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Research Article

Weed Control in Corn (*Zea mays* L.) as Influenced by Preemergence Herbicides

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Field studies were conducted in central and south-central Texas from 2013 through 2015 to evaluate crop tolerance and efficacy of various preemergence herbicides alone and in combination for weed control in field corn. Acetochlor and pendimethalin alone, *S*-metolachlor plus mesotrione, and the three-way combination of *S*-metolachlor plus atrazine plus mesotrione provided the most consistent control of annual grasses including browntop panicum (*Panicum fasciculatum* L.), Texas millet (*Urochloa texana* L.), barnyardgrass (*Echinochloa crus-galli* L.), and sprawling signalgrass (*Brachiaria reptans* L.). Palmer amaranth [*Amaranthus palmeri* (S.) Wats.] control was at least 90% with fluthiacet-methyl plus pyroxasulfone, atrazine plus either acetochlor, alachlor, dimethenamid-P, *S*-metolachlor, or *S*-metolachlor plus mesotrione, saflufenacil plus dimethenamid-P, and *S*-metolachlor plus mesotrione. Hophornbeam copperleaf (*Acalypha ostryifolia* L.) was difficult to control; however, acetochlor, saflufenacil or pyroxasulfone alone, saflufenacil plus dimethenamid-P, and *S*-metolachlor plus mesotrione provided at least 90% control. Acetochlor or saflufenacil alone, thiencarbazone-methyl plus isoxaflutole, dimethenamid-P plus atrazine, rimsulfuron plus mesotrione, and saflufenacil plus dimethenamid-P controlled common sunflower (*Helianthus annuus* L.) at least 90%. Corn injury was minimal (≤3%) with all herbicides. In general, corn grain yield was greatest with herbicide treatments containing more than one active ingredient compared with a single active ingredient.

1. Introduction

Corn (*Zea mays* L.) weed management programs in Texas have traditionally relied on preemergence (PRE) applications of a broadleaf and grass herbicide for residual season-long weed control. These PRE programs usually have included atrazine in combination for broad-spectrum weed control. Atrazine is used on greater than 60% of the US corn ha, with the dose decreasing over time with most doses of no more than 1.12 kg/ha, and some growers do not apply in excess of 0.84 kg/ha [1].

However, over the past twenty years the use of glyphosate-resistant corn has been rapidly adopted and used extensively in corn grown areas across the state [2]. In 2009, nearly 61 million ha of soybean [*Glycine max* (L.) Merr.], corn, and cotton (*Gossypium hirsutum* L.) in the US contained a modified 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS) gene that confers resistance to glyphosate [3]. The popularity of glyphosate-resistant crops, reduction of traditional herbicide and cultivation practices, and intense management of weeds using glyphosate as the predominant control strategy have caused a shift in weed populations [4, 5] and created a selective advantage for glyphosate-resistant weeds. Glyphosate-resistant weeds, specifically *Amaranthus* species, have become an issue across Texas and the US corn-producing areas [6, 7].

Atrazine and 4-hydroxyphenylpyruvate dioxygenase (HPPD) inhibiting herbicides are commonly used for weed control in corn and are effective in controlling glyphosate-resistant weeds, including *A. palmeri* [8–10]. Atrazine can be applied PRE or POST alone or in tank-mixtures with several herbicides [11]. The HPPD-inhibiting herbicides have become popular among corn growers because of their broad-spectrum weed control, flexible application timing, tank-mix compatibilities, and crop safety [11–13].

Amaranthus species are some of the most common weed species found in annual crop production throughout the US [14]. *A. palmeri* is not ranked as the number one weed or even as a principal weed in several major crops, but it is a common weed in many major crops around the world and in Texas [15]. Up till the 1990s its distribution in North America was the southern half of the US [16]; however, since then it has become established in every state with the exception of North Dakota and Minnesota [17]. In Texas, *A. palmeri* can be found in all areas of the state [18]. *A. palmeri* and *A. rudis* Sauer are the two *Amaranthus* species with confirmed resistance to glyphosate across Texas [19].

A. palmeri is a dioecious, summer-annual species that is native to the desert southwest region of the US [20, 21]. Despite its origin, *A. palmeri* is able to survive in many diverse environments because of its biological characteristics [7, 22]. It has a lengthy germination window and robust growth habit and is a prolific seed producer [22–25] and these characteristics make control of this weed difficult.

A. rudis is an obligate outcrossing annual broadleaf weed that is capable of long-distance pollen dispersal [26]. It germinates optimally between 20/25 and 30/35°C [27], has an aggressive growth habit, may grow 1.6 mm per growing degree day [24], and is capable of producing greater than 250,000 seeds per plant [22]. These factors make it a strong competitor with most crop plants.

Herbicide resistance complicates weed management in corn and many other crops. Estimates are that more than 1.2 million ha of cropland in the US is now affected by glyphosate-resistant *Amaranthus* species [28]. Also, weeds resistant to photosystem II- (PSII-) inhibiting herbicides, including atrazine, and HPPD-inhibiting herbicides have been documented [28]. Resistance to PSII inhibitors has been documented in seven monocot and 17 dicot species in the corn producing regions of the US [29].

The concerns pertaining to the overuse of atrazine including detection in surface and groundwater, rotational crop injury, and the development of triazine-resistant weeds as well as the increase in acreage with glyphosate-resistant weeds have resulted in questions from growers about the renewed use of PRE herbicides for early-season and possibly season-long weed control in corn. Although many relatively new soil-applied herbicides have been on the market for several years there is little field based information in the scientific literature on the efficacy of weeds commonly found in the south and central Texas corn growing regions. Therefore, the objective of this research was to evaluate the effect of various PRE herbicides for crop tolerance and weed control efficacy in these corn-producing regions.

2. Materials and Methods

Field studies were conducted during the 2013 through 2015 growing season in central Texas near Taylor (30.5326°N, 97.4548°W) and in south-central Texas near Ganado (29.0438°N, 96.4849°W). Study sites were located in different fields within the same general area of each year. Soils at the Taylor location were a Burleson clay (fine, montmorillonitic, thermic Udic Pellusterts) with less than 1% organic matter and 7.6 pH while soils at the Ganado location were a Houston Black clay (fine, montmorillonitic, thermic Udic Pellusterts) with less than 1% organic matter and 7.4 pH. Studies were arranged in a randomized complete block design with three replicates. Plot dimensions were two or four corn rows wide spaced 76 to 97 cm apart and 6.3 or 7.9 m long (depending on location). The corn hybrids BH 8846RR (2013), BH 8844VTTP (2014), and BH 8475SS (2015) were planted mid- to late-February near Taylor and late-February to early-March near Ganado in each year to a depth of 2.5 to 3.5 cm at the rate of 54,000 to 65,500 seeds/ha.

Herbicides were applied within 5 to 7 d after planting with a CO_2-pressurized backpack sprayer with Teejet 11002 flat fan nozzles (Spraying Systems Co., North Avenue and Schmale Road, Wheaton, IL 60188) using a pressure of 180 kPa and calibrated to deliver 140 or 187 L/ha (depending on location). Herbicide treatments are shown in Table 1. An untreated check was included for comparison at each location. All herbicide doses were based on the US label dose with the exception of the acetochlor (74.8% formulation) dose which was applied at 2x of the labeled rate throughout the study by mistake. Once the error was realized, it was decided to maintain this dose throughout the study.

Weed populations varied from year to year and were from naturally occurring populations. At the Taylor location, *Panicum fasciculatum* populations in 2013 were moderate (3 to 4 plants/m^2) while in 2014 populations were higher (6 to 8 plants/m^2). *Echinochloa crus-galli* populations in 2015 ranged from 4 to 8 plants/m^2. At Ganado, *Urochloa texana* populations ranged from 6 to 10 plants/m^2. *Brachiaria reptans* populations were moderate to heavy (5 to 10 plants/m^2). *A. palmeri* populations varied from 4 to 8 plants/m^2 at the Taylor location to 2 to 10 plants/m^2 at the Ganado location. *Acalypha ostryifolia* populations at Taylor in both years were low to moderate (2 to 6 plants/m^2) while *Helianthus annuus* populations ranged from 2 to 6 plants/m^2 depending on the year. Crop injury and weed control were visually estimated on a scale of 0 to 100 (0 indicating no control or injury and 100 indicating complete control or plant death). Crop injury consisted of plant stunting and early-season (30 d after herbicide application) and late-season (95 to 140 d after application) crop injury was taken. Late-season weed control ratings (95 to 140 days after herbicide application) are presented for all weeds with the exception of *A. palmeri* control at Ganado in 2015 where populations of this weed were low (<4 plants/m^2) and somewhat inconsistent. Crop yield was determined by hand harvesting 3.8 m of each plot, shelling the kernels from the corn ear, and then weighing the kernels. Crop weights were adjusted to 12% moisture.

Visual estimates of weed control and corn injury were arcsine square root transformed prior to analysis of variance. Data are presented in their original form since the transformation did not alter interpretation. Means were compared with Fisher's Protected LSD test at the 5% probability level [30]. The nontreated check was not included in the weed control or corn injury analysis but was included in corn yield analysis.

Table 1: Herbicides, composition, and manufacturer.

Common name	Trade name	Composition (%)	Manufacturer
Atrazine (A)	AAtrex	42.0	Syngenta Crop Protection
S-Metolachlor (S)	Dual Magnum	83.6	Syngenta Crop Protection
(S) + (A)	Bicep II Magnum	26.1 + 33.0	Syngenta Crop Protection
Mesotrione (M)	Callisto	40.0	Syngenta Crop Protection
(A) + (S)+ (M) + bicyclopyrone	Acuron	10.93 + 23.4 + 2.6 + 0.65	Syngenta Crop Protection
Fluthiacet-methyl (F) + pyroxasulfone (P)	Anthem	0.69 + 22.61	FMC Corporation
(F) + (P) + (A)	Anthem ATZ	0.15 + 5.15 + 42.5	FMC Corporation
Isoxaflutole	Balance Flexx	20.0	Bayer CropScience
Alachlor + (A)	Bullet	25.4 + 14.5	Monsanto Company
Thiencarbazone-methyl + isoxaflutole	Corvus	7.6 + 19.0	Bayer CropScience
Acetochlor + (A)	Degree Xtra	29.0 + 14.5	Monsanto Company
Dimethenamid-P + (A)	Guardsman Max	18.2 + 35.3	BASF Corporation
Acetochlor (74.8% formulation)	Harness	75.9	Monsanto Company
Rimsulfuron + (M)	Instigate	4.17 + 41.67	DuPont Crop Protection
Rimsulfuron + thifensulfuron-methyl	Leadoff	16.7 + 16.7	DuPont Crop Protection
(S) + (A) + (M)	Lexar	19.0 + 19.0 + 2.44	Syngenta Crop Protection
Dimethenamid-P	Outlook	63.9	BASF Corporation
Pendimethalin	Prowl H_2O	38.7	BASF Corporation
Saflufenacil	Sharpen	29.74	BASF Corporation
Saflufenacil + dimethenamid-P	Verdict	6.24 + 55.04	BASF Corporation
Acetochlor (33% formulation)	Warrant	33.3	Monsanto Company
(S) + (M)	Zemax	36.8 + 3.68	Syngenta Crop Protection
(P)	Zidua	85.0	BASF Corporation

Table 2: Rainfall amounts at test locations for twenty-one days following application of PRE herbicides.

Day	2013		2014		2015	
	Taylor	Ganado	Taylor	Ganado	Taylor	Ganado
			Mm			
1–7	29.5	0	2.8	0	7.4	3.3
8–14	6.6	0	0.5	18.6	65.6	78.2
15–21	7.3	0	0	0	0	3.3

3. Results and Discussion

Since not all treatments were included in each year of the study no attempt was made to combine results over years or locations. Also, rainfall amounts varied from site to site and year to year affecting herbicide response (Table 2). Rainfall during the 7 d after the PRE herbicide treatments occurred at all locations with the exception of Ganado in 2013 and 2014 when no rainfall occurred. Rainfall between 8 and 14 d after the PRE application varied from no rainfall at Ganado in 2013 to 78.2 mm at Ganado in 2015 (Table 2). Rainfall 15 to 21 d after the PRE application was low at Taylor in 2013 and Ganado in 2015 and there was no rainfall at the other sites.

With respect to the annual grasses, *Panicum fasciculatum* and *Urochloa texana* were present in 2013 and 2014 at the Taylor and Ganado sites while *Echinochloa crus-galli* and *Brachiaria reptans* were present only in 2015 at Taylor and Ganado. All broadleaf weeds were present at the Taylor and Ganado locations. *A. palmeri* was present in 2013 and 2015 while *Acalypha ostryifolia* and *Helianthus annuus* were present in 2013 and 2014.

3.1. Annual Grass Control

Brachiaria reptans (Sprawling Signalgrass). This weed was present at Ganado only in 2015. Atrazine alone provides only 40% control while the high rate of acetochlor (at the 74.8% formulation) provided perfect control (Table 3). *S*-Metolachlor alone, fluthiacet-methyl plus pyroxasulfone, thiencarbazone-methyl plus isoxaflutole, dimethenamid-P plus atrazine, or *S*-metolachlor plus mesotrione controlled this weed 93 to 99% while dimethenamid-P alone, fluthiacet-methyl plus pyroxasulfone plus atrazine, *S*-metolachlor plus atrazine, or saflufenacil plus dimethenamid-P provided 82 to 87% control. Taylor-Lovell and Wax [31] and Johnson et al. [32] reported that isoxaflutole did not improve *Setaria faberi* control when compared with atrazine plus *S*-metolachlor.

Echinochloa crus-galli (Barnyardgrass). This weed was present at Taylor only in 2015. Atrazine alone controlled barnyardgrass 33% while acetochlor (74.8% formulation) or pendimethalin alone, acetochlor plus atrazine, *S*-metolachlor plus mesotrione, or *S*-metolachlor plus atrazine plus mesotrione provided 90 to 97% control (Table 3). The dinitroaniline herbicides, such as pendimethalin, are registered for use in over forty crops [33]. These herbicides usually provide excellent control of annual grasses [34–36].

Table 3: Annual grass control in corn with PRE herbicides.

Treatment	Dose Product/ha[b]	PANFA[a] 2013 Taylor	PANFA 2014 Taylor	UROTE 2013 Ganado	UROTE 2014 Ganado	ECHCG 2015 Taylor	BRARE 2015 Ganado
		Days after treatment					
		95	138	109	112	101	42
		%					
Atrazine (A)	2.34 L	33	3	23	0	33	40
Fluthiacet-methyl + pyroxasulfone (P)	0.75 L	—	—	—	—	58	99
Fluthiacet-methyl + (P) + (A)	2.62 L	—	—	—	—	40	86
S-Metolachlor (S)	1.59 L	82	57	78	75	68	93
Isoxaflutole	0.47 L	80	38	94	80	67	65
(S) + (A)	4.96 L	85	53	86	83	63	82
Alachlor + (A)	8.23 L	99	—	89	—	—	—
Mesotrione (M)	0.47 L	37	8	53	88	55	10
Thiencarbazone-methyl + isoxaflutole	0.19 L	47	15	98	72	73	93
Acetochlor + (A)	8.23 L	72	0	98	86	90	72
(S) + (A) + (M) + bicyclopyrone	2.90 L	—	—	—	—	65	65
Dimethenamid-P + (A)	4.12 L	55	45	85	58	89	97
Acetochlor (74.8%)	8.23 L	—	83	—	73	97	100
Rimsulfuron + (M)	0.47 L	60	33	77	47	—	—
Rimsulfuron + thifensulfuron-methyl	0.09 L	74	10	60	61	40	47
(S) + (A) + (M)	7.02 L	98	44	83	73	92	76
Dimethenamid-P	1.22 L	78	53	55	63	73	87
Pendimethalin	3.55 L	96	52	86	99	97	58
Saflufenacil	0.19 L	69	7	81	23	33	78
Saflufenacil + dimethenamid-P	1.12 L	61	28	92	78	57	83
Acetochlor (33%)	3.55 L	75	10	78	96	63	49
(S) + (M)	7.02 L	98	65	67	95	96	94
(P)	210.16 G	88	37	75	99	42	78
Untreated	—	0	0	0	0	0	0
LSD (0.05)		33	33	22	48	29	33

[a]Bayer code for weeds: BRARE: *Brachiaria reptans* L.; ECHCG, *Echinochloa crus-galli* L.; PANFA, *Panicum fasciculatum* L.; UROTE, *Urochloa texana* (Buckl.) R. Webster.
[b]L = liters; G = grams.

Panicum fasciculatum (Browntop Panicum). In 2013, pendimethalin alone, alachlor plus atrazine, *S*-metolachlor plus mesotrione, or *S*-metolachlor plus atrazine plus mesotrione provided 96% or better browntop panicum control while isoxaflutole, *S*-metolachlor, and pyroxasulfone alone and *S*-metolachlor plus atrazine controlled this weed 80 to 88% (Table 3). In 2014, only acetochlor (74.8% formulation) provided acceptable control (83%). The lack of effective control in 2014 can be attributed to higher plant populations at the test site in 2014 compared to 2013 and also the low rainfall amounts after PRE application in 2014 (Table 2). Since many of the PRE herbicides can volatilize and photodegrade on the soil surface over time, these herbicides need to be mechanically incorporated or need rainfall or irrigation to move these herbicides into the weed seed zone [37–39] which explains the erratic control noted with these herbicides under the drought conditions observed at Taylor in 2014.

Urochloa texana (Texas Millet). In 2013, atrazine alone controlled only 23% while isoxaflutole alone, thiencarbazone-methyl plus isoxaflutole, acetochlor plus atrazine, or saflufenacil plus dimethenamid-P controlled *U. texana* at least 92% (Table 3). Pendimethalin or saflufenacil alone, atrazine plus either *S*-metolachlor, alachlor, or dimethenamid-P, and the three-way combination of *S*-metolachlor plus atrazine plus mesotrione provided 81 to 89% control. In 2014, acetochlor, pendimethalin, or pyroxasulfone alone or *S*-metolachlor plus mesotrione controlled this weed at least 95% while isoxaflutole or mesotrione alone and atrazine plus either acetochlor or *S*-metolachlor provided 80 to 89% control (Table 3).

S-Metolachlor alone provided 75 to 78% *U. texana* control compared with 75 to 99% control with pyroxasulfone. Typically, *S*-metolachlor alone provides poor control of this weed [40, 41]. With high populations of *U. texana*, Grichar et al. [40] reported less than 70% control with 1.7 and 3.4 kg/ha

Table 4: *Amaranthus palmeri* control in corn with PRE herbicides.

Treatment	Dose Product/ha[a]	2013 Taylor	2013 Ganado	2015 Taylor	2015 Ganado
		Days after treatment			
		95	109	101	44
		%			
Atrazine (A)	2.34 L	73	99	79	72
Fluthiacet-methyl (F) + pyroxasulfone (P)	0.75 L	—	—	99	98
(F) + (P) + (A)	2.62 L	—	—	40	93
Isoxaflutole	0.47 L	100	98	51	67
S-Metolachlor (S)	1.59 L	100	76	99	69
(S) + (A)	4.96 L	100	99	99	92
Alachlor + (A)	8.23 L	100	99	—	—
Mesotrione (M)	0.47 L	99	61	71	52
Thiencarbazone-methyl + isoxaflutole	0.19 L	100	92	99	83
(S) + (A) + (M) + bicyclopyrone	2.90 L	—	—	99	72
Acetochlor + (A)	8.23 L	100	100	99	93
Dimethenamid-P + (A)	4.12 L	100	100	99	95
Acetochlor (74.8%)	8.23 L	—	—	100	100
Rimsulfuron + (M)	0.47 L	100	27	—	—
Rimsulfuron + thifensulfuron-methyl	0.09 L	99	90	98	37
(S) + (A) + (M)	7.02 L	100	97	99	90
Dimethenamid-P	1.22 L	98	53	96	92
Pendimethalin	3.55 L	97	83	98	47
Saflufenacil	0.19 L	99	72	70	73
Saflufenacil + dimethenamid-P	1.12 L	100	95	99	100
Acetochlor (33%)	3.55 L	100	50	99	88
(S) + (M)	7.02 L	100	91	100	94
(P)	210.16 G	100	91	99	84
Untreated	—	0	0	0	0
LSD (0.05)		17	27	22	24

[a]L = liters; G = grams.

of metolachlor in dryland peanut (*Arachis hypogaea* L.) and 25 to 76% control under irrigated conditions. Steele et al. [41] reported that pyroxasulfone, at a 10-fold lower use rate than *S*-metolachlor, controlled *U. texana* 84 to 96% while *S*-metolachlor provided 75 to 85% control when rated 9 weeks after treatment. They attributed the results to the longer residual activity of pyroxasulfone [42].

3.2. Broadleaf Weed Control

Amaranthus palmeri (Palmer Amaranth). At Taylor in 2013, under moderate weed pressure (4 plants/m^2), all herbicides, with the exception of atrazine (73%), provided at least 97% control while in 2015 under higher populations (8 plants/m^2), atrazine controlled 79% while isoxaflutole, mesotrione, or saflufenacil controlled this weed no better than 71% (Table 4). All other herbicide treatments provided at least 96% control.

At the Ganado location, in 2013 and 2015, control was more erratic than at the Taylor location. This may be due to the higher weed populations noted in 2013 (10 plants/m^2) and variable populations in 2015. In 2013, either atrazine or isoxaflutole alone, acetochlor, alachlor, *S*-metolachlor, or dimethenamid plus atrazine or the three-way combination of *S*-metolachlor plus atrazine plus mesotrione provided 97 to 100% *A. palmeri* control while mesotrione, dimethenamid-P, or acetochlor (33%) alone and rimsulfuron plus mesotrione controlled this weed 61% or less (Table 4). In 2015, acetochlor (74.8%) alone, dimethenamid-P plus atrazine, fluthiacet-methyl plus pyroxasulfone, and saflufenacil plus dimethenamid-P controlled *A. palmeri* at least 95% while isoxaflutole, mesotrione, *S*-metolachlor, and pendimethalin alone and rimsulfuron plus thifensulfuron-methyl controlled less than 70%.

In previous research, mesotrione applied PRE controlled *Amaranthus hybridus* L. but control of *Ipomoea* spp. and *Chenopodium album* L. was inconsistent and dependent upon a timely rainfall following application [43–45]. Armel et al. [43] reported improved weed control with mixtures of

Table 5: *Acalypha ostryifolia* and *Helianthus annuus* control in corn with PRE herbicides.

Treatment	Dose Product/ha[b]	ACCOS[a]		HELAN	
		2013	2014	2013	2014
		Days after treatment			
		95	109	95	48
		%			
Atrazine	2.34 L	38	80	73	77
Isoxaflutole	0.47 L	77	98	100	79
S-Metolachlor + atrazine	4.96 L	76	90	100	85
Alachlor + atrazine	8.23 L	93	—	98	—
Mesotrione	0.47 L	55	60	99	60
Thiencarbazone-methyl + isoxaflutole	0.19 L	100	77	98	100
Acetochlor + atrazine	8.23 L	79	—	99	—
S-Metolachlor	1.59 L	79	83	97	77
Dimethenamid-P + atrazine	4.12 L	80	72	97	93
Acetochlor (74.8% formulation)	8.23 L	—	99	—	97
Rimsulfuron + mesotrione	0.47 L	60	67	97	93
Rimsulfuron + thifensulfuron-methyl	0.09 L	98	70	87	99
S-Metolachlor + atrazine + mesotrione	7.02 L	98	74	100	87
Dimethenamid-P	1.22 L	72	82	97	79
Pendimethalin	3.55 L	69	85	95	58
Saflufenacil	0.19 L	96	98	100	90
Saflufenacil + dimethenamid-P	1.12 L	99	98	100	97
Acetochlor (33% formulation)	3.55 L	92	63	100	72
S-Metolachlor + mesotrione	7.02 L	92	93	99	98
Pyroxasulfone	210.16 G	96	93	97	55
Untreated	—	0	0	0	0
LSD (0.05)		34	30	20	36

[a]Bayer code for weeds: ACCOS: *Acalypha ostryifolia* Riddell; HELAN: *Helianthus annuus* L.
[b]L = liters; G = grams.

mesotrione plus acetochlor or atrazine over that of mesotrione alone. As seen in this study, the combination of mesotrione with metolachlor plus atrazine has enhanced weed control in other studies [43].

Acalypha ostryifolia (Hophornbeam Copperleaf). In 2013, thiencarbazone-methyl plus isoxaflutole provided perfect control (100%) while acetochlor (33% formulation), saflufenacil or pyroxasulfone alone, alachlor plus atrazine, rimsulfuron plus thifensulfuron-methyl, *S*-metolachlor plus atrazine plus mesotrione, saflufenacil plus dimethenamid-P, and *S*-metolachlor plus mesotrione controlled this weed at least 92% (Table 5). Atrazine and mesotrione alone and rimsulfuron plus mesotrione provided unacceptable control (≤60%).

In 2014, either acetochlor (74.8% formulation), isoxaflutole, saflufenacil, or pyroxasulfone alone controlled *A. ostryifolia* at least 93% (Table 5). The combinations of *S*-metolachlor plus either atrazine or mesotrione and saflufenacil plus dimethenamid-P controlled this weed 90 to 98% while rimsulfuron plus either mesotrione or thifensulfuron-methyl and acetochlor (33% formulation) provided 63 to 70% control.

Helianthus annuus (Common Sunflower). In 2013 under low weed pressure (2 to 3 plants/m^2), all herbicides with the exception of atrazine alone (73%) and rimsulfuron plus thifensulfuron-methyl (87%) controlled this weed at least 95% (Table 5). In 2014, under slightly higher weed populations (4 to 6 plants/m^2) control was more variable. Acetochlor (74.8% formulation) alone, thiencarbazone-methyl plus isoxaflutole, rimsulfuron plus thifensulfuron-methyl, saflufenacil plus dimethenamid-P, and *S*-metolachlor plus mesotrione controlled this weed at least 97%. Mesotrione, pendimethalin, or pyroxasulfone alone provided unacceptable control (≤60%).

The development of ALS-resistant *H. annuus* has limited the options for growers having to control this weed with POST herbicides [46, 47]. Results from this study are consistent with previous findings that *H. annuus* control with herbicide systems containing isoxaflutole was at least 85% [32, 47].

3.3. Corn Injury and Yield. Grain yields were obtained only in 2013 at both locations and 2015 at Taylor due to late-season time constraints.

Table 6: Corn yield as influenced by herbicides.

Treatment	Dose Product/ha[a]	2013 Taylor	2013 Ganado	2015 Taylor
		kg/ha		
Fluthiacet-methyl (F) + pyroxasulfone (P)	0.75 L	—	—	9342
(F) + (P) + atrazine	2.62 L	—	—	8092
Atrazine	2.34 L	5586	7695	7556
Isoxaflutole	0.47 L	5434	6980	7669
S-Metolachlor + atrazine	4.96 L	5396	7627	8582
Alachlor + atrazine	8.23 L	4940	7466	—
Mesotrione	0.47 L	4851	7727	8970
Thiencarbazone-methyl + isoxaflutole	0.19 L	5256	7318	9494
Acetochlor + atrazine	8.23 L	4915	7031	8899
S-Metolachlor	1.59 L	5143	7082	8806
Dimethenamid-P + atrazine	4.12 L	5294	8350	9611
Acetochlor (74.8%)	8.23 L	—	—	8738
Rimsulfuron + mesotrione	0.47 L	4972	8295	—
Rimsulfuron + thifensulfuron-methyl	0.09 L	5168	7991	7934
S-Metolachlor + atrazine + mesotrione	7.02 L	5589	8556	9962
Dimethenamid-P	1.22 L	5275	7172	9447
Pendimethalin	3.55 L	5264	7881	8958
Saflufenacil	0.19 L	4524	8311	7477
Saflufenacil + dimethenamid-P	1.12 L	4906	7495	9377
Acetochlor (33%)	3.55 L	5099	8310	8691
S-Metolachlor + mesotrione	7.02 L	5501	6160	8695
Pyroxasulfone	210.16 G	5346	7548	9691
Untreated	—	4506	6816	8218
LSD (0.05)		796	1800	1969

[a]L = liters; G = grams.

Corn Injury. Early-season crop injury consisted of stunting and was never more than 3% with any herbicide treatment (including the 2x rate of acetochlor). Corn recovered from the slight early-season stunting and typically by harvest no differences in corn plant growth between the untreated check and any herbicide treatments were noted (data not shown). Although no appreciable crop injury was noted in these studies this is not always true. Instances of isoxaflutole phytotoxicity in corn have been documented [31, 32] and attributed to several factors, including application timing [48], high use rate [49], and varied susceptibility of corn hybrids to isoxaflutole [50]. Environmental factors (cool and wet) and soil characteristics [49] can also lead to corn injury by isoxaflutole. Johnson et al. [32] reported that preplant incorporated herbicide applications resulted in greater injury than PRE applications and this was probably due to high amount of precipitation. Armel et al. [43] reported that acetochlor, atrazine, or mesotrione combinations caused 11 to 18% corn stunting when followed by 32 mm of rainfall but that the corn recovered quickly and by four weeks after treatment injury did not exceed 2%.

Corn Yield. In 2013 at the Taylor location, atrazine, isoxaflutole, and pyroxasulfone alone and *S*-metolachlor plus either atrazine or mesotrione produced grain yields that were greater than the untreated check (Table 6). Despite not being significant, all herbicide treatments resulted in a numerical increase in grain yield over the untreated check. At the Ganado location, grain yields from the herbicide treatments were not significantly different from the untreated check; however, all yields from the herbicide treatments were numerically higher than the untreated check with the exception of *S*-metolachlor plus mesotrione which produced a 10% decrease in yield from the untreated check. No reason for this reduction can be determined.

In 2014, no significant differences between the untreated check and any herbicide treatments were noted although several herbicide treatments produced numerically higher yields than the untreated check (Table 5). Dimethenamid-P and pyroxasulfone alone, fluthiacet-methyl plus pyroxasulfone, thiencarbazone-methyl plus isoxaflutole, dimethenamid-P plus atrazine, *S*-metolachlor plus atrazine plus mesotrione, and saflufenacil plus dimethenamid-P produced grain yields that were 14 to 21% greater than the untreated check.

With glyphosate-resistant *Amaranth* spp. becoming more widespread throughout the state, the use of soil-applied herbicides can not only control resistant weed species in glyphosate-resistant corn production systems but also reduce the risk of new herbicide-resistant weed species occurring. In general, many treatments with two or three herbicides provided better weed control than one herbicide alone and the chance of corn injury appears to be minimal with any herbicide combinations under normal growing conditions. Our results indicate that in a year with little or no rainfall within 7 to 14 d after PRE herbicide application any combination of PRE herbicides may need to be followed by POST herbicides for control of escaped weeds.

Competing Interests

The authors declare that there are no competing interests regarding publication of this paper.

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