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Tank Mixing Pendimethalin with Pyroxasulfone and Chloroacetamide Herbicides Enhances In-Season Residual Weed Control in Corn

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Kochia, common lambsquarters, and wild buckwheat are major problem weeds in glyphosate-resistant corn production in the northern Great Plains of the United States. Field research was conducted in 2011 and 2012 near Huntley, MT to investigate effective PRE herbicides applied alone or in premixes with or without tank-mixed pendimethalin for extended in-season residual control of the selected broadleaf weeds in glyphosate-resistant corn. Control of kochia, common lambsquarters, and wild buckwheat with recently registered herbicide premixes, including saflufenacil + dimethenamid-P and *S*-metolachlor + mesotrione, was as high as 95 and 90% at 21 and 63 d after treatment (DAT), and mostly similar to the standard atrazine treatment. Residual control of common lambsquarters and wild buckwheat from pyroxasulfone was higher at 298 compared with 149 g ai ha^{-1} rate. Pyroxasulfone and other chloroacetamide herbicides (acetochlor or dimethenamid-P) applied alone failed to provide greater than 79, 70, and 54% residual control at 21, 35, and 63 DAT, respectively, of the weed species investigated. Residual weed control throughout the growing season was significantly improved with the addition of pendimethalin to pyroxasulfone (149 g ha^{-1}), acetochlor, or dimethenamid-P when compared with any of the three herbicides applied alone. Kochia control by pyroxasulfone, acetochlor, or dimethenamid-P tank mixed with pendimethalin was as high as 94, 92, and 81% at 21, 35, and 63 DAT, respectively. Control of common lambsquarters with the addition of pendimethalin to pyroxasulfone or acetochlor was improved to 94, 89, and 81% at 21, 35, and 63 DAT, respectively. Similarly, wild buckwheat control with acetochlor plus pendimethalin was improved to 87, 85, and 82% at 21, 35, and 63 DAT, respectively. Consistent with the extended in-season (up to 9 wk) residual weed control, pyroxasulfone, acetochlor, or dimethenamid-P treatments when tank mixed with pendimethalin had higher corn yields compared with the herbicides applied alone. The investigation on residual herbicides that provide extended in-season weed control should be continued as an important aspect of glyphosate stewardship and to mitigate the occurrence of glyphosate-resistant weed populations in grower fields.
Nomenclature: Acetochlor; dimethenamid-P; pyroxasulfone; saflufenacil + dimethenamid-P; *S*-metolachlor + mesotrione; atrazine; pendimethalin; kochia, *Kochia scoparia* (L.) Schard.; common lambsquarters, *Chenopodium album* L.; wild buckwheat, *Polygonum convolvulus* L.; corn, *Zea mays* L.
Key words: Glyphosate-resistant corn, herbicide efficacy, herbicide resistance management, preemergence, residual weed control.

Kochia scoparia, *Chenopodium album*, y *Polygonum convolvulus* son malezas problemáticas en la producción de maíz resistente a glyphosate en las Grandes Planicies del Norte de Estados Unidos. En 2011 y 2012, se realizó una investigación de campo en Huntley, Montana, para investigar herbicidas efectivos PRE aplicados solos o en premezclas con o sin pendimethalin mezclada en tanque para el control residual de malezas de hoja ancha extendido durante la temporada de crecimiento en maíz resistente a glyphosate. El control de *K. scoparia*, *C. album*, y *P. convolvulus* con premezclas de herbicidas recientemente registradas, incluyendo saflufenacil + dimethenamid-P y *S*-metolachlor + mesotrione, alcanzó 95 y 90% a 21 y 63 d después del tratamiento, y fue similar al tratamiento estándar con atrazine. El control residual de *C. album* y de *P. convolvulus* con pyroxasulfone fue mayor con la dosis de 278 que con la de 149 g ai ha^{-1}. Pyroxasulfone y otros herbicidas de tipo chloroacetamide (acetochlor o dimethenamid-P) aplicados solos, fallaron en brindar un control residual de las especies investigadas superior a 79, 70, y 54% a 21, 35, y 63 DAT, respectivamente. El control residual durante la temporada de crecimiento mejoró significativamente con la adición de pendimethalin a pyroxasulfone (149 g ha^{-1}), acetochlor, o dimethenamid-P, cuando se comparó con cualquiera de los tres herbicidas aplicados solos. El control de *K. scoparia* con pyroxasulfone, acetochlor, o dimethenamid-P mezclados en tanque con pendimethalin alcanzó 94, 92, y

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81% a 21, 35, y 63 DAT, respectivamente. La adición de pendimethalin a pyroxasulfone o acetochlor incrementó el control de *C. album* a 94, 89, y 81% a 21, 35, y 63 DAT, respectivamente. En forma similar, el control de *P. convolvulus* con acetochlor más pendimethalin mejoró a 87, 85, y 82%, a 21, 35, y 63 DAT, respectivamente. Consistentemente con el control residual extendido de malezas durante la temporada (hasta 9 semanas), los tratamientos de pyroxasulfone, acetochlor, o dimethenamid-P, mezclados en tanque con pendimethalin tuvieron mayores rendimientos de maíz al compararse con los herbicidas aplicados solos. La investigación de herbicidas residuales que brinden un control residual extendido durante la temporada de crecimiento debería continuar como un aspecto importante del buen uso y mantenimiento de glyphosate y para mitigar la aparición de poblaciones de malezas resistente a glyphosate en los campos de los productores.

Weed management is one of the major production challenges for corn growers (Parker et al. 2006; Rajcan et al. 2004). Kochia, common lambsquarters, and wild buckwheat are problem broadleaf weeds in corn production in the northern Great Plains (NGP) of the United States. If not controlled early, these weeds can reduce corn yields by 30 to 69% (Hall et al. 1992; King and Garcia 2008; Wicks et al. 1993).

Glyphosate-resistant corn is grown on approximately 90% of the U.S. corn hectares (USDA-ERS 2014). Overreliance on glyphosate for weed control in glyphosate-resistant crops has caused weed population shifts to species that vary in their natural susceptibility to glyphosate, including common lambsquarters and wild buckwheat (Shaner 2000; Wilson et al. 2007). Additionally, the widespread occurrence of glyphosate-resistant weeds is a major concern for producers, with a total of 14 weed species that evolved resistance to glyphosate in the United States (Heap 2014). The recent evolution of glyphosate-resistant kochia is an increasing concern for producers in the NGP, including Montana (Heap 2014; Kumar et al. 2014).

Soil-applied PRE herbicides can potentially reduce reliance on glyphosate in glyphosate-resistant crops (Culpepper 2006; Norsworthy et al. 2012). Effective PRE herbicides in corn can minimize early-season weed interference by controlling weed cohorts that emerge with corn (King and Garcia 2008; Parker et al. 2006). Atrazine, *S*-metolachlor, acetochlor, and isoxaflutole are the PRE-applied herbicides most used by corn growers for many years because of their effectiveness and low cost (Swanton et al. 2002); however, potential movement of the herbicides into groundwater and herbicide losses in surface water runoff are the major concerns. Furthermore, the occurrence of atrazine-resistant weeds including kochia and common lambsquarters (Radosevich 1977; Wicks et al. 1993) in the NGP warrants investigation of alternative PRE herbicide chemistries for weed control in corn.

Pyroxasulfone is a relatively new herbicide that acts as a root/shoot growth inhibitor in germinating seedlings of susceptible weeds (Tanetani et al. 2009), and is registered as a PRE herbicide in corn. Pyroxasulfone applied PRE in corn controls broadleaf weeds such as Palmer amaranth (*Amaranthus palmeri* S. Wats.), velvetleaf (*Abutilon theophrasti* Medicus), tall waterhemp [*Amaranthus tuberculatus* (Moq.)], common lambsquarters, and common ragweed (*Ambrosia artemisiifolia* L.) (Knezevic et al. 2009; Nurse et al. 2011; Steele et al. 2005). In previous research, residual control of Palmer amaranth, velvetleaf, and common ragweed with pyroxasulfone was superior to chloroacetamide herbicides (seedling root/shoot growth inhibitor) such as *S*-metolachlor and acetochlor (Geier et al. 2006; Steele et al. 2005).

S-Metolachlor + mesotrione (4-hydroxyphenylpyruvate dioxygenase inhibitor) is a new premix registered for PRE/POST weed control in corn. Although mesotrione alone PRE at 150 to 310 g ai ha^{-1} controls certain broadleaf weeds such as smooth pigweed (*Amaranthus hybridus* L.) and common lambsquarters, efficacy and spectrum of weed control can be enhanced when used in conjunction with *S*-metolachlor (Armel et al. 2003; Whaley et al. 2009).

Saflufenacil plus dimethenamid-P is a premix recently registered for PRE weed control in corn. Saflufenacil is a protoporphyrinogen IX oxidase-inhibiting herbicide with POST and soil-residual activity (Grossman et al. 2010), and dimethenamid-P is a chloroacetamide herbicide that acts as a seedling shoot growth inhibitor (Anonymous 2005). Saflufenacil + dimethenamid-P applied PRE at low-use rates of 115 to 325 g ai ha^{-1} controls broadleaf weeds such as wild mustard (*Sinapis arvensis* L.) and *Amaranthus* species (Moran et al. 2011; Odero et al. 2014); however, rates as

Table 1. Monthly mean temperature and precipitation totals during the 2011 and 2012 growing seasons near Huntley, MT.

	Temperature		Total precipitation	
Month	2011	2012	2011	2012
	C		mm	
March	2.9	7.7	20.1	44.9
April	6.0	9.8	68.6	22.6
May	10.6	12.6	237.5	82.3
June	16.9	19.8	39.1	9.9
July	23.2	25.2	67.3	12.2
August	22.7	22.2	16.0	9.1
September	17.0	17.0	6.4	0.5
October	10.5	7.5	54.1	51.0

high as 933 g ha^{-1} (higher than the recommended rate of 735 g ha^{-1} in corn) are needed to improve residual control of certain broadleaf weeds such as common ragweed (Moran et al. 2011).

Pendimethalin, a microtubule assembly inhibitor, is labeled for PRE application in corn. Pendimethalin was found more effective for controlling certain broadleaf weeds such as common lambsquarters when compared with *S*-metolachlor or acetochlor (Chomas and Kells 2004). There is limited information in the literature on the effectiveness of relatively new herbicides including pyroxasulfone, saflufenacil + dimethenamid-P premix, and *S*-metolachlor + mesotrione premix for controlling kochia, common lambsquarters, and wild buckwheat in corn. Utilizing these new soil-residual herbicides in conjunction with the standard products such as pendimethalin would add diversity (multiple modes of action) to the weed-control program in glyphosate-resistant corn. The objective of this research was to compare effectiveness of selected PRE herbicides applied alone or in combination with pendimethalin for extended in-season residual control of broadleaf weeds, and their impact on grain yield in glyphosate-resistant corn.

Materials and Methods

Field experiments were conducted in 2011 and 2012 at the Montana State University Southern Agricultural Research Center near Huntley, MT. The soil type was a Fort Collins clay loam (fine-loamy, mixed, superactive, mesic Aridic Haplustalfs) with 2.8% organic matter and pH of 7.8. Seedbed preparation at the test site included fall disking followed by two passes of a field cultivator and a cultipacker in the spring before corn planting. Glyphosate-resistant corn hybrid (DK36-30 RR) was planted in 76-cm row spacing at a rate of 86,500 seeds ha^{-1} on May 18, 2011 and May 20, 2012. Plots were 3 m wide by 9 m long. Corn was lightly cultivated to make the furrows approximately 4 to 5 wk after corn emergence for flood irrigation. Plots were irrigated three times during the growing season. Corn was fertilized with nitrogen–phosphorous–potash as per the local standards. The test plots each year were uniformly infested with kochia, common lambsquarters, and wild buckwheat. Monthly mean air temperatures and precipitation totals in 2011 and 2012 at the study location are shown in Table 1.

PRE herbicide treatments (Table 2) were applied within 1 d after corn planting using a CO_2-pressurized backpack sprayer equipped with flat-fan spray nozzles (TeeJet TP8001, Wheaton, IL 60189) calibrated to deliver 94 L ha^{-1} at 276 kPa. A nontreated control was included for comparison. Weed densities were recorded 60 DAT within two 0.5-m^2 quadrats placed between the center two rows of corn in nontreated plots. Visual estimates of percent corn injury were recorded 14, 21, and 35 DAT using a scale of 0 to 100%, where 0 was no crop injury and 100 was complete plant death. Percent weed control was visually rated at 21, 35, and 63 DAT using a scale of 0 to 100%, where 0 was no weed control and 100 was complete weed control. The center two rows of corn in each plot were harvested on October 15, 2011 and October 20, 2012 using a plot combine, and the grain yield was adjusted to 15.5% moisture.

Statistical Analyses. The experimental design was a randomized complete block and treatments were replicated four times. Data for percent crop injury, percent weed control, and corn grain yield were subjected to ANOVA using PROC MIXED in SAS (Statistical Analysis Systems®, version 9.2, SAS Institute Inc., SAS Campus Drive, Cary, NC 27513). Year and herbicide treatments were considered fixed effects, and replication and interactions involving replication were random effects in the model. The year-by-treatment interaction was significant for weed control and corn yield; therefore, data were analyzed separately by year. Data on percent control were arcsine-square-root transformed before analysis to improve the normality of residuals and homogeneity of variance. Nontransformed

Table 2. List of PRE herbicide treatments for weed control in glyphosate-resistant corn in 2011 and 2012 near Huntley, MT.

Herbicide treatment	Rate (g ae or ai ha^{-1})	Trade name	Manufacturer
Pyroxasulfone	149	Zidua®	BASF Corporation, Research Triangle Park, NC 27709
Pyroxasulfone	298	Zidua	BASF Corporation
Acetochlor	1,960	Harness®	Monsanto Company, St. Louis, MO 63167
Dimethenamid-P	840	Outlook®	BASF Corporation
Saflufenacil + dimethenamid-P	737	Verdict®	BASF Corporation
Atrazine	1,120	AAtrex® 4L	Syngenta Crop Protection, LLC. Greensboro, NC 27419
S-Metolachlor + mesotrione	2,050	Zemax®	Syngenta Crop Protection
Pyroxasulfone plus pendimethalin	119 + 1,064	Zidua plus Prowl® H_2O	BASF Corporation
Acetochlor plus pendimethalin	1,960 + 1,064	Harness plus Prowl H_2O	Monsanto Company BASF Corporation
Dimethenamid-P plus pendimethalin	840 + 1,064	Outlook plus Prowl H_2O	BASF Corporation
Saflufenacil + dimethenamid-P plus pendimethalin	737 + 1,064	Verdict plus Prowl H_2O	BASF Corporation
Atrazine plus pendimethalin	1,120 + 1,064	AAtrex 4L plus Prowl H_2O	Syngenta Crop Protection BASF Corporation

means are presented in tables on the basis of the interpretation from the transformed data. Means were separated using Fisher's protected LSD test at $P < 0.05$. Orthogonal contrasts were conducted on the percent control data to compare pyroxasulfone and to chloroacetamide herbicides applied alone vs. in tank mixture with pendimethalin.

Results and Discussion

Kochia Control. Kochia density in the nontreated plots averaged 58 and 72 plants m^{-2} in 2011 and 2012, respectively (data not shown). Kochia control 21 DAT with saflufenacil + dimethenamid-P premix, *S*-metolachlor + mesotrione premix, and atrazine applied PRE was > 90% in both years, but at 63 DAT control had declined to as low as 67% in 2011 and 86% in 2012; differences within years and evaluation times were not significant (Table 3). Furthermore, those three treatments were superior to pyroxasulfone, acetochlor, or dimethenamid-P at all evaluation dates in both years.

Kochia control with pyroxasulfone did not differ between 149 and 298 g ha^{-1} rates, except at the 21 DAT evaluation date in 2012 (Table 3). Averaged over the rates, control with pyroxasulfone in 2011 was 76% at 21 DAT, similar to dimethenamid-P, but declined to 53% at 63 DAT. Knezevic et al. (2009) also reported that residual control of broadleaf weeds such as velvetleaf and tall waterhemp with pyroxasulfone declined significantly beyond 28 DAT, when applied at similar rates (150 to 300 g ha^{-1}) in corn. Pyroxasulfone doses up to 658 g ha^{-1} (much higher than the in-season maximum-use rate of 298 g ha^{-1}) were needed for adequate weed control later in the season (45 to 65 DAT). PRE control with pyroxasulfone (149 or 298 g ha^{-1}), acetochlor, or dimethenamid-P was relatively less in 2012 than in 2011. The differences in kochia control between years observed with pyroxasulfone and chloroacetamide herbicides (dimethenamid-P and acetochlor) in this study might be due to the differences in precipitation at or 7 to 10 d after the PRE herbicide application. Precipitation in the months of April and May (before irrigation) totaled 306 mm in 2011 compared with 105 mm in 2012. The greater amount of soil moisture might have resulted in greater soil-residual control of kochia from the herbicides observed in 2011 compared with 2012.

The addition of pendimethalin to pyroxasulfone, acetochlor, or dimethenamid-P improved residual control of kochia compared with pyroxasulfone and the chloroacetamides applied alone. Kochia control at 21, 35, and 63 DAT with pyroxasulfone plus pendimethalin was as high as 94, 92, and 81%, respectively, consistent with most other pendimethalin-containing herbicide treatments other than lower control with acetochlor plus pendimethalin in both years and dimethanamid-P plus pendimethalin

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Table 3. Influence of PRE herbicides on kochia control in glyphosate-resistant corn near Huntley, MT in 2011 and 2012.[a]

Herbicide treatment	Control[b]					
	2011			2012		
	21 DAT	35 DAT	63 DAT	21 DAT	35 DAT	63 DAT
	%					
Pyroxasulfone[c]	76 c	67 de	52 e	50 e	16 d	16 cd
Pyroxasulfone[d]	77 bc	67 de	54 de	61 d	22 d	22 c
Acetochlor	59 d	47 f	15 g	47 e	15 d	10 d
Dimethenamid-P	72 c	60 ef	32 f	50 e	21 d	14 cd
Saflufenacil + dimethenamid-P[e]	94 a	80 b	67 abc	91 a	89 ab	86 a
Atrazine	91 a	79 bc	71 ab	90 ab	87 ab	87 a
S-Metolachlor + mesotrione[e]	94 a	84 ab	75 ab	93 a	95 a	90 a
Pyroxasulfone plus pendimethalin	94 a	92 a	70 ab	90 ab	87 ab	81 ab
Acetochlor plus pendimethalin	84 b	76 bcd	55 cde	76 c	76 c	72 b
Dimethenamid-P plus pendimethalin	94 a	77 bcd	62 bcde	88 ab	83 bc	75 b
Saflufenacil + dimethenamid-P plus pendimethalin	96 a	85 ab	66 abcd	89 ab	86 abc	85 a
Atrazine plus pendimethalin	94 a	85 ab	76 a	92 a	90 ab	90 a
Contrasts[f]						
Pyroxasulfone[c] vs. pyroxasulfone[c] plus pendimethalin	***	***	**	***	***	***
Acetochlor vs. ccetochlor plus pendimethalin	***	***	***	***	***	***
Dimethenamid-P vs. dimethenamid-P plus pendimethalin	**	**	***	***	***	***
Saflufenacil + dimethenamid-P vs. saflufenacil + dimethenamid-P plus pendimethalin	NS	NS	NS	NS	NS	NS
Atrazine vs. ctrazine plus pendimethalin	NS	NS	NS	NS	NS	NS

[a] Abbreviation: DAT, days after treatment.

[b] Means within a column followed by different letters are significantly different on the basis of Fisher's protected LSD test at $P < 0.05$.

[c] Pyroxasulfone was applied at 149 g ha^{-1}.

[d] Pyroxasulfone was applied at 298 g ha^{-1}.

[e] The treatment is a prepackaged mixture.

[f] Contrasts were nonsignificant (NS) or significant at $P < 0.0001$ (***) or $P < 0.001$ (**).

in 2011 (Table 3). However, tank mixing pendimethalin with atrazine or saflufenacil + dimethenamid-P premix did not further increase kochia control achieved with any of the two treatments when applied alone.

Common Lambsquarters Control. Common lambsquarters density in nontreated plots averaged 39 and 27 plants m^{-2} in 2011 and 2012, respectively (data not shown). Saflufenacil + dimethenamid-P premix, atrazine, and *S*-metolachlor + mesotrione premix provided 93, 82, and 66% average control at 21, 35, and 63 DAT, respectively, in 2011. Control with the herbicides in 2012 averaged 91, 89, and 86% at 21, 35, and 63 DAT, respectively (Table 4). Also in a dose–response experiment conducted by Moran et al. (2011), a similar dose of 735 g ha^{-1} of saflufenacil + dimethenamid-P premix applied PRE reduced growth of common lambsquarters by 90% 28 DAT; extended residual control was not evaluated. No benefit was gained at any evaluation time in either year by tank mixing pendimethalin with atrazine or saflufenacil + dimethenamid-P premix.

In general, common lambsquarters control was improved by increasing the pyroxasulfone rate from 149 to 298 g ha^{-1} (Table 4). Control with pyroxasulfone (298 g ha^{-1}) and dimethenamid-P applied alone was up to 79% at 21 DAT; however, control was poor (as low as 33%) by 63 DAT. In a dose–response study, Nurse et al. (2011) estimated a dose of 500 g ha^{-1} of pyroxasulfone to obtain 90% control of common lambsquarters. End-of-season control of common lambsquarters with dimethenamid-P alone at 720 g ha^{-1} in potatoes was also poor (27% only) (Hutchinson 2012). Acetochlor applied alone was not effective on

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Table 4. Influence of PRE herbicides on common lambsquarters control in glyphosate-resistant corn near Huntley, MT in 2011 and 2012.[a]

Herbicide treatment	Control[b]					
	2011			2012		
	21 DAT	35 DAT	63 DAT	21 DAT	35 DAT	63 DAT
	%					
Pyroxasulfone[c]	56 d	46 d	15 f	66 e	48 e	17 e
Pyroxasulfone[d]	79 bc	69 bc	39 de	72 cde	70 cd	37 d
Acetochlor	51 d	45 d	12 f	65 e	47 e	17 e
Dimethenamid-P	77 c	66 c	33 e	69 de	67 cd	47 d
Saflufenacil + dimethenamid-P[e]	95 a	84 a	64 ab	89 a	84 ab	78 b
Atrazine	89 ab	82 a	67 a	95 a	94 a	91 a
S-Metolachlor + mesotrione[e]	94 a	81 a	67 a	89 a	89 a	88 ab
Pyroxasulfone plus pendimethalin	94 a	81 a	48 cd	80 b	72 cd	64 c
Acetochlor plus pendimethalin	91 a	81 a	61 abc	91 a	89 a	81 ab
Dimethenamid plus pendimethalin	87 abc	79 ab	50 bcd	75 bcd	75 bc	58 c
Saflufenacil + dimethenamid-P plus pendimethalin	98 a	86 a	61 abc	91 a	89 a	85 ab
Atrazine plus pendimethalin	92 a	82 a	64 ab	90 a	89 a	90 a
Contrast[f]						
Pyroxasulfone[c] vs. pyroxasulfone[c] plus pendimethalin	***	***	***	**	***	***
Acetochlor vs. acetochlor plus pendimethalin	***	***	**	***	***	***
Dimethenamid-P vs. dimethenamid-P plus pendimethalin	NS	*	*	NS	NS	*
Saflufenacil + dimethenamid-P vs. saflufenacil + dimethenamid-P plus pendimethalin	NS	NS	NS	NS	NS	NS
Atrazine vs. atrazine plus pendimethalin	NS	NS	NS	NS	NS	NS

[a] Abbreviation: DAT, days after treatment.

[b] Means within a column followed by different letters are significantly different on the basis of Fisher's protected LSD test at $P < 0.05$.

[c] Pyroxasulfone was applied at 149 g ha^{-1}.

[d] Pyroxasulfone was applied at 298 g ha^{-1}.

[e] The treatment is a prepackaged mixture.

[f] Contrasts were nonsignificant (NS) or significant at $P < 0.0001$ (***), $P < 0.001$ (**), or $P < 0.05$ (*).

common lambsquarters, with only 51% control 21 DAT.

Addition of pendimethalin to acetochlor noticeably improved residual control of common lambsquarters, which was 91, 81, and 61% at 21, 35, and 63 DAT, respectively, in 2011. In 2012, the control was 91, 89, and 81% at 21, 35, and 63 DAT, respectively. Similarly, tank mixing pendimethalin with pyroxasulfone (149 g ha^{-1}) increased residual control by 33 to 38% across the evaluation dates in 2011 and up to 47% in 2012 when compared with the pyroxasulfone (149 g ha^{-1})-alone treatment.

Wild Buckwheat Control. Wild buckwheat density in nontreated plots averaged 28 and 36 plants m^{-2} in 2011 and 2012, respectively (data not shown). Control with saflufenacil + dimethenamid-P premix, *S*-metolachlor + mesotrione premix, or atrazine was higher than pyroxasulfone, acetochlor, or dimethenamid-P (Table 5). Control with atrazine declined from 81% at 21 DAT to 59% at 63 DAT in 2011, whereas the decline was negligible (4% only) in 2012. Atrazine degradation in soil primarily occurs by hydrolysis to hydroxyatrazine (Moyer and Blackshaw 1993), and a faster degradation of atrazine may be expected because of greater soil moisture accumulation in 2011 compared with 2012; precipitation from May through July totaled 344 mm in 2011 compared with 104 mm in 2012 (Table 2). Also, residual control from saflufenacil + dimethenamid-P was reduced from 89% (21 DAT) to 50% (63 DAT) in 2011 compared with a slight reduction from 79% (21 DAT) to 74% (63 DAT) in 2012.

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Table 5. Influence of PRE herbicides on wild buckwheat control in glyphosate-resistant corn near Huntley, MT in 2011 and 2012.[a]

	Control[b]					
	2011			2012		
Herbicide treatment	21 DAT	35 DAT	63 DAT	21 DAT	35 DAT	63 DAT
	%					
Pyroxasulfone[c]	16 f	15 e	13 f	21 f	27 e	27 f
Pyroxasulfone[d]	52 d	46 d	36 e	58 e	56 d	50 de
Acetochlor	12 f	10 e	11 f	29 f	33 e	33 ef
Dimethenamid-P	32 e	20 e	20 f	30 f	29 e	23 f
Saflufenacil + dimethenamid-P[e]	89 ab	79 ab	50 bcde	79 bc	77 bc	74 bc
Atrazine	81 abc	79 ab	59 abcd	94 a	92 a	90 a
S-Metolachlor + mesotrione[e]	76 bc	71 abc	60 abc	78 bc	73 bc	72 bc
Pyroxasulfone plus pendimethalin	49 d	46 d	45 de	65 de	67 cd	67 bcd
Acetochlor plus pendimethalin	87 ab	76 ab	56 abcd	86 ab	85 ab	82 ab
Dimethenamid plus pendimethalin	74 c	60 c	47 cde	72 cd	54 d	55 cd
Saflufenacil + dimethenamid-P plus pendimethalin	92 a	82 a	63 ab	86 ab	85 ab	83 ab
Atrazine plus pendimethalin	89 ab	80 ab	65 a	92 a	92 a	90 a
Contrasts[f]						
Pyroxasulfone[c] vs. pyroxasulfone[c] plus pendimethalin	***	***	***	***	***	***
Acetochlor vs. acetochlor plus pendimethalin	***	***	***	***	***	***
Dimethenamid-P vs. dimethenamid-P plus pendimethalin	***	***	**	***	**	***
Saflufenacil + dimethenamid-P vs. saflufenacil + dimethenamid-P plus pendimethalin	NS	NS	NS	NS	NS	NS
Atrazine vs. atrazine plus pendimethalin	NS	NS	NS	NS	NS	NS

[a] Abbreviation: DAT, days after treatment.

[b] Means within a column followed by different letters are significantly different on the basis of Fisher's protected LSD test at $P < 0.05$.

[c] Pyroxasulfone was applied at 149 g ha^{-1}.

[d] Pyroxasulfone was applied at 298 g ha^{-1}.

[e] The treatment is a prepackaged mixture.

[f] Contrasts were nonsignificant (NS) or significant at $P < 0.0001$ (***) or $P < 0.001$ (**).

Increasing the rate of pyroxasulfone from 149 to 298 g ha^{-1} improved wild buckwheat control, although it did not exceed 58% at 21 DAT. Also, control with acetochlor or dimethenamid-P applied alone was inadequate (Table 5). The results indicate that pyroxasulfone and chloroacetamide herbicides applied alone PRE were relatively more effective on kochia and common lambsquarters than wild buckwheat, at least early in the season.

Wild buckwheat control was improved by adding pendimethalin to pyroxasulfone, acetochlor, or dimethenamid-P compared with the herbicides applied alone (Table 5). Control with acetochlor plus pendimethalin was 87, 76, and 56% at 21, 35, and 63 DAT, respectively, in 2011. Control in 2012 was 86, 85, and 82% at 21, 35, and 63 DAT, respectively. Also, the treatment was superior to pyroxasulfone plus pendimethalin or dimethenamid-P plus pendimethalin at 21 and 35 DAT.

Corn Yield. None of the PRE herbicide treatments caused noticeable injury to corn. Corn yields were higher in 2011 than in 2012 (Table 6), which was likely due to greater rainfall throughout the 2011 compared with 2012 growing season (Table 1). All herbicide treatments increased corn grain yield in 2011, and all except acetochlor and the lower rate of pyroxasulfone increased grain yields in 2012 compared with nontreated corn (Table 6). In both years, corn receiving treatments containing pendimethalin yielded more than most other treatments, except atrazine, *S*-metolachlor + mesotrione premix, and saflufenacil + dimethenamid-P premix. Inadequate weed control by pyroxasulfone (149 g ha^{-1}), acetochlor, and dimethenamid-P

Table 6. Influence of PRE herbicides on glyphosate-resistant corn yield near Huntley, MT in 2011 and 2012.

Herbicide treatment[a]	Yield 2011	Yield 2012
	kg ha^{-1}	
Nontreated	3,451 e	1,763 d
Pyroxasulfone[b]	4,936 cd	2,324 cd
Pyroxasulfone[c]	6,132 bc	3,416 b
Acetochlor	3,714 de	2,274 cd
Dimethenamid-P	5,482 c	2,954 bc
Saflufenacil + dimethenamid-P[d]	6,767 ab	5,065 a
Atrazine	7,586 a	5,266 a
S-Metolachlor + mesotrione[d]	7,631 a	5,442 a
Pyroxasulfone[b] plus pendimethalin	7,063 ab	5,138 a
Acetochlor plus pendimethalin	6,706 ab	5,067 a
Dimethenamid plus pendimethalin	7,179 ab	5,009 a
Saflufenacil + dimethenamid-P plus pendimethalin	7,573 a	5,184 a
Atrazine plus pendimethalin	7,555 a	5,677 a

[a] Means within a column followed by different letters are significantly different on the basis of Fisher's protected LSD test at $P < 0.05$.

[b] Pyroxasulfone was applied at 149 g ha^{-1}.

[c] Pyroxasulfone was applied at 298 g ha^{-1}.

[d] The treatment is a prepackaged mixture.

alone caused almost twofold yield reductions compared with the atrazine-alone plots. Although the difference was not significant in 2011, corn yield in 2012 was 47% higher with pyroxasulfone applied at 298 compared with 149 g ha^{-1}.

In these studies, PRE-applied saflufenacil + dimethenamid-P premix and S-metolachlor + mesotrione premix were similarly effective as atrazine in controlling kochia, common lambsquarters, and wild buckwheat up to 9 wk into the growing season. There was no benefit of adding pendimethalin with saflufenacil + dimethenamid-P premix or atrazine; however, the presence of atrazine-resistant kochia and common lambsquarters in the region may limit the use of atrazine as a stand-alone PRE herbicide in corn. Pyroxasulfone and other chloroacetamide herbicides (e.g., acetochlor and dimethenamid-P) were relatively weak on wild buckwheat compared with kochia and common lambsquarters. PRE control of the weeds with pyroxasulfone, acetochlor, or dimethenamid-P when applied alone was up to 79% 21 DAT, but was poor later in the growing season (35 to 63 DAT), suggesting that those herbicides cannot be used as a stand-alone treatment in corn. However, the inclusion of pendimethalin as a tank-mix partner with pyroxasulfone, acetochlor, or dimethenamid-P enhanced residual control of the weeds through the growing season, and prevented yield reductions in glyphosate-resistant corn. Corn growers in the NGP should utilize these relatively new premixes or tank mixtures (multiple modes of action) for extended in-season residual weed control in corn, as weed populations with resistance to herbicide chemistries used in corn including group 9 (glyphosate), group 2 (sulfonylureas), group 5 (atrazine), or group 4 (dicamba, fluroxypyr) continue to spread and affect larger hectares in the NGP.

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