weedy check (data not shown). The treatment of nicosulfuron + rimsulfuron + halosulfuron + dicamba had the greatest reduction in weed populations among all POST treatments at 6 WAT but had lower weed control than the standard herbicide treatment of S-metolachlor + atrazine + mesotrione. The standard herbicide treatment provided the greatest reduction in weed biomass at 6 WAT. Among all POST treatments, the treatment of nicosulfuron + rimsulfuron + halosulfuron + dicamba provided the greatest reduction in weed biomass of barnyardgrass, green foxtail, giant foxtail, velvetleaf, and ivyleaf morningglory at 6 WAT (Table 1.3).

In general, grain yield was greater in plots treated with herbicides than in the non-treated weedy check. The highest yields were in plots treated with nicosulfuron + rimsulfuron + halosulfuron + dicamba, nicosulfuron + rimsulfuron + prosulfuron, and S-metolachlor + atrazine + mesotrione at 3,359, 3,469, and 3,443 kg/ha, respectively (Table 1.4). There was a positive relationship between weed control and sorghum grain yield at 6 WAT ($r = 0.66$).

This research showed that POST applications of nicosulfuron + rimsulfuron can effectively control weeds in the new ALS-resistant grain sorghum, including several troublesome grasses such as barnyardgrass, green foxtail, and giant foxtail. This study also demonstrated that nicosulfuron + rimsulfuron applied alone significantly decreased weed population and biomass.

The increase in weed control and decrease in weed population and biomass resulted in significant increases in grain sorghum yields. To obtain the greatest broadleaf weed control, nicosulfuron + rimsulfuron needs to be tank mixed with other broadleaf herbicides. In addition, adding atrazine to the tank mix may result in a pronounced decrease in control of weedy grass species.

SOURCES OF MATERIALS

[1]TeeJet Spraying Systems, Wheaton, IL 60189-7900.

[2]Activate Plus, Agriliance, LLC, P.O. Box 64089, St. Paul, MN 55164-0089.

[3]Dickey-John GACII grain analysis computer, Dickey-John Corporation, P.O. Box 10, Auburn, IL 62615.

[4]SAS version 9.1, SAS Institute Inc., 100 SAS Campus Drive, Cary, NC 27513.

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Table 1.1. Visual control of overall grass, barnyardgrass, green foxtail, and giant foxtail at 2, 4, and 6 wk after treatment as affected by nicosulfuron + rimsulfuron applied alone or in combination with selected herbicides.

		Weeks after treatment (WAT)											
		Overall grass			Barnyardgrass			Green foxtail			Giant foxtail		
Herbicide[a]	Rate	2	4	6	2	4	6	2	4	6	2	4	6
	g ai/ha	% control											
Nicosulfuron + rimsulfuron	26 + 13	97	95	89	100	100	99	95	87	86	99	94	91
Nicosulfuron + rimsulfuron + atrazine	26 + 13 + 1121	89	81	78	96	87	90	94	85	70	94	94	86
Nicosulfuron + rimsulfuron + atrazine	26 + 13 + 561	95	87	85	98	93	92	95	94	80	97	95	94
Nicosulfuron + rimsulfuron + bromoxynil	26 + 13 + 280	99	94	97	100	99	100	95	95	94	99	96	97
Nicosulfuron + rimsulfuron + bromoxynil + atrazine	26 + 13 + 280 + 561	94	87	68	99	90	81	96	91	56	97	98	86
Nicosulfuron + rimsulfuron + carfentrazone-ethyl	26 + 13 + 8	100	87	74	100	95	90	98	87	71	100	94	89
Nicosulfuron + rimsulfuron + carfentrazone-ethyl + atrazine	26 + 13 + 8 + 561	96	71	33	99	86	71	93	74	53	99	87	69
Nicosulfuron + rimsulfuron + dicamba	26 + 13 + 280	98	96	95	100	99	99	95	91	65	97	96	96
Nicosulfuron + rimsulfuron + dicamba + atrazine	26 + 13 + 280 + 561	95	85	87	99	91	91	86	85	85	90	90	96
Nicosulfuron + rimsulfuron + halosulfuron + dicamba	26 + 13 + 34 + 56	99	96	97	100	100	100	99	95	97	99	97	99
Nicosulfuron + rimsulfuron + halosulfuron + dicamba + atrazine	26 + 13 + 34 + 56 + 561	96	91	82	99	91	89	96	90	89	99	96	97
Nicosulfuron + rimsulfuron + prosulfuron	26 + 13 + 22	98	94	95	100	100	100	99	94	92	99	94	95
Nicosulfuron + rimsulfuron + prosulfuron + atrazine	26 + 13 + 22 + 561	99	93	89	99	96	96	94	89	86	99	96	94
Nicosulfuron + rimsulfuron + 2,4-D	26 + 13 + 421	99	96	94	100	100	100	94	89	71	100	97	96
Nicosulfuron + rimsulfuron + 2,4-D + atrazine	26 + 13 + 421 + 561	94	84	69	99	94	87	94	86	73	96	94	89
Nicosulfuron + rimsulfuron + metsulfuron methyl + 2,4-D	26 + 13 + 2 + 280	99	95	96	100	100	100	95	92	86	99	98	95
Nicosulfuron + rimsulfuron + metsulfuron methyl + 2,4-D + atrazine	26 + 13 + 2 + 280 + 561	97	89	85	99	96	96	94	80	76	99	94	92
S-metolachlor + atrazine + mesotrione	1884 + 706+188	100	100	100	100	100	100	100	100	100	100	100	100
LSD (0.05)		5	6	13	2	7	12	6	8	15	7	5	15

[a]All treatments except S-metoalchlor + atrazine + mesotrione included 0.25% (vol/vol) nonionic surfactant and 2.2 kg/ha ammonium sulfate.

Table 1.2. Visual control of overall broadleaves, velvetleaf, and ivyleaf morningglory at 2, 4, and 6 wk after treatment as affected by nicosulfuron + rimsulfuron applied alone or in combination with selected herbicides.

		Weeks after treatment (WAT)								
		Overall broadleaves			Velvetleaf			Ivyleaf morningglory		
Herbicide[a]	Rate	2	4	6	2	4	6	2	4	6
	g ai/ha	% control								
Nicosulfuron + rimsulfuron	26 + 13	65	62	81	78	69	64	87	86	78
Nicosulfuron + rimsulfuron + atrazine	26 + 13 + 1121	81	77	72	85	80	72	86	93	88
Nicosulfuron + rimsulfuron + atrazine	26 + 13 + 561	76	71	65	74	68	63	79	78	86
Nicosulfuron + rimsulfuron + bromoxynil	26 + 13 + 280	72	66	72	86	80	74	93	94	91
Nicosulfuron + rimsulfuron + bromoxynil + atrazine	26 + 13 + 280 + 561	96	95	97	99	97	100	97	97	96
Nicosulfuron + rimsulfuron + carfentrazone-ethyl	26 + 13 + 8	100	99	100	100	99	99	99	100	100
Nicosulfuron + rimsulfuron + carfentrazone-ethyl + atrazine	26 + 13 + 8 + 561	92	90	92	100	100	94	99	100	97
Nicosulfuron + rimsulfuron + dicamba	26 + 13 + 280	97	99	97	99	99	99	94	98	100
Nicosulfuron + rimsulfuron + dicamba + atrazine	26 + 13 + 280 + 561	88	97	88	85	96	96	93	98	100
Nicosulfuron + rimsulfuron + halosulfuron + dicamba	26 + 13 + 34 + 56	98	100	98	100	100	100	99	100	100
Nicosulfuron + rimsulfuron + halosulfuron + dicamba + atrazine	26 + 13 + 34 + 56 + 561	95	99	95	94	99	99	100	100	99
Nicosulfuron + rimsulfuron + prosulfuron	26 + 13 + 22	98	96	98	99	95	97	99	100	99
Nicosulfuron + rimsulfuron + prosulfuron + atrazine	26 + 13 + 22 + 561	87	90	87	85	84	76	90	94	96
Nicosulfuron + rimsulfuron + 2,4-D	26 + 13 + 421	100	100	100	100	100	100	100	100	100
Nicosulfuron + rimsulfuron + 2,4-D + atrazine	26 + 13 + 421 + 561	93	98	93	96	97	96	100	98	100
Nicosulfuron + rimsulfuron + metsulfuron methyl + 2,4-D	26 + 13 + 2.2 + 280	100	100	100	100	100	100	100	100	83
Nicosulfuron + rimsulfuron + metsulfuron methyl + 2,4-D + atrazine	26 + 13 + 2.2 + 280 + 561	99	100	99	100	100	100	100	100	100
S-metolachlor + atrazine + mesotrione	1884 + 706 + 188	100	100	100	100	100	100	100	100	100
LSD (0.05)		9	10	9	11	13	13	8	5	8

[a]All treatments except S-metoalchlor + atrazine + mesotrione included 0.25% (vol/vol) nonionic surfactant and 2.2 kg/ha ammonium sulfate.

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Table 1.3. Biomass of barnyardgrass, green foxtail, giant foxtail, velvetleaf, and ivyleaf morningglory at 6 wk after treatment as affected by nicosulfuron + rimsulfuron applied alone or in combination with selected herbicides.

Herbicide[a]	Rate	Barnyardgrass	Green foxtail	Giant foxtail	Velvetleaf	Ivyleaf morningglory
	g ai/ha			g/m^2		
Nicosulfuron + rimsulfuron	26 + 13	0.5	3.5	1.9	52.5	4.3
Nicosulfuron + rimsulfuron + atrazine	26 + 13 + 1121	2.4	4.7	1.8	22.9	2.8
Nicosulfuron + rimsulfuron + atrazine	26 + 13 + 561	1.7	3.4	1.5	57.1	2.5
Nicosulfuron + rimsulfuron + bromoxynil	26 + 13 + 280	0	0.7	0.5	61.3	1.5
Nicosulfuron + rimsulfuron + bromoxynil + atrazine	26 + 13 + 280 + 561	6.1	11.0	2.1	0	0.8
Nicosulfuron + rimsulfuron + carfentrazone-ethyl	26 + 13 + 8.3	3.2	8.4	4.8	1.7	0
Nicosulfuron + rimsulfuron + carfentrazone-ethyl + atrazine	26 + 13 + 8.3 + 561	18.9	21.3	11.4	4.1	0.6
Nicosulfuron + rimsulfuron + dicamba	26 + 13 + 280	0.5	9.9	0.7	0.7	0
Nicosulfuron + rimsulfuron + dicamba + atrazine	26 + 13 + 280 + 561	2.0	1.8	1.4	1.1	0
Nicosulfuron + rimsulfuron + halosulfuron + dicamba	26 + 13 + 34 + 56	0	0.3	0.3	0	0
Nicosulfuron + rimsulfuron + halosulfuron + dicamba + atrazine	26 + 13 + 34 + 56 + 561	4.2	1.2	0.4	1.0	0.1
Nicosulfuron + rimsulfuron + prosulfuron	26 + 13 + 22.4	0	2.3	1.5	1.6	0.1
Nicosulfuron + rimsulfuron + prosulfuron + atrazine	26 + 13 + 22.4 + 561	1.1	3.0	1.9	27.7	0.3
Nicosulfuron + rimsulfuron + 2,4-D	26 + 13 + 421	0	12.7	0.5	0	0
Nicosulfuron + rimsulfuron + 2,4-D + atrazine	26 + 13 + 421 + 561	3.4	14.3	3.4	3.9	0
Nicosulfuron + rimsulfuron + metsulfuron methyl + 2,4-D	26 + 13 + 2.2 + 280	0	2.2	1.1	0	2.2
Nicosulfuron + rimsulfuron + metsulfuron methyl + 2,4-D + atrazine	26 + 13 + 2.2 + 280 + 561	0.7	14.2	1.2	0	0
Weedy Check	0	33.7	40.6	94.7	105.5	60.2
S-metolachlor + atrazine + mesotrione	1884 + 706 + 188	0	0	0	0	0
LSD (0.05)		2.8	4.3	3.1	17.1	4.5

[a]All treatments except S-metoalchlor + atrazine + mesotrione included 0.25% (vol/vol) nonionic surfactant and 2.2 kg/ha ammonium sulfate.

Table 1.4. Grain sorghum yield as affected by nicosulfuron + rimsulfuron applied alone or in combination with various broadleaf herbicides with and without atrazine.

Herbicide[a]	Rate	Grain yield
	g ai/ha	kg /ha
Nicosulfuron + rimsulfuron	26 + 13	2,776
Nicosulfuron + rimsulfuron + atrazine	26 + 13 + 1121	2,331
Nicosulfuron + rimsulfuron + atrazine	26 + 13 + 561	2,615
Nicosulfuron + rimsulfuron + bromoxynil	26 + 13 + 280	2,260
Nicosulfuron + rimsulfuron + bromoxynil + atrazine	26 + 13 + 280 + 561	2,426
Nicosulfuron + rimsulfuron + carfentrazone-ethyl	26 + 13 + 8.3	2,307
Nicosulfuron + rimsulfuron + carfentrazone-ethyl + atrazine	26 + 13 + 8.3 + 561	2,145
Nicosulfuron + rimsulfuron + dicamba	26 + 13 + 280	2,488
Nicosulfuron + rimsulfuron + dicamba + atrazine	26 + 13 + 280 + 561	2,536
Nicosulfuron + rimsulfuron + halosulfuron + dicamba	26 + 13 + 34 + 56	3,359
Nicosulfuron + rimsulfuron + halosulfuron + dicamba + atrazine	26 + 13 + 34 + 56 + 561	2,754
Nicosulfuron + rimsulfuron + prosulfuron	26 + 13 + 22.4	3,469
Nicosulfuron + rimsulfuron + prosulfuron + atrazine	26 + 13 + 22.4 + 561	2,816
Nicosulfuron + rimsulfuron + 2,4-D	26 + 13 + 421	2,624
Nicosulfuron + rimsulfuron + 2,4-D + atrazine	26 + 13 + 421 + 561	2,049
Nicosulfuron + rimsulfuron + metsulfuron methyl + 2,4-D	26 + 13 + 2.2 + 280	3,018
Nicosulfuron + rimsulfuron + metsulfuron methyl + 2,4-D + atrazine	26 + 13 + 2.2 + 280 + 561	2,457
Weedy Check	0	1,653
S-metolachlor + atrazine + mesotrione	1884 + 706 + 188	3,443
LSD (0.05)		366

[a]All treatments except S-metoalchlor + atrazine + mesotrione included 0.25% (vol/vol) nonionic surfactant and 2.2 kg/ha ammonium sulfate.

CHAPTER 2 - Weed Control with Selected Herbicides in Acetolactate Synthase Resistant Grain Sorghum

ABSTRACT

With the development of ALS-resistant grain sorghum, several postemergence (POST) ALS-inhibiting herbicides can be used to control weeds in grain sorghum. Field experiments were conducted at four sites in Kansas in 2008 to evaluate the efficacy of nicosulfuron and nicosulfuron + rimsulfuron applied alone or in combination with, dicamba, metsulfuron methyl, and atrazine. All POST treatments injured grain sorghum 2 wk after treatment (WAT) in Garden City and Hesston, while in Hays and Manhattan only treatments that included dicamba caused sorghum injury. Nicosulfuron + rimsulfuron applied alone provided 41, 83, 74, and 93% control of grasses 4 WAT at Garden City, Hays, Hesston, and Manhattan, respectively. Overall grass control was not increased with the addition of metsulfuron methyl, atrazine or metsulfuron methyl + atrazine to nicosulfuron + rimsulfuron. In addition, the POST treatment of nicosulfuron + metsulfuron methyl + dicamba + atrazine provided 90% or greater control of all broadleaf weeds at sorghum flowering. Grain sorghum yield was greater in all herbicides treatments compared to the weedy check. The POST treatment that provided the highest yield at Garden City was nicosulfuron + rimsulfuron + atrazine, whereas in Hesston and Manhattan, nicosulfuron + metsulfuron methyl + dicamba + atrazine provided the highest yields. This research showed that many grasses can be effectively controlled with postemergence applications of nicosulfuron or nicosulfuron + rimsulfuron in ALS-resistant grain sorghum. The research also indicated that broadleaf weed control is greater when nicosulfuron or nicosulfuron + rimsulfuron is applied with other broadleaf control herbicides such as dicamba, metsulfuron methyl, and atrazine.

Nomenclature: Atrazine; dicamba; nicosulfuron; rimsulfuron; S-metolachlor; metsulfuron methyl; grain sorghum, *Sorghum bicolor* (L.) Moench;

Key words: ALS-inhibiting herbicides, sulfonylurea, herbicide-resistant crops.

INTRODUCTION

Grain sorghum is one of the most important cereal crops in the central and southern Great Plains of the United States. Because of its drought tolerance, grain sorghum can be cultivated in areas that are often too hot and dry for other crops to be grown (Bennett et al. 1990; Stahlman and Wicks 2000). In 2009, almost 42% of the 2.8 million ha of grain sorghum planted in the United States were in Kansas (Anonymous 2009b).

Weed management is one of the most important considerations in sorghum production. Weeds compete with grain sorghum for light, nutrients, and water, which can cause yield loss, decrease grain quality, and increase harvest difficulty (Burnside and Wicks 1969; Feltner et al. 1969a, 1969b; Smith et al. 1990; Zimdahl 1999). Research has shown that sorghum yield losses from weed competition can range from 8 to 56% or higher depending on the environmental conditions and weed population (Feltner et al. 1969a; Graham et al. 1998; Knezevic et al. 1997; Stahlman and Wicks 2000).

Weeds can be managed in grain sorghum by effective tillage and cultural practices such as crop rotation; however, herbicides are a major component of any grain sorghum weed management program (Bridges 1994; Brown et al. 2004). Weed management in grain sorghum currently includes the use of several PRE and POST herbicides such as chloroacetamides, protoporphyrinogen oxidase inhibitors, triazines, acetolactate synthase (ALS)-inhibitors, and auxin-type herbicides (Brown et al. 2004; Martin 2004; Smith and Scott 2006; Stahlman and Wicks 2000; Thompson et al. 2009). Typically, broadleaf weeds are the major concern in grain sorghum, but annual grass species are becoming a greater concern in some areas (Stahlman and Wicks 2000). Currently, the main options for control of annual grasses in grain sorghum are

PRE herbicides. But because grain sorghum is typically produced in areas with dry conditions, the efficacy of PRE herbicides may be reduced, especially on grasses, because of the lack of moisture that is needed for herbicide activation. Therefore, any annual grass escapes need to be controlled either through cultivation or by treatment with POST herbicides. However, an effective broad-spectrum POST grass-control herbicide is not currently available in grain sorghum (Thompson et al. 2009).

Acetolactate synthase is the first enzyme in biosynthesis of the branched-chain amino acid (i.e., valine, leucine, and isoleucine) pathway (Durner et al. 1990). Five different chemical classes of commercial herbicides inhibit ALS: sulfonylureas, imidazolinones, triazolopyrimidines, pyrimidinylthio-benzoates, and sulfonylamino-carbonyltriazolinones (Westwood et al. 2007). Today, there are more than 50 commercial herbicides targeting the ALS enzyme (Heap 2008), and ALS-inhibiting herbicides are widely used in many cropping systems because of their control of a wide spectrum of grass and broadleaf weeds, wide crop selectivity, and high efficacy (Green 2007; Westwood et al. 2007).

In grain sorghum, ALS-inhibiting herbicides are used to control many broadleaf weeds; however, grain sorghum is susceptible to grass-control ALS-inhibiting herbicides. This susceptibility makes it impossible for herbicides like nicosulfuron and rimsulfuron, which are used to effectively control grasses in corn (*Zea mays* L.) and other crops, to be used in grain sorghum. However, in 2004, researchers at Kansas State University indentified a wild sorghum accession with tolerance to ALS herbicides and were able to incorporate the trait and develop ALS-herbicide resistant grain sorghum hybrids (Tuinstra and Al-Khatib 2007; Tuinstra et al. 2009).

Nicosulfuron and rimsulfuron are two POST ALS-inhibiting herbicides used in corn to control many weeds. Many grassy weeds and certain broadleaf weeds have been shown to be controlled effectively by nicosulfuron and rimsulfuron. In previous research, rimsulfuron provided greater than 95% control of johnsongrass (*Sorghum halepense* L. Pers.), whereas nicosulfuron provided more than 80% control of giant foxtail (*Setaria faberi* Herrm.) and velvetleaf (*Abutilon theohrasti* Medicus) (Damalas and Eleftherohorinos 2001; Dobbels and Kapusta 1993). In other research, the combination of nicosulfuron and rimsulfuron provided greater than 80% control of several grasses in corn (Schuster et al. 2008; Swanton et al. 1996). The effectiveness of nicosulfuron and rimsulfuron for controlling weedy grass species led to use of these herbicides on 18% of the corn hectares in the United States in 2005 (USDA 2006). The objective of this research was to study the efficacy of nicosulfuron, rimsulfuron, and nicosulfuron + rimsulfuron applied alone or in combination with various broadleaf herbicides in ALS-resistant grain sorghum.

MATERIAL AND METHODS

Experiments were conducted at Kansas State University Agronomy Department fields in Garden City, Hays, Hesston, and Manhattan, KS, in 2008. Geographic location, soil type, taxonomic class, soil pH, and percentage organic matter were recorded for each soil (Table 1). All sites were under dryland production.

A genetic line of ALS-resistant grain sorghum ‘06MN8419’ was planted at 109,000 seeds/ha, 104,000 seeds/ha, 94,000 seeds/ha, and 136,000 seeds/ha in Garden City, Hays, Hesston, and Manhattan, respectively, on June 12, May 20, June 14, and June 11, 2008. Plots were 3.1 m by 7.6 m and consisted of four 0.76-m wide rows. The most prominent naturally occurring weeds present in the fields in Garden City, Hesston, and Manhattan were Palmer amaranth (*Amaranthus palmeri* S. Wats.) and large crabgrass (*Digitaria sanguinalis*). Broadleaf weeds present in Hays were puncturevine (*Tribulus terrestris* L.), tumble pigweed (*Amaranthus albus* L.), redroot pigweed (*Amaranthus retroflexus* L.), common lambsquarter (*Chenopodium album* L.), and kochia (*Kochia scoparia* (L.) Schrad.). The only grass present at Hays was green foxtail (*Setaria virdis* (L.) Beauv.). Common sunflower (*Helianthus annuus* L. HELAN) was also present in both Garden City and Hesston. Proso millet (*Pamicum miliaceum* L.) was also present in Garden City. Herbicides were applied with a tractor-mounted sprayer equipped with TeeJet[1] XR8002 flat fan nozzle tips calibrated to deliver 190 L/ha at 140 kPa.

Herbicide treatments consisted of POST applications of nicosulfuron, rimsulfuron, or nicosulfuron + rimsulfuron at rates of 35, 13, and 26 + 13 g ai/ha, respectively, applied alone and in combination with dicamba or metsulfuron methyl. These herbicide treatments were applied with and without atrazine at a rate of 1,121 g ai/ha. Dicamba and metsulfuron methyl rates were 280 and 4 g ai/ha, respectively. A nontreated control plot and standard PRE treatment of S-metolachlor + atrazine at 1,391 + 1,794 g ai/ha were included for comparison. The PRE herbicide treatment was applied immediately after planting, whereas POST herbicides were applied when weeds were 5 to 25 cm in height. All POST herbicides treatments included ammonium sulfate at 1.1 kg/ha and crop oil concentrate[2] (COC) at 1% vol/vol; however, treatments including dicamba were applied with nonionic surfactant[3] at 0.25% vol/vol as recommended on the herbicide label.

Visual ratings of weed control were taken 2 and 4 wk after treatment (WAT) and at grain sorghum flowering in Garden City, Hesston, and Manhattan. In Hays, visual ratings were only taken 4 WAT and at grain sorghum flowering. Weed control ratings were based on a scale of 0 to 100%, where 0% = no control and 100% = mortality. Sorghum grain was mechanically harvested from the middle two rows of each plot. Moisture content and test weight were determined using a grain analyzer[4], and yield was adjusted to 14% moisture.

The experiments were organized in a randomized complete block design. Treatments were replicated four times. Data were tested for homogeneity of variances and normality of distribution (Ramsey and Schafer 1997). All data were subjected to ANOVA using PROC MIXED in SAS[5], and means were separated using Fisher's protected LSD at $P \leq 0.05$. Correlation coefficient analysis between visual weed ratings and grain sorghum yield was performed using PROC CORR in SAS.

RESULTS AND DISCUSSION

Site by treatment interactions prevented the pooling of data; therefore, data are presented by site and treatment for all weed control ratings. All POST treatments injured grain sorghum 2 WAT in Garden City and Hesston, whereas in Hays and Manhattan, only the POST treatments with dicamba caused auxin-type injury symptoms (data not shown). Injury symptoms from nicosulfuron and rimsulfuron consisted of interveinal chlorosis and stunting, whereas injury symptoms from dicamba were leaf rolling and epinasty at 2 WAT; however, injury symptoms were no longer visible 4 WAT. Symptoms caused by nicosulfuron and rimsulfuron were similar to sulfonylurea herbicide symptoms observed on other crops (Al-Khatib and Peterson 1999; Al-Khatib and Tamhane 1999). In addition, injury symptoms caused by dicamba were similar to auxin-type injury symptoms described by Brown et al. (2004).

Overall grass control from POST herbicide treatments varied between sites (Table 2). At 2 WAT, the greatest grass control for all POST treatments was 84, 34, and 93% for Garden City, Hesston, and Manhattan, respectively. In Garden City, the POST treatments of nicosulfuron + rimsulfuron + atrazine and nicosulfuron + rimsulfuron + dicamba + atrazine resulted in the greatest grass control, whereas in Hesston and Manhattan, nicosulfuron + rimsulfuron provided the greatest grass control 2 WAT (Table 2). The PRE treatment of S-metolachlor + atrazine provided 98% or greater control of grasses 2 WAT across all locations.

At 4 WAT, the only two POST treatments that provided greater than 80% grass control in Garden City were nicosulfuron + rimsulfuron + dicamba + atrazine and nicosulfuron + rimsulfuron + metsulfuron methyl + dicamba + atrazine (Table 2). Nicosulfuron + rimsulfuron and nicosulfuron + dicamba + atrazine both gave 83% control of grasses in Hays 4 WAT. In Hesston, the POST treatments of nicosulfuron, nicosulfuron + rimsulfuron + metsulfuron methyl, and nicosulfuron + metsulfuron methyl + atrazine provided 80% or greater control of grasses 4 WAT. All POST treatments except rimsulfuron and metsulfuron methyl, however, provided greater than 80% control of grasses 4 WAT in Manhattan. In addition, the PRE treatment of S-metolachlor + atrazine provided 96, 100, 99, and 98% control of all grasses in Garden City, Hays, Hesston, and Manhattan, respectively, 4 WAT. The high level of grass control from the PRE treatment in this study may be due to timely rainfall after herbicide application that provided greater herbicide activation (Anonymous 2009a; Carey and DeFelice 1991; Moomaw and Martin 1985).

At grain sorghum flowering, all POST treatments provided less than 56% grass control in Garden City (Table 2). In Hays, however, all POST treatments provided greater than 70% control of grasses except the treatments of nicosulfuron and nicosulfuron + rimsulfuron +

atrazine. In Hesston, nicosulfuron + rimsulfuron + metsulfuron methyl and nicosulfuron + metsulfuron methyl + atrazine gave 80% or greater grass control. In addition, all POST treatments in Manhattan controlled at least 80% of grasses except the treatments of rimsulfuron and metsulfuron methyl. At sorghum flowering, the PRE treatment of S-metolachlor + atrazine continued to provide 96% or greater control of grasses across all sites except Hays, where grass control was 75%. The reduction in grass control in Garden City and Hesston from POST treatments was not surprising. In Garden City, lack of adequate moisture may have contributed to slow sorghum growth, leading to a poor crop canopy development that may have caused more weeds to emerge later in the season. The reduced grass control in Hesston might be due to increased sorghum injury from POST herbicide applications that resulted in slower sorghum growth and canopy development (data not shown).

In general, broadleaf weed control was greater when nicosulfuron or nicosulfuron + rimsulfuron were applied with various broadleaf herbicides than when they were applied alone (Table 3). The greatest broadleaf weed control 2 WAT for all POST treatments at Garden City, Hesston, and Manhattan was 99, 63, and 95%, respectively. The POST treatments of nicosulfuron + rimsulfuron + dicamba + atrazine, nicosulfuron + rimsulfuron + metsulfuron methyl + dicamba + atrazine, nicosulfuron + dicamba + atrazine, and nicosulfuron + metsulfuron methyl + dicamba + atrazine controlled 99% of broadleaf weeds 2 WAT in Garden City. In Hesston 2 WAT, the POST treatments of nicosulfuron + metsulfuron methyl + atrazine and nicosulfuron + metsulfuron methyl + dicamba + atrazine provided the greatest broadleaf weed control at 60 and 63%, respectively. This decrease in weed control compared with other sites may be due to the presence of more developed broadleaf weeds at the time of herbicide application, which may have resulted in less herbicide absorption (Chachalis et al. 2001; Devine et al. 1993; Post-Beitenmiller 1996; Krausz et al. 1996; Wanamarta and Penner 1989). All POST treatments except nicosulfuron, rimsulfuron, metsulfuron methyl, and nicosulfuron + rimsulfuron provided 83% or greater control of broadleaf weeds 2 WAT in Manhattan. The PRE treatment of S-metolachlor + atrazine provided 96, 89, and 100% control of broadleaf weeds 2 WAT in Garden City, Hesston, and Manhattan, respectively. Again, the excellent weed control provided by the PRE treatment is likely due to timely rainfall after herbicide application (Anonymous 2009a).

At 4 WAT, all POST treatments consisting of nicosulfuron or nicosulfuron + rimsulfuron in combination with various broadleaf herbicides, except metsulfuron methyl, provided 95% or greater control of broadleaf weeds in Garden City (Table 3). In Hays, broadleaf weed control was 85% or greater with all POST treatments except nicosulfuron and rimsulfuron. In Hesston, nicosulfuron + dicamba + atrazine provided 90% control of broadleaf weeds, whereas all other POST treatments except nicosulfuron and rimsulfuron provided at least 70% control of broadleaf weeds. All POST treatments provided at least 80% control of broadleaf weeds 4 WAT in Manhattan except for the treatments of nicosulfuron, rimsulfuron, and nicosulfuron + rimsulfuron.

By grain sorghum flowering, the nicosulfuron + metsulfuron methyl + dicamba + atrazine treatment provided 98% of broadleaf weeds in Garden City. In Hays, all POST treatments except nicosulfuron and rimsulfuron provided 89% control or greater of broadleaf weeds. Nicosulfuron + dicamba + atrazine and nicosulfuron + metsulfuron methyl + dicamba + atrazine both provided 90% control of broadleaf weeds in Hesston. In Manhattan, all treatments except nicosulfuron and rimsulfuron provided 75% or greater control of broadleaf weeds at time of sorghum flowering. The PRE treatment of S-metolachlor + atrazine provided 88% control or greater of broadleaf weeds at all four sites.

Grains sorghum yields varied between sites. These differences may be due to differences in rainfall amounts throughout the growing season, weed pressure, sorghum injury from herbicide treatments, and lodging that occurred in Hays. Total rainfall amounts throughout the growing season were 36, 60, 72, and 88 cm at Garden City, Hays, Hesston, and Manhattan, respectively (Anonymous 2009a). Grain yield was greater in plots treated with herbicides than in the nontreated weedy check. The highest yield at all four sites was in plots treated with S-metolachlor + atrazine (Table 4). The POST treatment that resulted in the highest grain yield in Garden City (1,630 kg/ha) was nicosulfuron + rimsulfuron + atrazine, whereas nicosulfuron + rimsulfuron + metsulfuron methyl + atrazine provided the greatest yield in Hays (3,387 kg/ha). The nicosulfuron + metsulfuron methyl + dicamba + atrazine treatment provided the highest yields in Hesston and Manhattan (2,259 and 5,052 kg/ha, respectively). There was a strong positive relationship between weed control at sorghum flowering and sorghum grain yield in Garden City, Hesston, and Manhattan, with r = 0.93, 0.83, 0.84, respectively. In Hays, there was no relationship between weed control and sorghum grain yield, which could be due to the high amount of lodging that occurred at that site.

This research showed that the new ALS-resistance technology in grain sorghum could be beneficial for POST control of weeds, especially grasses. The study also demonstrated that POST applications of nicosulfuron or nicosulfuron + rimsulfuron can result in a significant increase in grain sorghum yields. However, to obtain the highest level broadleaf weed control, nicosulfuron or nicosulfuron + rimsulfuron need to be applied with other broadleaf herbicides.

SOURCES OF MATERIALS

[1]TeeJet Spraying Systems, Wheaton, IL 60189-7900.

[2]Prime Oil, Terra International Inc., P.O. Box 6000, Sioux City, IA 53102-6000.

[3]Activate Plus, Agriliance, LLC, P.O. Box 64089, St. Paul, MN 55164-0089.

[4]Dickey-John GACII grain analysis computer, Dickey-John Corporation, P.O. Box 10, Auburn, IL 62615.

[5]SAS version 9.1, SAS Institute Inc., 100 SAS Campus Drive, Cary, NC 27513.

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Table 2.1. Geographic location, soil type, percentage organic matter, and soil pH for four sites used in Kansas to evaluate the efficacy of POST acetolactate synthase (ALS) in ALS-resistant grain sorghum.

Site	Geographic location	Soil series	Soil taxonomic class	% organic matter	Soil pH
Garden City	Southwest Kansas	Keith silt loam	Aridic Agriusdolls	2.2	8.2
Hays	West Kansas	Crete silty clay loam	Cumulic Haplustolls	1.6	6.6
Hesston	South-central Kansas	Ladysmith silty clay loam	Udertic Agriussolls	2.2	6.8
Manhattan	Northeast Kansas	Wymore silty clay loam	Aquic Argriusdolls	2.2	6.2

Table 2.2. Overall grass control 2 and 4 wk after treatment and at grain sorghum flowering as affected by nicosulfuron, rimsulfuron, or nicosulfuron + rimsulfuron applied alone or in combination with selected herbicides.

		2 WAT				4 WAT				Flowering			
Herbicide[a]	Rate	Garden City	Hays	Hesston	Manhattan	Garden City	Hays	Hesston	Manhattan	Garden City	Hays	Hesston	Manhattan
	g ai/ha	%											
Nicosulfuron	35	46	-	28	60	44	75	80	83	23	73	78	80
Rimsulfuron	13	58	-	30	58	45	75	69	60	25	65	71	76
Metsulfuron methyl	4	0	-	0	0	5	50	0	3	11	75	0	7
Nicosulfuron + rimsulfuron	26 + 13	59	-	34	93	41	83	74	93	30	85	78	88
Nicosulfuron + rimsulfuron + metsulfuron methyl	26 + 13 + 4	75	-	32	90	65	75	86	83	34	80	85	82
Nicosulfuron + rimsulfuron + atrazine	26 + 13 + 1121	84	-	33	80	66	75	73	90	44	68	76	88
Nicosulfuron + rimsulfuron + metsulfuron methyl + atrazine	26 + 13 + 4 + 1121	82	-	31	85	72	68	66	83	44	83	66	82
Nicosulfuron + rimsulfuron + dicamba + atrazine	26 + 13 + 280 + 1121	84	-	24	80	83	70	61	85	56	78	63	80
Nicosulfuron + rimsulfuorn + metsulfuron methyl + dicamba + atrazine	26 + 13 + 4 + 280 + 1121	83	-	28	88	81	75	57	83	36	80	61	80
Nicosulfuron + metsulfuron methyl	35 + 4	61	-	28	84	59	68	76	93	22	75	76	93
Nicosulfuron + atrazine	35 + 1121	65	-	29	80	44	73	75	89	36	78	78	93
Nicosulfuron + metsulfuron methyl + atrazine	35 + 4 + 1121	81	-	31	85	64	75	80	95	48	85	80	91
Nicosulfuron + dicamba + atrazine	35 + 280 + 1121	68	-	24	89	51	83	55	93	33	78	54	89
Nicosulfuron + metsulfuron methyl + dicamba + atrazine	35 + 4 + 280 + 1121	81	-	23	85	78	75	48	89	50	85	51	88
S-metolachlor + atrazine	1391 + 1794	98	-	99	100	96	100	99	98	98	75	99	96
LSD (0.05)		16	-	4	11	21	9	13	15	19	8	10	15

[a]All treatments except S-metolachlor + atrazine include 1% (vol/vol) crop oil concentrate and 1.1 kg/ha ammonium sulfate. In treatments that include dicamba, crop oil concentrate is replaced with 0.25% (vol/vol) nonionic surfactant.

- = No data available

Table 2.3. Overall broadleaf control 2 and 4 wk after treatment and at grain sorghum flowering as affected by nicosulfuron, rimsulfuron, or nicosulfuron + rimsulfuron applied alone or in combination with selected herbicides.

		2 WAT				4 WAT				Flowering			
Herbicide[a]	Rate	Garden City	Hays	Hesston	Manhattan	Garden City	Hays	Hesston	Manhattan	Garden City	Hays	Hesston	Manhattan
	g ai/ha	%				%				%			
Nicosulfuron	35	39	-	31	58	40	67	64	70	19	80	62	60
Rimsulfuron	13	75	-	40	58	49	67	67	72	18	77	66	60
Metsulfuron methyl	4	39	-	36	76	46	95	70	80	18	94	71	81
Nicosulfuron + rimsulfuron	26 + 13	70	-	39	63	40	85	73	75	13	89	71	75
Nicosulfuron + rimsulfuron + metsulfuron methyl	26 + 13 + 4	86	-	39	83	64	87	76	85	24	96	73	82
Nicosulfuron + rimsulfuron + atrazine	26 + 13 + 1121	98	-	49	84	98	94	73	91	92	91	72	84
Nicosulfuron + rimsulfuron + metsulfuron methyl + atrazine	26 + 13 + 4 + 1121	98	-	46	95	97	98	77	93	86	97	77	97
Nicosulfuron + rimsulfuron + dicamba + atrazine	26 + 13 + 280 + 1121	99	-	53	90	98	93	89	99	97	97	86	99
Nicosulfuron + rimsulfuorn + metsulfuron methyl + dicamba + atrazine	26 + 13 + 4 + 280 + 1121	99	-	53	94	99	96	89	98	96	99	87	95
Nicosulfuron + metsulfuron methyl	35 + 4	79	-	38	86	53	85	72	88	21	99	71	87
Nicosulfuron + atrazine	35 + 1121	96	-	50	88	95	90	74	93	76	95	73	83
Nicosulfuron + metsulfuron methyl + atrazine	35 + 4 + 1121	97	-	60	88	96	97	80	97	85	98	78	95
Nicosulfuron + dicamba + atrazine	35 + 280 + 1121	99	-	59	90	99	89	90	96	96	98	90	95
Nicosulfuron + metsulfuron methyl + dicamba + atrazine	35 + 4 + 280 + 1121	99	-	63	91	99	97	89	98	98	99	90	97
S-metolachlor + atrazine	1391 + 1794	96	-	89	100	97	91	89	99	96	94	88	99
LSD (0.05)		11	-	8	11	16	4	6	11	11	3	6	14

[a]All treatments except S-metolachlor + atrazine include 1% (vol/vol) crop oil concentrate and 1.1 kg/ha ammonium sulfate. In treatments that include dicamba, crop oil concentrate is replaced with 0.25% (vol/vol) nonionic surfactant.

- = No data available

Table 2.4. Grain sorghum yield as affected by nicosulfuron, rimsulfuron, or nicosulfuron + rimsulfuron applied alone or in combination with selected herbicides.

Herbicide[a]	Rate	Garden City	Hays	Hesston	Manhattan
	g ai/ha	kg/ha			
Nicosulfuron	35	0	2,446	1,255	3,034
Rimsulfuron	13	63	2,635	1,506	3,309
Metsulfuron methyl	4	188	2,823	1,318	3,286
Nicosulfuron + rimsulfuron	26 + 13	63	2,823	1,946	3,739
Nicosulfuron + rimsulfuron + metsulfuron methyl	26 + 13 + 4	439	2,635	2,258	3,782
Nicosulfuron + rimsulfuron + atrazine	26 + 13 + 1121	1,631	2,886	2,134	4,434
Nicosulfuron + rimsulfuron + metsulfuron methyl + atrazine	26 + 13 + 4 + 1121	1,192	3,387	1,883	4,522
Nicosulfuron + rimsulfuron + dicamba + atrazine	26 + 13 + 280 + 1121	1,630	2,509	2,008	4,105
Nicosulfuron + rimsulfuorn + metsulfuron methyl + dicamba + atrazine	26 + 13 + 4 + 280 + 1121	502	2,886	2,134	4,486
Nicosulfuron + metsulfuron methyl	35 + 4	251	3,074	2,008	3,509
Nicosulfuron + atrazine	35 + 1121	1,129	2,886	1,883	4,249
Nicosulfuron + metsulfuron methyl + atrazine	35 + 4 + 1121	1,317	3,325	2,071	5,013
Nicosulfuron + dicamba + atrazine	35 + 280 + 1121	1,443	2,321	2,008	3,394
Nicosulfuron + metsulfuron methyl + dicamba + atrazine	35 + 4 + 280 + 1121	1,506	2,823	2,259	5,052
S-metolachlor + atrazine	1391 + 1794	2,384	3,701	3,012	5,246
Weedy Check		0	1,945	753	1,547
LSD (0.05)		559	861	565	1,233

[a]All treatments except S-metolachlor + atrazine include 1% (vol/vol) crop oil concentrate and 1.1 kg/ha ammonium sulfate. Treatments that include dicamba crop oil concentrate is replace with 0.25% (vol/vol) nonionic surfactant.

CHAPTER 3 - Response of Acetolactate Synthase Resistant Grain Sorghum to Nicosulfuron plus Rimsulfuron

ABSTRACT

The lack of postemergence (POST) herbicides to control grasses in grain sorghum prompted researchers to develop acetolactate synthase (ALS)-resistant grain sorghum. Field experiments were conducted to evaluate the differential response of ALS-resistant grain sorghum to POST application of nicosulfuron + rimsulfuron applied at three growth stages. ALS-resistant grain sorghum was treated with 0, 13 + 7, 26 + 13, 39 + 20, 52 + 26, 65 + 33, 78 + 39, and 91 + 46 g ai/ha of nicosulfuron + rimsulfuron when plants were at the three- to five-leaf, seven- to nine-leaf, or 11- to 13-leaf collar stage. In general, as nicosulfuron + rimsulfuron rates increased, visual injury increased at the three- to five-leaf and seven- to nine-leaf collar stages. Visual injury was greatest 1 wk after treatment for the three- to five-leaf and seven- to nine-leaf collar stages across all ratings, and plants then began to recover. There was no injury observed at any rating time for the eleven- to thirteen-leaf collar stage. Plant height and sorghum grain yield were reduced as nicosulfuron + rimsulfuron rates increased when applied at the three- to five-leaf collar stage. However, nicosulfuron + rimsulfuron applied at the seven- to nine-leaf and eleven- to thirteen-leaf collar stages did not decrease sorghum yield. This research indicated that nicosulfuron + rimsulfuron application at the three- to five-leaf collar stage injured ALS-resistant grain sorghum, but application at seven- to nine-leaf and eleven- to thirteen-leaf collar stages did not result in grain yield reduction.

Nomenclature: Nicosulfuron; rimsulfuron; grain sorghum, *Sorghum bicolor* (L.) Moench.

Key words: ALS-inhibiting herbicides, sulfonylurea, herbicide-resistant crops.

INTRODUCTION

Grain sorghum is the fifth major cereal crop worldwide in terms of production (Anonymous 2009a). In the United States, grain sorghum is also one of the most important cereal crops, with an average of 2.6 million ha harvested per year in the last 5 yr (Anonymous 2009b). The ability of grain sorghum to tolerate drought conditions allows for its cultivation in areas that often are too hot and dry for other crops to be grown (Bennett et al. 1990; Stahlman and Wicks 2000).

Weeds adversely affect grain sorghum production by competing for light, nutrients, and water and may also decrease grain quality while increasing harvest difficulty (Burnside and Wicks 1969; Feltner et al. 1969a, 1969b; Smith et al. 1990; Zimdahl 1999). Tillage and cultural practices such as crop rotation are important weed management practices in grain sorghum production, but herbicides are the most important component of weed management, especially in grain sorghum grown in no-till systems (Bridges 1994; Brown et al. 2004).

Currently, U.S. grain sorghum producers use preemergence (PRE) herbicides, such as atrazine alone or in combination with alachlor, dimethamide, or metolachlor, followed by POST herbicide treatments of bromoxynil, 2,4-D, dicamba, prosulfuron, fluroxypyr, carfentrazone, or halosulfuron (Brown et al. 2004; Regehr et al. 2008). Broadleaf weed species are typically the predominant weeds in grain sorghum, but annual grass species are increasing in importance in some production areas (Stahlman and Wicks 2000). The main options for annual grass control in grain sorghum are PRE herbicides such as metolachlor, dimethamide, or alachlor. However, grain sorghum is typically grown in dry conditions, and the lack of soil moisture may decrease the efficacy of PRE herbicide treatments, especially on grasses, because these herbicides need moisture for activation. These annual grass escapes need to be cultivated or treated with POST herbicides, but there is no effective broad spectrum POST grass control herbicide currently available for grain sorghum (Regehr et al. 2008).

Acetolactate synthase (ALS)-inhibiting herbicides are among the most widely used herbicides in many cropping systems and are composed of five different groups of chemistry: sulfonylureas, imidazolinones, triazolopyrimidines, pyrimidinylthio-benzoates, and sulfonylamino-carbonyltriazolinones (Westwood et al. 2007). Acetolactate synthase is the first common enzyme in the biosynthetic pathway of the branched-chain amino acids, valine, leucine, and isoleucine (Durner et al. 1990; Ray 1984). It has been shown to be the single site of action of these herbicides because exogenous applications of valine, leucine, and isoleucine reverse their effects (Ray 1984). Acetolactate synthase is the target site for more than 50 commercial herbicides (Heap 2008). Today, ALS-inhibiting herbicides are used to effectively control weeds both PRE and POST in corn and other crops.

Grain sorghum is susceptible to grass control ALS-herbicides, which makes it impossible to use these herbicides in our current sorghum hybrids. However, in 2004, a wild sorghum accession with tolerance to ALS-herbicides was identified (Tuinstra and Al-Khatib 2007). The wild sorghum accession had cross-resistance to sulfonylurea, imidazolinone, and pyrimidinylthio-benzoates herbicide chemistries. The resistance was caused by two amino acid substitutions on the ALS-enzyme that caused the enzyme to be less sensitive to ALS-inhibiting herbicides (Tuinstra and Al-Khatib 2007). The ALS resistance is controlled by a major dominant gene with two modifier genes present in certain genetic backgrounds (Tuinstra and Al-Khatib 2007; Tuinstra et al. 2009). The trait was incorporated to develop ALS-resistant grain sorghum hybrids that are adapted for production and use in many sorghum producing areas (Tuinstra and Al-Khatib 2007; Tuinstra et al. 2009).

Acetolactate synthase herbicides are used extensively as POST herbicides to control weeds in many crops. Previous research has shown that nicosulfuron and rimsulfuron provide excellent control of many grassy weeds and certain broadleaf weed species. Dobbles and Kapusta (1993) reported that nicosulfuron provided greater than 80% control of giant foxtail (*Setaria faberi*) and velvetleaf (*Abutilon theophrasti*). In other research, rimsulfuron provided more than 95% control of johnsongrass (*Sorghum halepense*) (Damalas and Eleftherohorinos 2001). Nicosulfuron and rimsulfuron provide an excellent POST option for grain sorghum producers to control weeds, especially grasses that are not controlled by PRE herbicides because of the lack of moisture required for adequate activation.

Plant response to herbicides varies depending on plant growth stage. Plants at early stages of growth are more susceptible to herbicides (Coetzer et al. 2002; Lee and Oliver 1982; Schuster et al. 2007) because young plants are rapidly growing and more metabolically active, resulting in more herbicide absorption (Wanamarta and Penner 1989). The decrease in herbicide injury at more developed stages may also be due to physical, biochemical, morphological, and anatomical properties such as overexpression of the active site, efficient metabolic activation, a thicker cuticle, and/or a more waxy cuticle structure (Chachalis et al. 2001; Devine et al. 1993; Post-Beittenmiller 1996; Sanyal et al. 2006). It follows that there could also be differences in the response of ALS-resistant grain sorghum to nicosulfuron + rimsulfuron at different growth stages. Therefore, the objectives of this study were to evaluate the differential response of ALS-resistant grain sorghum to nicosulfuron + rimsulfuron applied POST at various growth stages and determine if injury symptoms from POST application of nicosulfuron + rimsulfuron are correlated to reduced grain sorghum yields.

MATERIALS AND METHODS

Field experiments were conducted at the Kansas State University Agronomy Department fields at Ashland Bottoms south of Manhattan, KS, in 2007 and 2008. The soil was a Reading silt loam (fine-silty, mixed, superactive, mesic Pachic Argiudolls) with a pH of 6.3 and 2.4% organic matter in 2007 and a Wymore silty clay loam (fine, montmorillonitic, mesic, Aquic Argiudolls) with a pH of 6.2 and 2.2% organic matter in 2008. The site was under dryland production in both years.

A genetic line of ALS-resistant grain sorghum '06MN8419' was planted in 0.76-m rows at 136,000 seeds/ha on 11 June in 2007 and 2008. Plots were 3.1 m wide by 7.6 m long. Grain sorghum plots were maintained weed free throughout the growing season with a PRE application of metolachlor + atrazine at 1,410 + 1,120 g ai/ha, respectively, and hand weeding as needed.

Nicosulfuron + rimsulfuron was applied at 0, 13 + 7, 26 + 13, 39 + 20, 52 + 26, 65 + 33, 78 + 39, and 91 + 46 g ai/ha when grain sorghum plants were at the three- to five-leaf, seven- to nine-leaf, and eleven- to thirteen-leaf collar stages. Nicosulfuron + rimsulfuron rates ranged from 0.5 to 3.5 times the labeled rate for corn. Herbicides were applied with a CO_2 pressurized backpack sprayer equipped with TeeJet[1] XR8002 flat fan nozzle tips calibrated to deliver 187 L/ha at a pressure of 138 kPa. All herbicide treatments included crop oil concentrate[2] at 1.0% v/v plus ammonium sulfate at 2.2 kg/ha as recommended on the herbicide label. Control plants, which received no herbicide treatment, were treated with water plus crop oil concentrate and ammonium sulfate.

Grain sorghum plant injury was visually rated 1, 3, and 6 wk after treatment (WAT). Injury ratings were based on a scale of 0 (no injury) to 100% (plant death). Grain sorghum flowering date was recorded at the beginning of anthesis on the main tiller. Grain sorghum height was determined at 50% flowering. Sorghum was mechanically harvested from the middle two rows of each plot to estimate yield. Moisture content and test weight were determined with a grain analyzer[3], and yield was adjusted to 14% moisture.

The study was a randomized complete block design with a split-plot arrangement of treatments. Main plots were the growth stages, and subplots were the herbicide rates. Treatments were replicated four times. Data were tested for homogeneity of variances and normality of distribution (Ramsey and Schafer 1997). All data were subjected to ANOVA using PROC MIXED in SAS[4], and means were separated using Fisher's protected LSD at $P \leq 0.05$. Mean separation tests revealed that the ranking of treatment means within experiments was similar between years; thus, the data were analyzed across years with treatments designated as a fixed effect and years and the interaction between years and treatments designated as random effects (Kuehl 2000).

RESULTS AND DISCUSSION

Data were averaged across years because no significant year by application timing by rate interactions occurred for response variables, including visual injury, plant height, and grain sorghum yield. Nicosulfuron + rimsulfuron at all rates injured grain sorghum at the three- to five-leaf and seven- to nine-leaf collar stages; however, at the eleven- to thirteen-leaf collar stage, no visible sorghum injury occurred at any rating date. Sorghum injury increased as nicosulfuron + rimsulfuron application rate increased. In general, injury symptoms were greatest in the three- to five-leaf collar stage and least in the seven- to nine-leaf collar stage 1 WAT (Table 3.1). At 1 and 3 WAT, sorghum injury symptoms observed at the three- to five-leaf collar stage varied from slight stunting, leaf chlorosis, and chlorotic banding at the lower two rates to severe stunting, interveinal chlorosis, and chlorotic banding at the other five rates, but by 6 WAT, these symptoms were only slightly visible (Table 3.1). The only injury symptom visible at the end of the growing season was plant stunting, which occurred with all rates at the three- to five-leaf and seven- to nine-leaf collar stages, except when the 13 + 7 g ai/ha rate was applied at the seven- to nine-leaf collar stage (Table 3.2). At the seven- to nine-leaf collar stage, injury symptoms in the form of leaf chlorosis, chlorotic banding, and slight stunting were observed 1 WAT across all herbicide rates, but by 3 WAT, these symptoms were no longer visible. Symptoms caused by nicosulfuron + rimsulfuron were similar to sulfonylurea herbicide symptoms observed on other crops (Al-Khatib and Peterson 1999; Al-Khatib and Tamhane 1999).

Grain sorghum injury from nicosulfuron + rimsulfuron applied at the three- to five-leaf collar stage was greatest at 1 WAT, after which plants began to recover. Nicosulfuron + rimsulfuron injury 1 WAT ranged from 13% when nicosulfuron + rimsulfuron were applied at 13 + 7 g ai/ha to 73% at the 91 + 46 g ai/ha rate (Table 3.1). Injury ratings 3 WAT ranged from 8 to 51% when nicosulfuron + rimsulfuron was applied at 13 + 7 to 91 + 46 g ai/ha, respectively. At 6 WAT at the three- to five-leaf collar stage, the lowest sorghum injury was 3% at the 13 + 7 g ai/ha rate, and the greatest injury was 18% at the 91 + 46 g ai/ha rate.

Sorghum injury was slight when nicosulfuron + rimsulfuron were applied at the seven- to nine-leaf collar stage. At 1 WAT, injury ranged from 4% at 13 + 7 g ai/ha nicosulfuron + rimsulfuron to 18% at 91 + 46 g ai/ha (Table 3.1). By 2 WAT, plants started to recover, symptoms dissipated, and new growth appeared normal (data not shown). Nicosulfuron + rimsulfuron applied at the eleven- to thirteen-leaf collar stage showed no visual injury symptoms across all ratings. Overall, sorghum injury ratings across all three growth stages were greatest at the three- to five-leaf collar stage and diminished as growth stage increased. Herbicide injury at the three- to seven-leaf collar stage is not surprising; plants at early growth stages are most susceptible to herbicides because young, rapidly growing plants absorb more herbicide (Coetzer et al. 2002; Krausz et al. 1996; Wanamarta and Penner 1989). This higher herbicide absorption at the early growth stages could result in high concentrations of nicosulfuron + rimsulfuron in cells, which may result in herbicidal partial binding. Differences in grain sorghum susceptibility to nicosulfuron + rimsulfuron may be due to partial binding of the herbicide to the active site or allosteric sites resulting in partial inhibition of the enzyme (Gressel 2002; LaRossa and Schloss 1984; Schloss et al. 1988).

Sorghum flowering dates differed among growth stages (data not shown). The flowering dates were the same for the seven- to nine-leaf and eleven- to thirteen-leaf collar stages compared with the non-treated control; however, flowering was delayed from 5 d for the 13 + 7 g ai/ha rate of nicosulfuron + rimsulfuron to 8 d for the 91 + 46 g ai/ha rate at the three- to five-leaf collar stage compared with the non-treated control.

Sorghum plant height at 50% flowering was reduced compared with the non-treated control across all rates of nicosulfuron + rimsulfuron applied at the three- to five-leaf collar stage. Plant heights at the three- to five-leaf collar stage ranged from 137 cm when nicosulfuron

+ rimsulfuron were applied at 13 + 7 g ai/ha to 126 cm at the 91 + 46 g ai/ha rate (Table 3.2). At the seven- to nine-leaf collar stage, sorghum plant height was also reduced across all rates of nicosulfuron + rimsulfuron, except for the 13 + 7 g ai/ha rate. Application of nicosulfuron + rimsulfuron at the eleven- to thirteen-leaf collar stage did not reduce plant height.

Sorghum grain yields were reduced when nicosulfuron + rimsulfuron were applied at the three- to five-leaf collar stage. Sorghum grain yield decreased as nicosulfuron + rimsulfuron rate increased, with the lowest yield of 2,888 kg/ha at the 91 + 46 g ai/ha nicosulfuron + rimsulfuron treatment. Grain yields, however, were not reduced at the seven- to nine-leaf collar stage despite visual injury symptoms and reduction in plant height (Table 3.2). This response suggests that grain sorghum plants can sustain some level of plant injury from nicosulfuron + rimsulfuron without reductions in yield. In addition, grain sorghum yields were not reduced from nicosulfuron + rimsulfuron application at the eleven- to thriteen-leaf collar stage.

This study demonstrated that POST application of nicosulfuron + rimsulfuron to ALS-resistant sorghum at the three- to five-leaf collar stage caused visual injury that resulted in reductions in plant height and sorghum yield. However, the injury symptoms and plant height reduction observed at the seven- to nine-leaf collar stage did not cause any sorghum yield reductions. In addition, application of nicosulfuron + rimsulfuron to ALS-resistant sorghum at the eleven- to thirteen-leaf collar stage had no effect on plant height or yield. Under field conditions, herbicides are typically applied after the three- to five-leaf collar stage because weeds are usually just emerging at this time. The majority of herbicides applied to grain sorghum for weed control in the field will be applied either during the seven- to nine-leaf or collar stage or later when the ALS-resistant sorghum shows good tolerance. Grain sorghum injury that occurs at this stage may not be important to growers as long as weed control is adequate. The benefits of weed control provided by nicosulfuron and rimsulfuron will overcome growers' concerns about crop injury.

SOURCES OF MATERIALS

[1]TeeJet Spraying Systems, Wheaton, IL 60189-7900.

[2]Prime Oil, Terra International Inc., P.O. Box 6000, Sioux City, IA 51102-6000.

[3]Dickey-John GACII grain analysis computer, Dickey-John Corporation, P.O. Box 10, Auburn, IL 62615.

[4]SAS version 9.1, SAS Institute Inc., 100 SAS Campus Drive, Cary, NC 27513.

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Table 3.1. Visible injury of ALS-resistant sorghum with nicosulfuron + rimsulfuron applied POST at 1, 3, and 6 wk after treatment at three growth stages at Manhattan, KS, in 2007 and 2008. Means were averaged across years and stage of growth.

Growth stage	Rate	% Injury 1 WAT	3 WAT	6 WAT
	nicosulfuron + rimsulfuron g ai/ha		%	
3-5 leaf	0	0	0	0
	13 + 7	13	8	3
	26 + 13	21	11	4
	39 + 20	39	15	7
	52 + 26	49	19	10
	65 + 33	66	39	14
	78 + 39	69	44	15
	91 + 46	73	51	18
7-9 leaf	0	0	0	0
	13 + 7	4	0	0
	26 + 13	8	0	0
	39 + 20	12	0	0
	52 + 26	13	0	0
	65 + 33	15	0	0
	78 + 39	16	0	0
	91 + 46	18	0	0
11-13 leaf	0	0	0	0
	13 + 7	0	0	0
	26 + 13	0	0	0
	39 + 20	0	0	0
	52 + 26	0	0	0
	65 + 33	0	0	0
	78 + 39	0	0	0
	91 + 46	0	0	0
LSD(0.05)		3	4	2

Table 3.2. Grain sorghum plant height and yield as affected by nicosulfuron + rimsulfuron applied POST at three growth stages at Manhattan, KS, in 2007 and 2008. Means were averaged across years and stage of growth.

Growth stage	Rate	Plant height	Yield
	nicosulfuron + rimsulfuron g ai/ha	cm	kg/ha
3-5 leaf	0	149	4,747
	13 + 7	137	4,003
	26 + 13	137	3,530
	39 + 20	134	3,458
	52 + 26	133	3,394
	65 + 33	129	3,098
	78 + 39	127	3,109
	91 + 46	126	2,888
7-9 leaf	0	149	4,747
	13 + 7	145	4,656
	26 + 13	144	4,533
	39 + 20	141	4,640
	52 + 26	138	4,653
	65 + 33	138	4,635
	78 + 39	138	4,413
	91 + 46	137	4,518
11-13 leaf	0	149	4,747
	13 + 7	147	4,515
	26 + 13	147	4,721
	39 + 20	146	4,645
	52 + 26	146	4,495
	65 + 33	146	4,570
	78 + 39	146	4,663
	91 + 46	145	4,720
LSD(0.05)		4	471

CHAPTER 4 - Efficacy of Nicosulfuron and Rimsulfuron on Barnyardgrass (*Echinochloa crus-galli*), Green Foxtail (*Setaria virdis*), Longspine Sandbur (*Cenchrus longispinus*), and Large Crabgrass (*Digitaria sanguinalis*)

ABSTRACT

Experiments were conducted to determine the efficacy, absorption, and translocation of nicosulfuron, rimsulfuron, and nicosulfuron + rimsulfuron on barnyardgrass, green foxtail, longspine sandbur, and large crabgrass. In the greenhouse, nicosulfuron, rimsulfuron, and nicosulfuron + rimsulfuron were applied at 0.0625, 0.125, 0.25, 0.5, 0.75, 1, and 2 times their label rates of 35, 13, and 26 + 13 g ai/ha, respectively, on 5 to 10 cm plants. Three weeks after treatment (WAT), the most susceptible species to all three herbicides was barnyardgrass and the least susceptible was large crabgrass. The nicosulfuron, rimsulfuron, or nicosulfuron + rimsulfuron rate causing 50% visible injury (GR_{50}) for barnyardgrass was 10.9, 4.8, and 6 + 3 g ai ha^{-1}, respectively, whereas the GR_{50} for large crabgrass was 25.6, 9.9, and 14.3 + 7.2 g ai ha^{-1}, respectively, 3 WAT. Absorption of nicosulfuron, rimsulfuron, and nicosulfuron + rimsulfuron was greater in barnyardgrass than in large crabgrass. At 7 day after treatment (DAT), absorption of nicosulfuron + rimsulfuron in barnyardgrass and large crabgrass was 74% and 57%, respectively. In addition, translocation of nicosulfuron, rimsulfuron, and nicosulfuron + rimsulfuron out of the treated leaf was 14, 12, and 14% higher in barnyardgrass than in large crabgrass, respectively. The differential response of these weed species to nicosulfuron, rimsulfuron, and nicosulfuron + rimsulfuron may be attributed to differences in herbicide absorption and translocation.

Nomenclature: Nicosulfuron; rimsulfuron; barnyardgrass, *Echinochloa crus-galli* (L.) P. Beauv; green foxtail, *Setaria virdis* (L.) Beauv.; large crabgrass, *Digitaria sanguinalis* (L.) Scop.; longspine sandbur, *Cenchrus longispinus* (Hack.) Fern.

Key words: ALS-inhibiting herbicides, sulfonylurea.

INTRODUCTION

The development of herbicide-resistant crops has been a great benefit for many cropping systems because it gives growers more options for managing weeds (Franz et al. 1997). Acetolactate synthase (ALS)-resistant grain sorghum [*Sorghum bicolor* (L.) Moench] was developed at Kansas State University with the goal of providing producers with an option for broad-spectrum POST grass control. The predominant weed species in grain sorghum are broadleaf weeds; however, annual grasses are increasing in some production areas (Stahlman and Wicks 2000). Previous research has shown that barnyardgrass, large crabgrass, green foxtail, and longspine sandbur are troublesome weeds in grain sorghum producing area and can cause significant yield reductions (Defelice 2002; Norris 1980; Smith et al. 1990; Stubbendieck et al. 2003).

Preemergence herbicides, such as metolachlor, dimethamide, or alachlor, are the only options for broad-spectrum annual grass control in grain sorghum (Thompson et al. 2009). However, this use of PRE herbicides is a concern in the dry conditions in which grain sorghum is typically grown. Efficacy of the PRE herbicides may be reduced in these conditions because of a lack of soil moisture, which is needed for herbicide activation (Tapia et al. 1997). Therefore, the option of using a broad-spectrum POST herbicide to control annual grasses in grain sorghum could be a great benefit. The two POST herbicides that will be labeled for use on the ALS-resistant grain sorghum are nicosulfuron and rimsulfuron (Anonymous 2009).

Nicosulfuron and rimsulfuron are selective POST herbicides that control many perennial and annual grasses as well as certain broadleaf weeds. The efficacy of these herbicides, especially on grasses, varies depending on weed species (Camacho et al. 1991; Dobbels and

Kapusta 1993; Prostko et al. 2006; Webster and Masson 2001; Williams and Harvey 2000). Previous research has indicated that nicosulfuron provided greater than 80% control of giant foxtail (*Setaria faberi* Herrm.), green foxtail, johnsongrass [*Sorghum halepense* (L.) Pers.], and velvetleaf (*Abutilon theophrasti* Medik.) (Camacho et al. 1991; Dobbels and Kapusta 1993; Schuster et al. 2008). Nicosulfuron also provided greater than 90% of wild proso millet (*Panicum miliaceu*) and red rice (*Oryza sativa*); however, it provided only 69% control of Texas panicum (*Panicum texanum*) (Prostko et al. 2006; Webster and Masson 2001; Williams and Harvey 2000). Rimsulfuron provided more than 80% control of barnyardgrass, large crabgrass, and redroot pigweed (*Amaranthus retroflexus* L.) (Boydston 2007; Renner and Powell 1998; Schuster et al. 2008) and more than 95% control of johnsongrass (Damalas and Eleftherohorinos 2001). In other research, quackgrass (*Elytrigia repens*) and red rice control from rimsulfuron was only 53 and 63%, respectively (Ivany 2002; Webster and Masson 2001). In addition, the combination of nicosulfuron and rimsulfuron applied together provided 80% control or greater of several annual grasses including yellow foxtail (*Setaria glauca* (L.) Beauv.), witchgrass (*Panicum capillare* L.), and black-seeded proso millet (*Panicum miliaceum* L.) (Swanton et al. 1996). The effectiveness of nicosulfuron and rimsulfuron at controlling grass and broadleaf weeds in corn (*Zea mays* L.) and potatoes (*Solanum tuberosum* L.) led to nicosulfuron and rimsulfuron being applied to 27 and 18% of the potato and corn hectares, respectively, in the United States in 2005 (USDA 2006).

Although previous research showed that nicosulfuron provided good control of green foxtail and rimsulfuron effectively controlled barnyardgrass, little data is available to directly compare the efficacy of nicosulfuron, rimsulfuron, and the combination of both herbicides on important grass weeds in grain sorghum such as barnyardgrass, green foxtail, longspine sandbur, and large crabgrass. Therefore, the objectives of this research were to (1) study the differential response of green foxtail, barnyardgrass, large crabgrass, and longspine sandbur to nicosulfuron, rimsulfuron, and nicosulfuron + rimsulfuron and (2) evaluate whether nicosulfuron, rimsulfuron, and nicosulfuron + rimsulfuron absorption and translocation are the basis for the differential response of grass weeds to these herbicides.

MATERIALS AND METHODS

Plant Materials. Green foxtail, large crabgrass, barnyardgrass, and longspine sandbur were selected for use in this study because they are troublesome weeds found in most grain sorghum fields. Plants were grown in 15-cm-diam containers filled with a 1:1 (v v^{-1}) mixture of sand and Morrill loam soil (fine-loamy, mixed, mesic Typic Argiudolls) with a pH of 7.4 and 1.6% organic matter. Plants were grown under greenhouse conditions of 26/24 ± 3 C day/night temperatures with a 16/8-h day/night period. The supplemental light intensity was 84 µmol/m^2/s photosynthetic photon flux density. Plants were watered as needed and fertilized weekly with a commercial fertilizer[1] solution containing 0.40 mg L^{-1} nitrogen, 0.34 mg L^{-1} phosphorus, and 0.33 mg L^{-1} potassium. Plants were thinned to one plant per container 1 wk before herbicide application.

Dose-Response Study. Green foxtail, large crabgrass, barnyardgrass, and longspine sandbur seedlings were treated when plants were 5 to 10 cm in height with 0, 0.0625, 0.125, 0.25, 0.5, 0.75, 1, and 2 times the labeled use rates of nicosulfuron, rimsulfuron, and nicosulfuron + rimsulfuron in corn. The use rates were 35, 13, and 26 + 13 g ai ha^{-1} for nicosulfuron, rimsulfuron, and nicosulfuron + rimsulfuron, respectively.

Herbicides were applied with a bench-type sprayer[2] equipped with an 80015LP[3] spray tip. The sprayer was calibrated to deliver 187 L ha^{-1} at 138 kPa. All treatments included crop oil concentrate[4] (COC) at 1.0% vol vol^{-1} plus urea ammonium nitrate (UAN) at 2.5% vol vol^{-1}. Nontreated control plants, which received no herbicide treatment, were treated with water plus COC plus UAN.

Visual ratings of herbicide control of green foxtail, barnyardgrass, large crabgrass, and longspine sandbur were made at 1, 2, and 3 wk after treatment (WAT) on a scale of 0 to 100%, where 0% = no control and 100% = mortality. At 3 WAT, plants were harvested at ground level and dried at 70 C for 96 h.

Absorption and Translocation. Barnyardgrass and large crabgrass were selected for the absorption and translocation study because barnyardgrass was most susceptible and large crabgrass was least susceptible to all the herbicides used in the dose-response study. Barnyardgrass and large crabgrass were treated at the four-leaf stage with ten 1-µl droplets of ^{14}C-nicosulfuron ([pyrimidine-2-^{14}C]-nicosulfuron, specific activity 2,300 MBq g^{-1}) and/or ^{14}C-rimsulfuron ([pyrimidine-2-^{14}C]-rimsulfuron, specific activity 1,302 MBq g^{-1}) applied uniformly across the adaxial surface of the third-oldest leaf of each plant. Unlabeled nicosulfuron, rimsulfuron, or nicosulfuron + rimsulfuron was added to the radioactive solutions to obtain 35, 13, and 23 + 13 g ha^{-1}, respectively in a carrier volume of 187 L ha^{-1}. Crop oil concentrate[4] was added to all treatments at 0.5% vol vol^{-1} to enhance droplet-to-leaf surface contact.

Plants were harvested at 1, 3, and 7 d after treatment (DAT) and separated into treated leaf, other tiller, and roots. Treated leaves were rinsed with 15 ml of 75% methanol solution to remove any unabsorbed herbicide, and radioactivity in the leaf rinsate was measured by using liquid scintillation spectrometry (LSS)[5]. Plant sections were air-dried at 26 C for 48 h and then combusted in a biological oxidizer[6]. Radioactivity recovered for each plant part was measured by using LSS. Herbicide absorption was calculated by dividing the radioactivity recovered in the entire plant by the total radioactivity applied to the plant. Herbicide translocation was calculated by dividing the radioactivity recovered in each plant part by the total radioactivity absorbed in the plant (Schuster et al. 2007).

Experimental Design and Data Analysis. Experiments were conducted as randomized complete block designs and were repeated in time. Treatments were replicated 10 times in the dose-response study and six times in the absorption and translocation study. All data were tested for homogeneity of variance (Ramsey and Schafer 1997). There were no interactions among runs for all studies; therefore, data were pooled over runs. Nonlinear regression analysis was used to determine the nicosulfuron, rimsulfuron, and nicosulfuron + rimsulfuron rate required to cause GR_{50} in the dose-response study (Seefeldt et al. 1995). Data for the absorption and translocation studies were analyzed by using ANOVA, and means were separated by using standard errors at $P \leq 0.05$ (Kuehl 2000).

RESULTS AND DISCUSSION

Dose-Response Study

In general, injury increased as herbicide rates increased, with nicosulfuron + rimsulfuron causing the greatest injury across all species. Injuries from all three herbicides developed around 1 WAT and were most severe 3 WAT. Nicosulfuron, rimsulfuron, and nicosulfuron + rimsulfuron injury symptoms consisted of general foliar chlorosis, stunting, and some foliar necrosis. Symptoms caused by nicosulfuron and rimsulfuron were similar to sulfonylurea herbicide symptoms observed on other weedy grasses (Schuster et al. 2008). Injury ratings 1 WAT were low for all herbicides and similar in all species (data not shown) but peaked 3 WAT. Therefore, only injury ratings at 3 WAT were used to determine the outcome of the herbicide treatment.

In general, barnyardgrass was the most sensitive species in the study to all herbicides. Injury to barnyardgrass was greater than 80% when nicosulfuron + rimsulfuron at 13 + 7 g ai ha^{-1} was applied. Greater than 90% injury occurred to barnyardgrass when nicosulfuron and rimsulfuron were applied at 26 and 10 g ai ha^{-1}, respectively. The mean GR_{50} for barnyardgrass treated with nicosulfuron, rimsulfuron, or nicosulfuron + rimsulfuron was 10.9, 4.8, and 6 + 3 g ai ha^{-1}, respectively (Figure 1). These rates represent 31, 37, and 23% of the label use rates.

In general, green foxtail response to nicosulfuron, rimsulfuron, and nicosulfuron + rimsulfuron was similar to that of barnyardgrass. Green foxtail injury 3 WAT was 80% or greater when nicosulfuron, rimsulfuron, and nicosulfuron + rimsulfuron were applied at a rate of 26, 10, and 20 + 10 g ai ha^{-1}, respectively. Nicosulfuron + rimsulfuron at 20 + 10 g ai ha^{-1} caused greater than 90% injury to green foxtail. The GR_{50} for green foxtail treated with nicosulfuron, rimsulfuron, or nicosulfuron + rimsulfuron was 14.4, 5.3, and 6.8 + 3.4 g ai ha^{-1}, respectively (Figure 2). These rates represent 41, 41, and 26% of the label use rates.

Longspine sandbur was more sensitive than large crabgrass and less sensitive than green foxtail and barnyardgrass to nicosulfuron, rimsulfuron, and nicosulfuron + rimsulfuron. Longspine sandbur tolerance to nicosulfuron, rimsulfuron, and nicosulfuron + rimsulfuron applied at the 1X rate increased 1.6-, 1.6-, and 1.3-fold, respectively, compared with barnyardgrass. Longspine sandbur GR_{50} was 21.7, 8.5, and 11.2 + 5.6 g ai ha^{-1} for nicosulfuron, rimsulfuron, and nicosulfuron + rimsulfuron, respectively (Figure 3). These rates represent 62, 65, and 43% of the label use rates.

In general, large crabgrass was the most tolerant species in the study to nicosulfuron, rimsulfuron, and nicosulfuron + rimsulfuron. At 3 WAT, injury was less than 90% for nicosulfuron, rimsulfuron, and nicosulfuron + rimsulfuron across all rates. Injury of large crabgrass was less than 80% when nicosulfuron + rimsulfuron was applied at 26 + 13 g ai ha^{-1}. The GR_{50} for large crabgrass increased as much as 2.4-fold from that of the most sensitive species in the study (Figure 4).

Reductions in the dry weights of barnyardgrass, green foxtail, longspine sandbur, and large crabgrass due to nicosulfuron, rimsulfuron, and nicosulfuron + rimsulfuron treatments showed a strong positive correlation (r = 0.91) with herbicide injury (data not shown). Again, reductions in plant dry weight due to nicosulfuron, rimsulfuron, and nicosulfuron + rimsulfuron were greatest in barnyardgrass and least in large crabgrass. The differential response to herbicides of the four weeds used in this study is not surprising. Other researchers have shown that weed species differ in absorption, translocation, and metabolism of herbicides, which leads to varying degrees of sensitivity to herbicides (Ballard et al. 1995; Chachalis et al. 2001; Devine et al. 1993; Hsu and Kleier 1990; Post-Beittenmiller 1996; Unland et al. 1999; Wanamarta and Penner 1989).

Foliar Absorption

In general, nicosulfuron, rimsulfuron, and nicosulfuron + rimsulfuron absorption increased over time. In addition, absorption of nicosulfuron, rimsulfuron, and nicosulfuron + rimsulfuron was higher in barnyardgrass than in large crabgrass. At 1 DAT, absorption of nicosulfuron applied alone to large crabgrass and barnyardgrass was 20 and 38%, respectively.

Absorption increased to 41 and 58% 3 DAT and was greater than 55 and 70% at 7 DAT in large crabgrass and barnyardgrass, respectively (Table 1).

Absorption of rimsulfuron was lower in large crabgrass than in barnyardgrass (Table 1). Rimsulfuron absorption was similar to nicosulfuron absorption in large crabgrass and barnyardgrass. At 1 DAT, 19 and 32% of rimsulfuron was absorbed in large crabgrass and barnyardgrass, respectively. Absorption of rimsulfuron increased to 39 and 57% 3 DAT and was greater than 50 and 70% by 7 DAT for large crabgrass and barnyardgrass, respectively.

Nicosulfuron + rimsulfuron absorption in barnyardgrass was similar to that of nicosulfuron applied alone at 1, 3 and 7 DAT (Table 1). Rimsulfuron absorption 1 DAT in barnyardgrass was lower than that when nicosulfuron and rimsulfuron were applied together; however, rimsulfuron absorption 3 and 7 DAT was similar to that of nicosulfuron + rimsulfuron applied together. In large crabgrass, absorption of nicosulfuron + rimsulfuron was greater 1 and 3 DAT compared with absorption when nicosulfuron and rimsulfuron were applied alone. Absorption of nicosulfuron + rimsulfuron 1 DAT was 26 and 42% for large crabgrass and barnyardgrass, respectively. At 3 DAT, large crabgrass and barnyardgrass absorbed 48 and 62%, respectively, of nicosulfuron + rimsulfuron. By 7 DAT, 57% of nicosulfuron + rimsulfuron was absorbed in large crabgrass, and 74% was absorbed in barnyardgrass.

The difference in absorption of nicosulfuron, rimsulfuron, and nicosulfuron + rimsulfuron between large crabgrass and barnyardgrass may partially explain differences in injury between the two species observed in the dose-response study. Differences in absorption between the two species may be due to the morphological and anatomical properties of the plant and the environmental conditions under which the plant developed (Chachalis et al. 2001; Devine et al. 1993; Post-Beittenmiller 1996; Wanamarta and Penner 1989).

Herbicide Translocation

Nicosulfuron, rimsulfuron, and nicosulfuron + rimsulfuron translocation in large crabgrass and barnyardgrass was determined by measuring ^{14}C translocation out of the treated leaf. In general, translocation of nicosulfuron increased over time for both large crabgrass and barnyardgrass, with 26 and 41%, respectively, translocated out of the treated leaves 7 DAT. At 1 DAT, 15 and 16% of the nicosulfuron translocated out of the treated leaf for large crabgrass and barnyardgrass, respectively. Translocation of nicosulfuron 3 DAT increased to 21 and 26% for large crabgrass and barnyardgrass, respectively (Table 2). At 7 DAT, 11 and 29% of the nicosulfuron translocated to the roots and treated tiller, respectively, in barnyardgrass, whereas in large crabgrass, 8 and 18% of the nicosulfuron translocated to the roots and treated tiller, respectively, 7 DAT. Translocation of nicosulfuron in large crabgrass was less than in barnyardgrass, with 60 and 74% of the absorbed herbicide remaining in the treated leaf of barnyardgrass and large crabgrass, respectively, 7 DAT.

Rimsulfuron translocation increased over time for both large crabgrass and barnyardgrass. In barnyardgrass, 3 and 17% of the rimsulfuron translocated 1 DAT to the roots and treated tiller, respectively (Table 2), whereas in large crabgrass, 3 and 14% of the rimsulfuron translocated to the roots and treated tiller, respectively. By 3 DAT, translocation of rimsulfuron out of the treated leaf increased to 22 and 30% for large crabgrass and barnyardgrass, respectively. Rimsulfuron translocation out of the treated leaf was greater in barnyardgrass than in large crabgrass, with 64 and 76%, respectively, of the absorbed herbicide remaining in the treated leaf at 7 DAT. In barnyardgrass, 11 and 25% of the rimsulfuron translocated to the roots and treated tiller, respectively, 7 DAT. Rimsulfuron translocation in large crabgrass was 6 and 18% to the roots and treated tiller, respectively, 7 DAT.

In general, nicosulfuron + rimsulfuron translocation increased over time for barnyardgrass and large crabgrass, with barnyardgrass having the highest translocation by 7 DAT. At 1 DAT, translocation of nicosulfuron + rimsulfuron out of the treated leaf in barnyardgrass was similar that in large crabgrass, with 79 and 81%, respectively, of the absorbed herbicide remaining in the treated leaf (Table 2). In barnyardgrass 3 DAT, 6 and 26% of the nicosulfuron + rimsulfuron translocated to the roots and treated tiller, respectively. In large crabgrass 3 DAT, 5 and 19% of the nicosulfuron + rimsulfuron translocated to the roots and treated tiller, respectively. By 7 DAT, 30 and 44% of the absorbed nicosulfuron + rimsulfuron was translocated out of the treated leaf in large crabgrass and barnyardgrass, respectively.

Translocation of nicosulfuron, rimsulfuron, and nicosulfuron + rimsulfuron was significantly less in large crabgrass than in barnyardgrass. These differences in herbicide translocation between large crabgrass and barnyardgrass may be due to greater absorption of the herbicides resulting in more herbicide being translocated in the plant or to differences in herbicide loading and unloading between the species (Ballard et al. 1995; Hsu and Kleier 1990; Unland et al. 1999). Herbicide translocation depends on the physiochemical properties of plant membranes and phloem, the assimilate transport rate and direction, and environmental factors (Devine 1989; Devine et al. 1993). The greater barnyardgrass injury from nicosulfuron, rimsulfuron, and nicosulfuron + rimsulfuron application compared with large crabgrass injury may be partly due to greater translocation. These results agree with earlier research, which showed greater plant injury with greater nicosulfuron translocation (Carey et al. 1997).

Of the four weed species in this study, barnyardgrass was the most sensitive to nicosulfuron, rimsulfuron, or nicosulfuron + rimsulfuron, followed by green foxtail and longspine sandbur. Large crabgrass was the most tolerant. Absorption and translocation of nicosulfuron, rimsulfuron, and nicosulfuron + rimsulfuron were greater in barnyardgrass than in large crabgrass. These differences in absorption and translocation between the two species may result in differences in the weeds' herbicide sensitivity.

SOURCES OF MATERIALS

[1] Miracle-Gro soluble fertilizer, Scotts Miracle-Gro Products Inc., P.O. Box 606, Marysville, OH 43040.

[2] Research Track Sprayer SB-8, Devries manufacturing, RR 1, Box 184, Hollandale, MN 56045.

[3] Spray tip, TeeJet XP Spraying Systems Co., North Ave., Wheaton, IL 60188.

[4] Prime Oil, Terra International Inc., P.O. Box 6000, Sioux City, IA 53102-6000.

[5] Tricarb 2100TR Liquid Scintillation Analyzer, Packard Instrument Co., 800 Research Parkway, Meriden, CT 06450.

[6] R. J. Harvey Biological Oxidizer, Model OX-600, R. J. Harvey Instrument Co., 123 Patterson Street, Hillsdale, NJ 07642.

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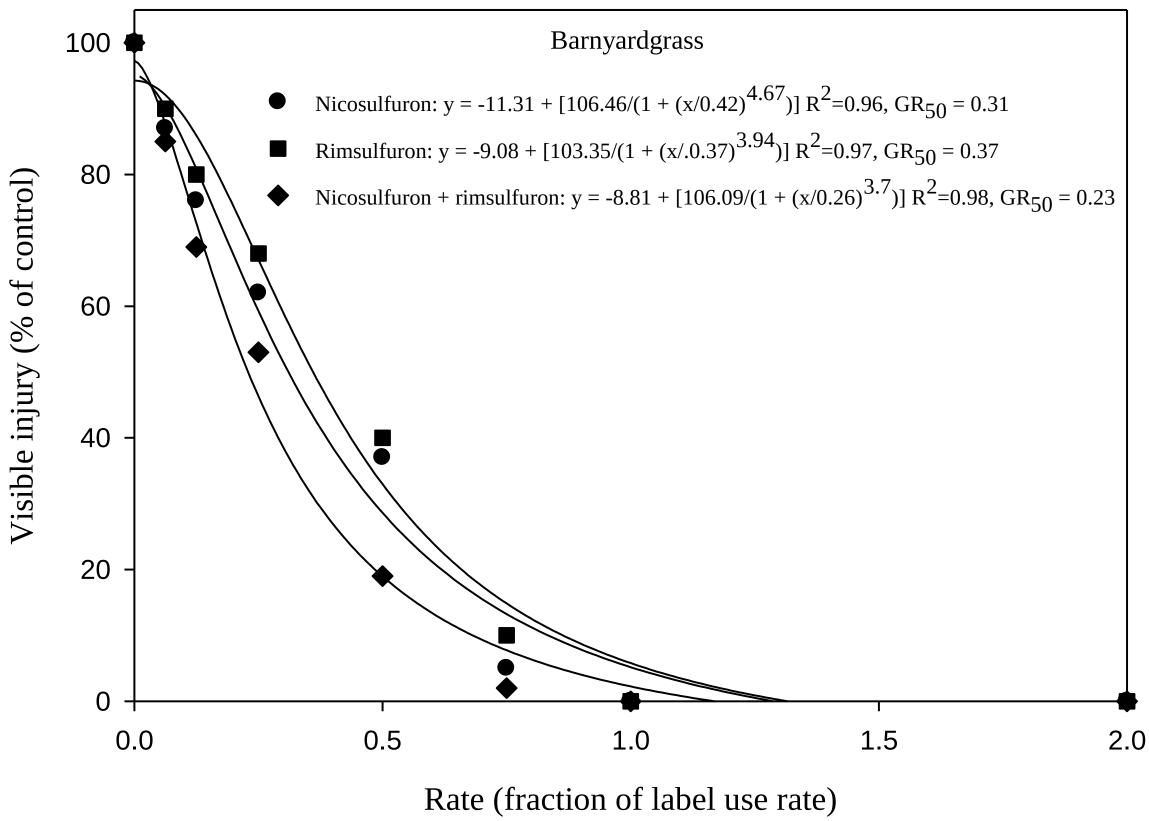
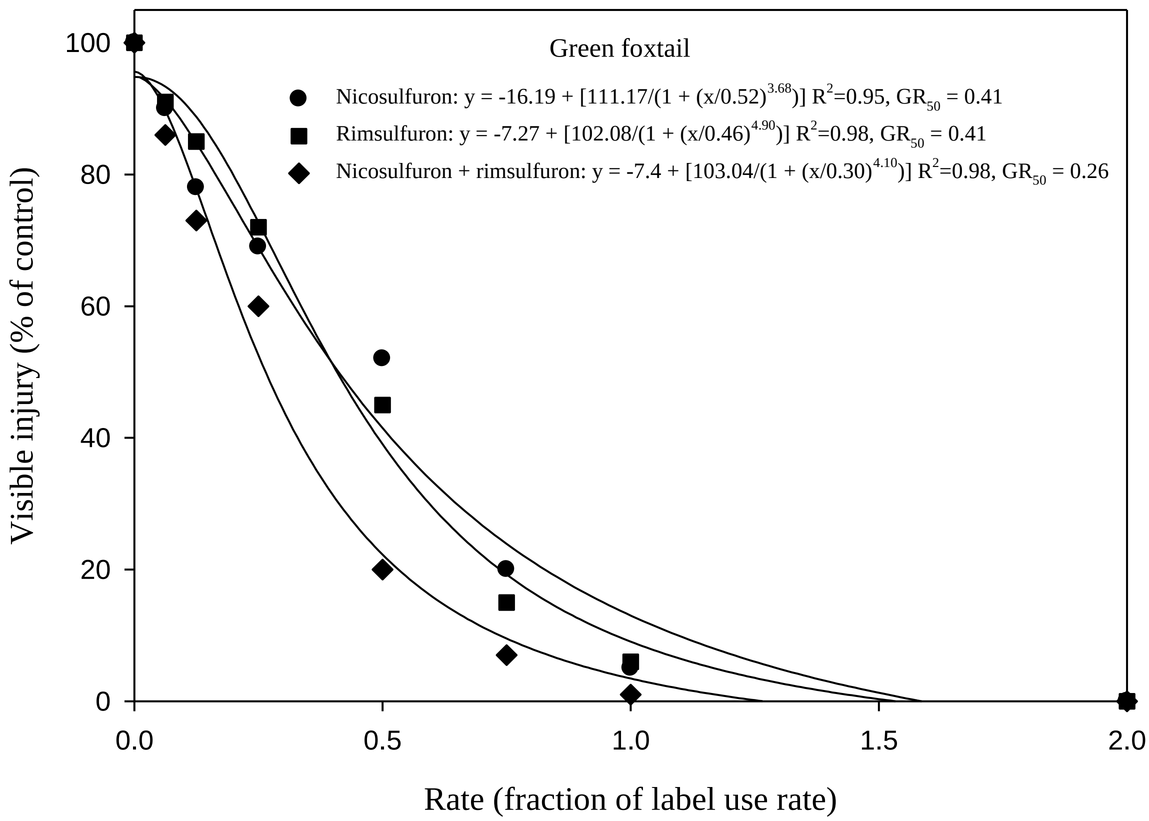
Figure 1.



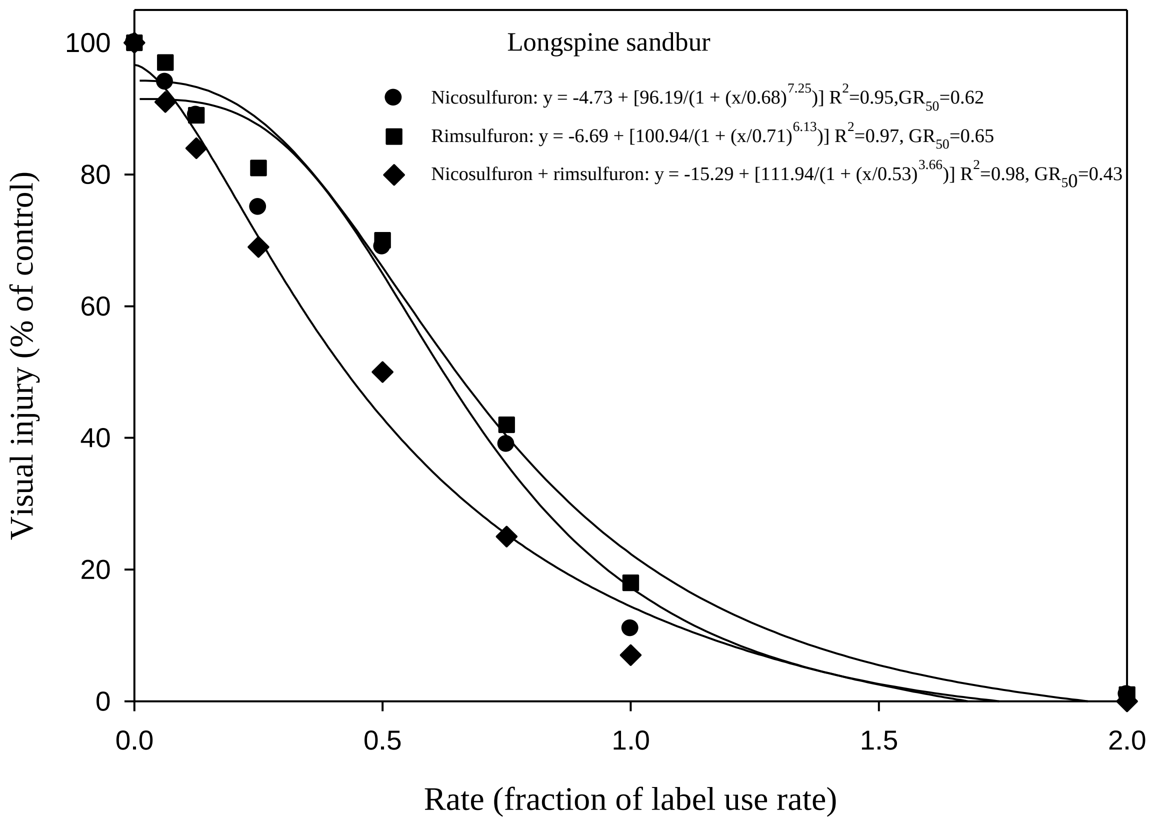
Barnyardgrass
Nicosulfuron: y = -11.31 + [106.46/(1 + (x/0.42)^4.67)] R^2=0.96, GR50 = 0.31
Rimsulfuron: y = -9.08 + [103.35/(1 + (x/.0.37)^3.94)] R^2=0.97, GR50 = 0.37
Nicosulfuron + rimsulfuron: y = -8.81 + [106.09/(1 + (x/0.26)^3.7)] R^2=0.98, GR50 = 0.23
100
80
60
40
20
0
0.0
0.5
1.0
1.5
2.0
Visible injury (% of control)
Rate (fraction of label use rate)

Figure 2.



Green foxtail
Nicosulfuron: y = -16.19 + [111.17/(1 + (x/0.52)^3.68)] R^2=0.95, GR50 = 0.41
Rimsulfuron: y = -7.27 + [102.08/(1 + (x/0.46)^4.90)] R^2=0.98, GR50 = 0.41
Nicosulfuron + rimsulfuron: y = -7.4 + [103.04/(1 + (x/0.30)^4.10)] R^2=0.98, GR50 = 0.26
Visible injury (% of control)
0
20
40
60
80
100
0.0
0.5
1.0
1.5
2.0
Rate (fraction of label use rate)

Figure 3.



Longspine sandbur
Nicosulfuron: y = -4.73 + [96.19/(1 + (x/0.68)^7.25)] R^2=0.95,GR50=0.62
Rimsulfuron: y = -6.69 + [100.94/(1 + (x/0.71)^6.13)] R^2=0.97, GR50=0.65
Nicosulfuron + rimsulfuron: y = -15.29 + [111.94/(1 + (x/0.53)^3.66)] R^2=0.98, GR50=0.43
Visual injury (% of control)
100
80
60
40
20
0
0.0
0.5
1.0
1.5
2.0
Rate (fraction of label use rate)

Figure 4.

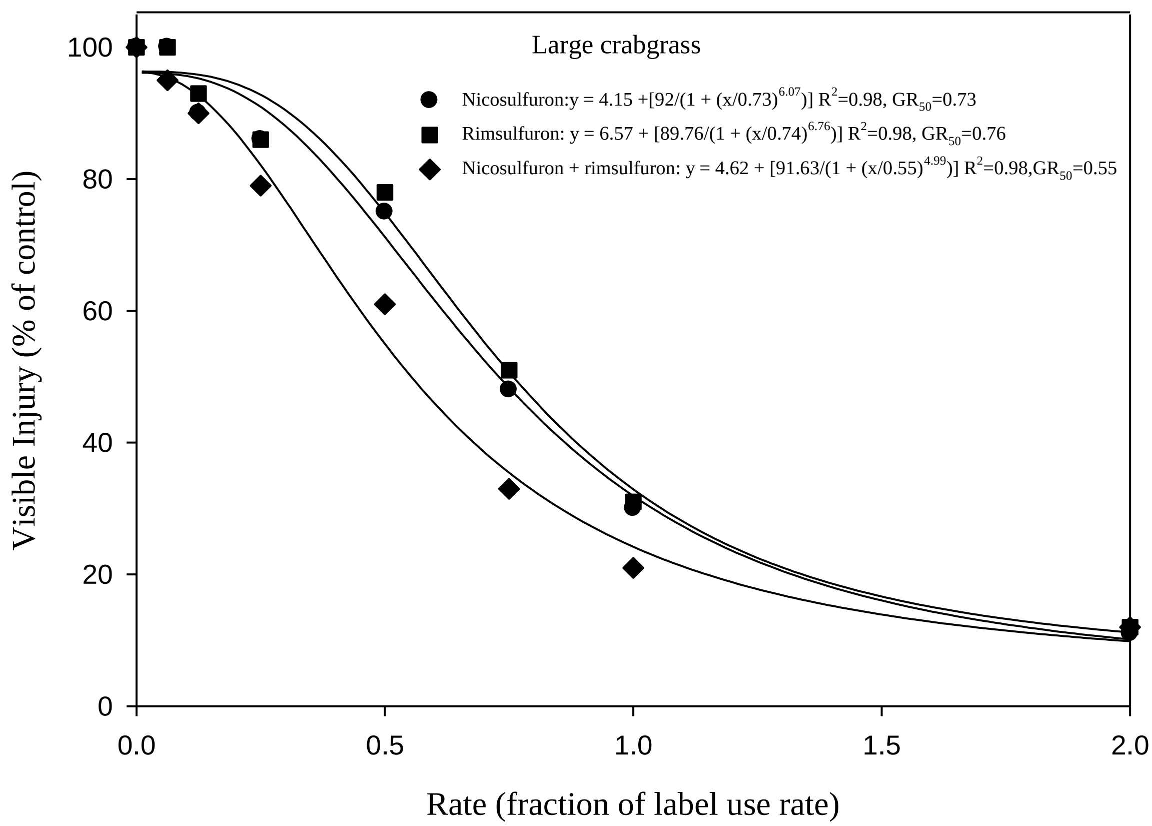

Large crabgrass
Nicosulfuron:y = 4.15 +[92/(1 + (x/0.73)^6.07)] R^2=0.98, GR50=0.73
Rimsulfuron: y = 6.57 + [89.76/(1 + (x/0.74)^6.76)] R^2=0.98, GR50=0.76
Nicosulfuron + rimsulfuron: y = 4.62 + [91.63/(1 + (x/0.55)^4.99)] R^2=0.98,GR50=0.55
Visible Injury (% of control)
0
20
40
60
80
100
0.0
0.5
1.0
1.5
2.0
Rate (fraction of label use rate)

Table 1. Nicosulfuron, rimsulfuron, and nicosulfuron + rimsulfuron absorption in barnyardgrass and large crabgrass 1, 3, and 7 d after treatment (DAT).[a]

	Barnyardgrass			Large crabgrass		
Herbicide	1 DAT	3 DAT	7 DAT	1 DAT	3 DAT	7 DAT
	% absorbed					
Nicosulfuron	38 ± 5	58 ± 4	71 ± 4	20 ± 2	41 ± 3	56 ± 4
Rimsulfuron	32 ± 4	57 ± 3	71 ± 3	19 ± 2	39 ± 3	57 ± 5
Nicosulfuron + rimsulfuron	42 ± 3	62 ± 3	74 ± 2	26 ± 2	48 ± 3	57 ± 4

[a] Table values are means ± standard error.

Table 2. Nicosulfuron, rimsulfuron, and nicosulfuron + rimsulfuron translocation in barnyardgrass and large crabgrass 1, 3, and 7 d after treatment (DAT).[a]

		Barnyardgrass			Large crabgrass		
Herbicide	Plant part	1 DAT	3 DAT	7 DAT	1 DAT	3 DAT	7 DAT
		% translocated					
Nicosulfuron	Other tiller	13 ± 2	21 ± 2	29 ± 4	13 ± 2	17 ± 3	18 ± 3
	Root	3 ± 1	5 ± 1	11 ± 2	2 ± 1	4 ± 1	8 ± 1
Rimsulfuron	Other tiller	17 ± 4	24 ± 2	25 ± 3	14 ± 2	18 ± 3	18 ± 2
	Root	3 ± 1	6 ± 2	11 ± 2	3 ± 1	4 ± 1	6 ± 1
Nicosulfuron + rimsulfuron	Other tiller	17 ± 1	26 ± 2	33 ± 3	16 ± 2	19 ± 3	21 ± 4
	Root	4 ± 1	6 ± 1	11 ± 1	3 ± 1	5 ± 1	9 ± 1

[a] Table values are means ± standard error.