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Effective Preemergence and Postemergence Herbicide Programs for Kochia Control

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Field experiments were conducted in 2011 through 2013 at the MSU Southern Agricultural Research Center near Huntley, MT, to evaluate the effectiveness of various PRE and POST herbicide programs for kochia control in the absence of a crop. PRE herbicides labeled for corn, grain sorghum, soybean, wheat/barley, and/or in chemical fallow were applied at recommended field-use rates. Acetochlor + atrazine, *S*-metolachlor + atrazine + mesotrione, and sulfentrazone applied PRE provided ≥91% control of kochia at 12 wk after treatment (WAT). Metribuzin, metribuzin + linuron, and pyroxasulfone + atrazine PRE provided 82% control at 12 WAT. PRE control with acetochlor + flumetsulam + clopyralid, pyroxasulfone alone, and saflufenacil + 2,4-D was ≤23% at 12 WAT. Paraquat + atrazine, paraquat + linuron, and paraquat + metribuzin controlled kochia ≥98% at 5 WAT. POST control with bromoxynil + fluroxypyr, paraquat, tembotrione + atrazine, and topramezone + atrazine treatments averaged 84% at 5 WAT, and did not differ from glyphosate. Control with POST-applied bromoxynil + pyrasulfotole, dicamba, diflufenzopyr + dicamba + 2,4-D, saflufenacil, saflufenacil + 2,4-D, saflufenacil + linuron was 67 to 78% at 5 WAT. Because of the presence of kochia resistant to acetolactate synthase-inhibiting herbicides at the test site, cloransulam-methyl was not a viable option for kochia control. In a separate greenhouse study, kochia accessions showed differential response to the POST herbicides (labeled for corn or soybean) tested. Tembotrione + atrazine, topramezone + atrazine, lactofen, or fomesafen effectively controlled the glyphosate-resistant kochia accession tested. Growers should utilize these effective PRE- or POST-applied herbicide premixes or tank mixtures (multiple modes of action) to control herbicide-resistant kochia accessions in the field. PRE herbicides with 8 wk of soil-residual activity on kochia would be acceptable if crop competition were present; however, a follow-up herbicide application may be needed to obtain season-long kochia control in the absence of crop competition.

Nomenclature: 2,4-D; acetochlor; atrazine; bromoxynil; carfentrazone-ethyl; clopyralid; cloransulam-methyl; dicamba; diflufenzopyr; flumetsulam; flumioxazin; fluroxypyr; fomesafen; glufosinate; glyphosate; isoxaflutole; lactofen; linuron; MCPA; mesotrione; metolachlor; paraquat; pyrasulfotole; pyroxasulfone; saflufenacil; sulfentrazone; tembotrione; thifensulfuron; tribenuron; topramezone; kochia, *Kochia scoparia* (L.) Schrad.

Key words: Glyphosate-resistant kochia, herbicide efficacy, residual control, herbicide resistance management, weed control.

Entre 2011 y 2013, se realizaron experimentos de campo en el Centro de Investigación Agrícola del Sur de MSU, cerca de Huntley, Montana, para evaluar la efectividad de varios programas de herbicidas PRE y POST para el control de *Kochia scoparia* en ausencia de un cultivo. Se aplicó herbicidas PRE registrados para maíz, sorgo para grano, soja, trigo/cebada, y/o barbecho químico a las dosis recomendadas para uso en campo. Acetochlor + atrazine, *S*-metolachlor + atrazine + mesotrione, y sulfentrazone aplicados PRE brindaron ≥91% de control de *K. scoparia* a 12 semanas después del tratamiento (WAT). Metribuzin, metribuzin + linuron, y pyroxasulfone + atrazine PRE brindaron 82% de control a 12 WAT. Control PRE con acetochlor + flumetsulam + clopyralid, pyroxasulfone solo, y saflufenacil + 2,4-D fue ≤23% a 12 WAT. Paraquat + atrazine, paraquat + linuron, y paraquat + metribuzin controlaron *K. scoparia* ≥98% a 5 WAT. Control POST con bromoxynil + fluroxypyr, paraquat, tembotrione + atrazine, y topramezone + atrazine promedió 84% a 5 WAT, y no difirió de glyphosate. El control con aplicaciones POST de bromoxynil + pyrasulfotole, dicamba, diflufenzopyr + dicamba + 2,4-D, saflufenacil, saflufenacil + 2,4-D, saflufenacil + linuron fue 67 a 78% a 5 WAT. Debido a la presencia en el lugar del estudio de *K. scoparia* resistente a herbicidas inhibidores de acetolactate synthase, cloransulam-methyl no fue una opción viable para el control de *K. scoparia*. En un estudio de invernadero, accesiones de *K. scoparia* mostraron respuestas diferenciadas a los herbicidas POST (registrados para maíz y soja) evaluados. Tembotrione + atrazine, topramezone + atrazine, lactofen, o fomesafen controlaron efectivamente la accesión de *K. scoparia* resistente a glyphosate

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evaluada. Los productores deberían utilizar en el campo. estas pre-mezclas o mezclas en tanque de herbicidas (múltiples modos de acción) aplicados PRE o POST para el control de accesiones de *K. scoparia* resistentes a herbicidas. Herbicidas PRE con 8 semanas de actividad residual en el suelo sobre *K. scoparia* deberían ser aceptables si la competencia del cultivo está presente. Sin embargo, una aplicación de seguimiento podría ser necesaria para obtener control de *K. scoparia* durante toda la temporada, en ausencia de competencia del cultivo.

Kochia is one of the most troublesome summer annual broadleaf weeds in croplands and noncroplands across the Great Plains of North America (Eberlein and Fore 1984; Forcella 1985; Wicks et al. 1994). The invasiveness of kochia is attributed to its unique biological characteristics, including early seedling emergence, C_4 photosynthesis, rapid growth rates, heat and salt tolerance, prolific seed production (>50,000 seeds plant^{-1}), and long-distance seed dispersal by tumbling (Baker et al. 2010; Christoffoleti et al. 1997; Friesen et al. 2009; Schwinghamer and Van Acker 2008). Furthermore, the protogynous nature of kochia flowering enforces a high degree of outcrossing and pollen-mediated gene flow (Mengistu and Messersmith 2002; Stallings et al. 1995). Consequently, the presence of high genetic diversity within and among kochia accessions has also been reported (Mengistu and Messersmith 2002).

Kochia causes season-long interference and yield reductions in agronomic crops of the Great Plains, including wheat (*Triticum aestivum* L.), corn (*Zea mays* L.), sorghum (*Sorghum bicolor* L.), sugar beet (*Beta vulgaris* L.), sunflower (*Helianthus annus* L.), and soybean [*Glycine max* (L.) Merr]. Season-long interference of kochia can reduce soybean, sorghum, wheat, corn, and sugar beet yields by 30, 38, 58, 40, and 95%, respectively (Dahl et al. 1982; Durgan et al. 1990; Waite et al. 2013; Weatherspoon 1971; Wicks et al. 1993, 1994).

Growers in the northern and central Great Plains are facing ever-increasing challenges in controlling kochia because of the widespread occurrence of kochia accessions resistant to one or more herbicide chemistries (Heap 2014). Kochia resistance to herbicide modes of action including group 5 (atrazine), group 2 (sulfonylurea and imidazolinone herbicides), group 4 (dicamba and fluroxypyr), and more recently to group 9 (glyphosate) has been reported in this region (Cranston et al. 2001; Heap 2014; Kumar et al. 2014; Preston et al. 2009; Primiani et al. 1990). Glyphosate-resistant (Gly-R) kochia has been reported in seven U.S. states and in Alberta, Canada (Beckie et al. 2013; Heap 2014). The escalating spread of Gly-R kochia is a potential threat to Gly-R cropping systems and to the no-till chemical fallow wheat rotation common in the region. Occurrence of Gly-R kochia accessions with 4.6- to 11-fold levels of resistance to glyphosate has been recently confirmed in chemical-fallow (chemical-fallow and wheat rotation) fields of Hill, Liberty, and Toole Counties of Montana (Kumar et al. 2014).

Weed control programs aimed at managing herbicide-resistant weeds recommend the use of annual herbicide rotation and tank mixtures with multiple modes of action (Beckie et al. 2006; Norsworthy et al. 2012). Diversifying herbicide programs with the use of soil-applied residual PRE herbicides in conjunction with effective POST herbicides is critical for management of herbicide-resistant weeds (Norsworthy et al. 2012; Stephenson et al. 2013). Previous researchers have reported variable levels of kochia control with PRE or POST herbicides. In addition, use of a single-mode-of-action herbicide often results in inconsistent control of kochia. For instance, kochia control with flumioxazin (0.28 kg ai ha^{-1}), pendimethalin (1.4 kg ai ha^{-1}), or pyroxasulfone (0.42 kg ai ha^{-1}) applied alone PRE was only 53 to 70% (Lloyd et al. 2011; Stahlman et al. 2010). Among POST herbicides tested by Lloyd et al. (2011), control with either fluroxypyr or glyphosate did not exceed 75%, and was as low as 35% with saflufenacil alone. Although bromoxynil + MCPA, carfentrazone, or paraquat applied POST controlled kochia ≥90% under greenhouse conditions (Nandula and Manthey 2002; Tonks and Westra 1997), control as low as 68% was observed with those herbicides under field conditions (Wicks et al. 1993). This might be due to potential regrowth of the treated plants or lack of residual activity of the herbicide on cohort(s) that emerged after the POST application, which obviates the need to investigate effective PRE- or POST-applied herbicide combinations (multiple modes of action) for full-season kochia control.

The ever-increasing frequency of herbicide-resistant kochia is a major threat to the Great Plains

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Table 1. Mean monthly air temperature and total precipitation at the Montana State University Southern Agricultural Research Center near Huntley, MT.

	Temperature			Total precipitation		
Month	2011	2012	2013	2011	2012	2013
	C			mm		
March	3	8	3	20.1	45.0	5.8
April	6	10	6	68.6	22.6	29.7
May	11	13	14	237.5	82.3	154.2
June	17	20	19	39.1	9.9	35.8
July	23	25	23	67.3	12.2	16.5
August	23	22	23	16.0	9.1	36.6

cropping systems. Although alternative (nonglyphosate) herbicide options for Gly-R kochia control in wheat–fallow rotation has been recently documented (Kumar et al. 2014), there is no published research on alternative herbicides for effective control of Gly-R kochia in Gly-R corn or soybean in the Great Plains. The objectives of this research were to determine effective PRE and POST herbicide programs for kochia control in the field, and to test the effectiveness of alternative (nonglyphosate) POST herbicides labeled in corn or soybean for control of Gly-R kochia accessions.

Materials and Methods

PRE Herbicide Programs. Field experiments were initiated at the Montana State University (MSU) Southern Agricultural Research Center (SARC) near Huntley, MT, in 2011, and repeated in 2012 and 2013, to test the effectiveness of soil-applied PRE herbicides labeled for corn, grain sorghum, soybean, wheat/barley, and/or chemical-fallow for kochia control. Experiments were conducted in a fallow situation for long-term evaluation of herbicide efficacy. The soil type at the study location was a Fort Collins clay loam (fine–loamy, mixed, superactive, mesic Aridic Haplustalfs) with 2.8% organic matter and a pH of 7.8. Monthly mean air temperatures and total precipitation during the study periods are shown in Table 1. The experimental site was in a minimum of 5-yr no-till dryland wheat–fallow rotation prior to the initiation of the study. Each year, the experimental site was moved to avoid any residual activity from herbicides applied the previous year. Historically, each experimental site had received two or three applications of glyphosate during the summer fallow period, and fluroxypyr and bromoxynil plus MCPA in the wheat crop for weed control. Furthermore, the sites selected had no history of kochia infestation. During fall of each year, fully matured kochia seeds were collected from a naturally infested area at the MSU-SARC research farm. Seeds were broadcasted in the fall to obtain uniform kochia densities in plots the following spring. PRE herbicide programs included in the study and their application date each year are presented in Tables 2 and 3. A nontreated control was included for comparison. PRE herbicide treatments were applied at their recommended field-use rates with a CO_2-pressurized backpack sprayer equipped with flat-fan nozzles (TeeJet 8001XR, Spraying Systems Co., P.O. Box 7900, Wheaton, IL), calibrated to deliver 94 L ha^{-1} of spray solution at 276 kPa.

Experiments were conducted in a randomized complete block design with four replications, and plot size of 2 × 4.5 m. Kochia densities were recorded within 1-m^2 quadrats placed at the center of a nontreated plot (Table 3). Percent control of kochia from PRE herbicides was visually rated at 6, 8, 10, and 12 wk after treatment (WAT) on a scale of 0 to 100% (0 being no control and 100 being complete control). Visual assessments for percent control were based on emergence and general suppression/stunting of kochia seedlings in treated compared with nontreated plots.

POST Herbicide Programs. Separate field experiments were conducted at the MSU-SARC near Huntley, in 2011, 2012, and 2013, to evaluate the effectiveness of various POST herbicide programs for kochia control. The soil and environmental conditions were similar to those described in the PRE herbicide trials. POST herbicide experiments were also conducted in a crop-free situation. In the fall of each year, the experimental site was uniformly infested with kochia seeds as described previously, and was kept free from other weed species throughout the growing season by hand weeding. POST herbicides labeled in wheat/barley, corn/grain sorghum, soybean, or chemical-fallow was selected. A nontreated control was included for comparison. POST herbicides were applied at their recommended field-use rates when kochia plants were 8 to 10 cm tall (Tables 3 and 4) in the field, with the use of a CO_2-pressurized backpack sprayer described above.

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Table 2. List of PRE herbicides treatments for kochia control in 2011, 2012, and 2013 at the Montana State University Southern Agricultural Research Center near Huntley, MT.

Herbicide(s)	Trade name	Application rate	Manufacturer
		(kg ai or ae ha^{-1})	
Acetochlor + atrazine	HarnessXtra5.6L	2.604 + 2.100	Monsanto Company, 800 North Lindberg Ave., St. Louis, MO
Acetochlor + flumetsulam + clopyralid	TripleFlex	1.047 + 0.033 + 0.106	Monsanto
Dicamba	Rifle	0.280	Loveland Products Inc., Greeley, CO
Dicamba + 2,4-D amine	Rifle + Weedar 64	0.280 + 0.560	Loveland Products and Nufarm, Inc., Burr Ridge, IL
Dicamba + pendimethalin	Rifle + Prowl®H2O	0.280 + 0.798	Loveland Products and BASF Corporation, 26 Davis Drive, Research Triangle Park, NC 27709
Flumioxazin	Valor	0.070	Valent U.S.A. Corporation, Walnut Creek, CA
Flumioxazin + pyroxasulfone	Fierce	0.188	Valent U.S.A.
Isoxaflutole	Balance®flexx	0.062	Bayer Crop Science, Research Triangle Park, NC 27709
Metribuzin	Sencor® 75DF	0.425	Bayer Crop Science
Metribuzin + linuron	Sencor® 75DF + Linex® 4L	0.425 + 0.840	Bayer Crop Science and Tessenderlo Kerley Inc., Phoenix, AZ
Pyroxasulfone	Zidua	0.118	BASF
Pyroxasulfone + atrazine	Zidua + AAtrex® 4L	0.118 + 0.560	BASF and Syngenta Crop Protection, Inc., Greensboro, NC
Saflufenacil + 2,4-D	Sharpen + Weedar 64	0.025 + 0.560	BASF and Nufarm
S-metolachlor + atrazine + mesotrione	Lumax	0.855 + 0.319 + 0.085	Syngenta Crop Protection
Sulfentrazone	Spartan	0.210	FMC Corporation, Philadelphia, PA

The experimental design was a randomized complete block with four replications. Kochia densities were recorded within 1-m^2 quadrats placed at the center of each plot (2 × 4.5 m) 1 d prior to the POST herbicide application (Table 3). Kochia control was recorded at 1, 3, and 5 WAT on a scale of 0 to 100% (0 being no control and 100 being complete control). Visual assessments for percent control were based on general chlorosis, stunting, or necrosis of treated plants.

Table 3. Average kochia density and application dates of PRE and POST herbicides in 2011, 2012, and 2013 at the Montana State University Southern Agricultural Research Center near Huntley, MT.

	Kochia density		Herbicide application date	
Years	PRE[a]	POST[b]	PRE	POST
	plants m^{-2}			
2011	54	79	April 26	June 12
2012	78	94	April 24	June 10
2013	69	108	April 28	June 14

[a] In the PRE herbicide study, kochia densities were recorded 3 wk after emergence in the nontreated plots.

[b] In the POST herbicide study, kochia densities were recorded 1 d prior to the application of the POST herbicides.

Gly-R Kochia Control. Experiments were conducted in a greenhouse at the MSU-SARC near Huntley during spring 2013, to determine the response of Gly-R kochia accessions to alternative POST herbicides (labeled in corn or soybean). The effectiveness of various POST herbicides was tested on four confirmed Gly-R kochia accessions from MT including GIL01, JOP01, CHES01, and CHES02 (as described in Kumar et al. 2014) in comparison to a known glyphosate-susceptible (Gly-S) accession. The Gly-R GIL01 and JOP01 accessions were collected in fall 2012 from two different fields within 5 km of each other in Hill County, MT; Gly-R CHES01 and CHES02 were collected from two separate fields within 3 km of each other near Chester, Liberty County, MT. The glyphosate-susceptible (Gly-S) accession was collected in fall 2012 from a field near Huntley used for long-term organic trials. Seeds of Gly-R and

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Table 4. List of burndown and in-crop POST herbicide treatments for kochia control in 2011, 2012, and 2013 at the Montana State University Southern Agricultural Research Center near Huntley, MT.

Herbicide(s)	Trade name	Application rate	Manufacturer
		(kg ai or ae ha^{-1})	
Bromoxynil + fluroxypyr	StaraneNXT	0.558 + 0.140	Dow AgroScience LLC, Indianapolis, IN
Bromoxynil + pyrasulfotole	Huskie	0.229 + 0.040	Bayer Crop Science, Research Triangle Park, NC 27709
Bromoxynil + MCPA	Bronate Advanced	0.560 + 0.560	Bayer Crop Science
Carfentrazone-ethyl + 2,4-D amine	Aim + Weedar 64	0.034 + 0.560	FMC Corporation, Philadelphia, PA and Nufarm, Inc., Burr Ridge, IL
Cloransulam-methyl	FirstRate	0.017	Dow AgroScience
Dicamba	Rifle	0.280	Loveland Products Inc., Greeley, CO
Diflufenzopyr + dicamba + 2,4-D	Distinct + Weedar 64	(0.056 + 0.140) + 0.560	BASF Corporation, 26 Davis Drive, Research Triangle Park, NC 27709 and Nufarm
Fomesafen	Flexstar	0.459	Syngenta Crop Protection, Greensboro, NC
Glyphosate	Roundup WeatherMax	1.260	Monsanto Company, 800 North Lindberg Ave., St. Louis, MO
Glufosinate	Liberty	0.593	Bayer Crop Science
Lactofen	Cobra	0.218	Valent U.S.A. Corporation, Walnut Creek, CA
Paraquat	Gramoxone Inteon	0.840	Syngenta Crop Protection
Paraquat + atrazine	Gramoxone Inteon + AAtrex	0.840 + 0.560	Syngenta Crop Protection
Paraquat + linuron	Gramoxone Inteon + linex	0.840 + 0.840	Syngenta Crop Protection
Paraquat + metribuzin	Gramoxone Inteon + Sencor75DF	0.840 + 0.425	Syngenta Crop Protection and Bayer Crop Science
Saflufenacil	Sharpen	0.025	BASF
Saflufenacil + 2,4-D	Sharpen + Weedar 64	0.025 + 0.560	BASF and Nufarm
Saflufenacil + linuron	Sharpen + Linex	0.025 + 0.840	BASF and Nufarm
S-metolachlor + mesotrione	Dual Magnum + Callisto	1.866 + 0.184	Syngenta Crop Protection
Tembotrione + atrazine	Laudis + AAtrex	0.089 + 0.560	Bayer Crop Science and Syngenta Crop Protection
Topramezone + atrazine	Impact + AAtrex	0.018 + 0.560	Amvac Chemical Corporation, Los Angeles, CA and Syngenta Crop Protection
Thifensulfuron-methyl + tribenuron-methyl + 2,4-D	HarmonyExtra SG + Weedar 64	0.017 + 0.008 + 0.560	DuPont, Wilmington, DE and Nufarm

Gly-S accessions were sown separately on the surface of 53 by 35 by 10 cm flats filled with a commercial potting media (VermiSoil^{TM}, Vermicrop Organics, 4265 Duluth Avenue, Rocklin, CA). Single kochia seedlings were transplanted into 10-cm-diam pots containing the same potting medium as the germination flats. Experiments were arranged in a randomized complete block design with eight replications (one plant per pot) for each accession and herbicide combination, and the experiment was repeated. The greenhouse was maintained at 26/23 ± 3 C day/night temperatures with 16/8 h day/night photoperiods, and the supplemental photoperiod was obtained with metal halide lamps (400 µmol m^{-2} s^{-1}).

Alternative herbicide programs included in the study and their application rates are summarized in Table 5. All herbicides were applied at their recommended field-use rates to 8- to 10-cm-tall kochia plants with the use of a cabinet spray chamber (Research Track Sprayer, De Vries Manufacturing, RR 1 Box 184, Hollandale, MN) equipped with a flat-fan nozzle tip (TeeJet 8001 XR) calibrated to deliver 94 L ha^{-1} of spray solution at 276 kPa. After the herbicide application, plants were returned to the greenhouse, watered daily to

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Table 5. List of alternative POST herbicides for glyphosate-resistant (Gly-R) kochia control.

Herbicide(s)[a,b]	Trade name	Application rate	Manufacturer
		(kg ai or ae ha^{-1})	
Cloransulam-methyl[c]	FirstRate	0.017	Dow AgroScience LLC, Indianapolis, IN
Fomesafen[c]	Flexstar	0.459	Syngenta Crop Protection, Inc. Greensboro, NC
Lactofen[d]	Cobra	0.218	Valent U.S.A. Corporation, Walnut Creek, CA
S-metolachlor + mesotrione[c]	Dual Magnum + Callisto	1.866 + 0.184	Syngenta Crop Protection
Tembotrione[d]	Laudis	0.089	Bayer CropScience, Research Triangle Park, NC
Tembotrione + atrazine[d]	Laudis + AAtrex	0.089 + 0.560	Bayer CropScience and Syngenta Crop Protection
Topramezone[d]	Impact	0.018	Amvac Chemical Corporation, Los Angeles, CA
Topramezone + atrazine[d]	Impact + AAtrex	0.018 + 0.560	Amvac Chemical Corporation and Syngenta Crop Protection

[a] Herbicides are labeled for corn or soybean

[b] All treatments were applied to 8- to 10-cm-tall kochia plants.

[c] Nonionic surfactant (NIS) at 0.25% (v/v) was included.

[d] Methylated seed oil (MSO) at 1% (v/v) was included.

avoid moisture stress, and fertilized (Miracle-Gro water soluble fertilizer [24–8–16], Scotts Miracle-Gro Products Inc., 14111 Scottslawn Road, Marysville, OH] weekly to maintain good growth.

Percent control of kochia was visually assessed at 1, 2, and 3 WAT with the use of the rating scale described for the field experiments. At 3 WAT, kochia plants were harvested at the soil level, and shoot dry weights were determined after oven-drying the samples at 60 C for 3 d. For each kochia accession, shoot dry weight data were expressed as percentage of the nontreated control.

Statistical Analyses. All data from field and greenhouse experiments were subjected to ANOVA with the use of the PROC MIXED procedure in SAS (Statistical Analysis Systems®, version 9.2, SAS Institute Inc., SAS Campus Drive, Cary, NC 27513).Variances were divided into random effects (year or run, replication nested within a year or run, and interactions involving either of these two variables) and fixed effects (herbicide treatment for the field studies or herbicide treatment, accession, and their interaction for the greenhouse study). Data on percent control and shoot dry weight (percent of nontreated) were arcsine-square-root transformed before analysis to improve the normality of residuals and homogeneity of variance. Nontransformed means are presented in tables based on the interpretation from the transformed data. Control data from nontreated plots were not included in the analyses. Means were separated with the use of Fisher's protected LSD test at $P < 0.05$.

Results and Discussion

The majority of the kochia emerged between May 10 and May 18 each year. Mean air temperatures during the month of May were 11, 13, and 14 C, in 2011, 2012, and 2013, respectively (Table 1). There was sufficient soil moisture from the major precipitation events (totaling ≥76 mm) that occurred between April 25 and May 10 each year to activate the PRE herbicides.

PRE Herbicide Programs. Kochia densities in PRE herbicide experiments ranged from 54 to 78 plants m^{-2} over the 3 yr (Table 3). Kochia control with acetochlor + atrazine, dicamba + pendimethalin, isoxaflutole, metribuzin, metribuzin + linuron, pyroxasulfone + atrazine, *S*-metolachlor + atrazine + mesotrione, and sulfentrazone treatments applied PRE was 93 to 100% at 8 WAT (Table 6). Flumioxazin + pyroxasulfone and dicamba alone or with 2,4-D PRE provided 84 to 90% control 8 WAT (Table 6). PRE control with flumioxazin + pyroxasulfone (90%) was superior to flumioxazin alone (66%) or pyroxasulfone alone (61%) 8 WAT.

Consistent with the previous evaluation dates (8 and 10 WAT), control at 12 WAT with acetochlor + atrazine, acetochlor + atrazine + mesotrione, and sulfentrazone was >90% (Table 6). In previous research, poor kochia control (<50%) has been

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Table 6. Kochia control at 8, 10, and 12 wk after treatment (WAT) with various PRE herbicide treatments at the Montana State University Southern Agricultural Research Center near Huntley, MT.[a,b]

Herbicide(s)	Rate(s)	8 WAT	10 WAT	12 WAT
	(kg ai or ae ha^{-1})		—%—	
Acetochlor + atrazine	2.604 + 2.100	100 a	100 a	100 a
Acetochlor + flumetsulam + clopyralid	1.047 + 0.033 + 0.106	66 d	38 f	23 g
Dicamba	0.280	89 bc	60 e	40 f
Dicamba + 2,4-D	0.280 + 0.56	84 c	62 e	41 f
Dicamba + pendimethalin	0.280 + 0.798	94 ab	74 d	44 f
Flumioxazin	0.070	66 d	54 e	38 f
Flumioxazin + pyroxasulfone	0.070 + 0.118	90 bc	81 cd	70 e
Isoxaflutole	0.062	94 ab	76 d	71 de
Metribuzin	0.425	95 ab	89 bc	83 bcd
Metribuzin + linuron	0.425 + 0.840	96 ab	92 ab	80 cde
Pyroxasulfone	0.118	61 d	36 f	18 g
Pyroxasulfone + atrazine	0.118 + 0.560	93 ab	89 bc	83 bcd
Saflufenacil + 2,4-D	0.025 + 0.560	66 d	35 f	14 g
S-metolachlor + atrazine + mesotrione	0.855 + 0.319 + 0.085	99 a	98 a	93 ab
Sulfentrazone	0.210	97 ab	96 ab	91 abc

[a] PRE treatments were applied prior to kochia emergence in the field.

[b] Means within a column followed by similar letters are not significantly different based on Fisher's protected LSD test at $P < 0.05$.

reported with acetochlor (1.960 kg ai ha^{-1}) or metolachlor (1.070 kg ai ha^{-1}) applied PRE in sunflower and corn (Jha et al. 2013; Reddy et al. 2012). Although atrazine-alone treatment was not included in this study, consistent control of kochia (up to 12 WAT) obtained with acetochlor + atrazine was possibly due to the residual activity of atrazine on kochia. However, widespread occurrence of triazine-resistant kochia in the U.S. Great Plains (Heap 2014) limits the use of atrazine as a stand-alone PRE herbicide in corn. Control with metribuzin, metribuzin + linuron, and pyroxasulfone + atrazine was 80 to 83% 12 WAT.

Control with flumioxazin + pyroxasulfone and isoxaflutole declined from 92 to 70% at 12 WAT. Also, residual activity of dicamba, dicamba + 2,4-D, dicamba + pendimethalin, and flumioxazin declined up to 50% by 12 WAT (Table 6). A shift in kochia accession to late-emerging cohorts was a mechanism to escape residual activity of isoxaflutole applied PRE in corn over 8 yr (Sbatella and Wilson 2010). Our results further suggest that kochia has an extended period of emergence (Dille et al. 2012). Although sequential herbicide applications may be desirable to obtain season-long kochia control in fallow with some of the PRE herbicides tested, treatments providing high residual control for 8 wk (Table 6) may still be acceptable in the presence of a crop that will compete with the late-emerging kochia cohort(s). Performance of acetochlor + flumetsulam + clopyralid, pyroxasulfone alone, or saflufenacil + 2,4-D was poor, with PRE control as low as 14% at 12 WAT.

POST Herbicide Programs. Kochia densities at the experimental sites ranged from 79 to 108 plants m^{-2} (Table 3). Paraquat + atrazine provided 100% control at all evaluation dates, and was comparable to paraquat + linuron and paraquat + metribuzin treatments (Table 7). The results indicate a combined soil and foliar activity of these effective herbicide mixtures on kochia.

POST control 1 WAT with bromoxynil + fluroxypyr, bromoxynil + pyrasulfotole, glyphosate, saflufenacil + linuron, and tembotrione + atrazine treatments was 92 to 95% (Table 7). Control with bromoxynil + MCPA, carfentrazone-ethyl + 2,4-D, glufosinate, lactofen, and saflufenacil was 87 to 90% 1 WAT. Control with dicamba alone, diflufenzopyr + dicamba + 2,4-D, and topramezone + atrazine was 82% at 1 WAT. Fomesafen and *S*-metolachlor + mesotrione applied POST provided 62 to 77% control of kochia 1 WAT. Control with cloransulam-methyl and thifensulfuron + tribenuron (Group 2, acetolactate synthase [ALS] inhibitor herbicides) + 2,4 D was 35 and 57%, respectively, which was due to the presence of ALS-inhibitor-resistant kochia at the experimental sites (data not shown).

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Table 7. Kochia control at 1, 3, and 5 wk after treatment (WAT) with various POST herbicide treatments at the Montana State University Southern Agricultural Research Center near Huntley, MT.

Herbicide(s)[a]	Rate(s)	1 WAT[b]	3 WAT	5 WAT
	(kg ai or ae ha^{-1})		%	
Bromoxynil + fluroxypyr[c]	0.558 + 0.140	95 bcd	92 cde	82 bcd
Bromoxynil + pyrasulfotole[c,d]	0.229 + 0.040	92 de	85 fg	77 de
Bromoxynil + MCPA	0.560 + 0.560	87 fg	77 jk	65 fg
Carfentrazone-ethyl + 2,4-D[c]	0.034 + 0.560	87 fg	82 ghi	60 gh
Cloransulam-methyl[c]	0.017	35 l	32 o	18 m
Dicamba	0.280	82 h	78 ij	77 de
Diflufenzopyr + dicamba + 2,4-D[c]	0.056 + 0.140 + 0.560	83 gh	82 ghi	78 cde
Fomesafen[c]	0.459	77 i	72 l	40 l
Glyphosate[d]	1.260	95 bcd	93 cd	88 b
Glufosinate[d]	0.593	87 fg	73 kl	52 ij
Lactofen[e]	0.218	88 ef	80 hij	57 hi
Paraquat[c]	0.840	99 ab	95 bc	85 bc
Paraquat + atrazine[c]	0.840 + 0.560	100 a	100 a	100 a
Paraquat + linuron[c]	0.840 + 0.840	99 ab	99 ab	98 a
Paraquat + metribuzin[c]	0.840 + 0.425	99 ab	98 ab	98 a
Saflufenacil[d,e]	0.025	90 ef	82 ghi	67 ef
Saflufenacil + 2,4-D[d,e]	0.025 + 0.560	97 abc	83 gh	72 ef
Saflufenacil + linuron[d,e]	0.025 + 0.840	95 bcd	90 de	78 cde
S-metolachlor + mesotrione[c]	1.866 + 0.184	62 j	57 m	48 jk
Tembotrione + atrazine[e]	0.089 + 0.560	93 cde	88 ef	85 bc
Topramezone + atrazine[e]	0.018 + 0.560	83 gh	83 gh	80 cd
Thifensulfuron + tribenuron + 2,4-D[c]	0.017 + 0.008 + 0.560	57 k	48 n	43 kl

[a] Herbicide treatments were applied to 8- to 10-cm-tall kochia plants in the field.

[b] Means within a column followed by similar letters are not significantly different based on Fisher's protected LSD test at $P < 0.05$.

[c] Nonionic surfactant (NIS) at 0.25% v/v was included.

[d] Ammonium sulfate (AMS) at 2% w/v was included.

[e] Methylated seed oil (MSO) at 1% v/v was included.

In general, kochia control declined by 3 or 5 WAT compared to 1 WAT with majority of the POST herbicides tested (Table 7), except paraquat + atrazine, paraquat + linuron, or paraquat + metribuzin treatments. The observed decline in control was partially due to recovery of treated plants from the herbicide injury and/or survival of late-emerging (July) kochia plants that escaped the POST herbicide application in the absence of a residual tank-mix partner.

In a greenhouse study, Wicks et al. (1993) also reported >95% control of 7.5- to 10-cm-tall kochia plants treated with paraquat (0.3 kg ha^{-1}) 15 DAT. Although carfentrazone or fluroxypyr were not tested alone in our study, >88% kochia control was reported with carfentrazone (0.02 kg ai ha^{-1}) or fluroxypyr (0.14 kg ai ha^{-1}) in a greenhouse study on dicamba-resistant kochia inbreds (Nandula and Manthey 2002). Although a dicamba rate of 0.28 kg ae ha^{-1} was not evaluated previously, kochia control ranged from 70 to 76% with dicamba applied at 0.14 kg ha^{-1} (Nandula and Manthey 2002; Tonks and Westra 1997). Consistent with our results, Lloyd et al. (2011) reported 68 to 77% kochia control 4 WAT with dicamba + diflufenzopyr POST at similar rates. Knezevic et al. (2009) also observed <90% control of 10-cm-tall kochia plants treated with glyphosate (1.059 kg ae ha^{-1}) in Gly-R soybean. Compared to our results, others reported greater kochia control (75 to 90%) with bromoxynil + MCPA applied even at lower rates (0.2 to 0.3 kg ai ha^{-1}) (Tonks and Westra 1997; Wolf et al. 2000), and control with glufosinate in our study was lower (52% with 0.593 kg ai ha^{-1} glufosinate) compared to that obtained (77% with 0.42 kg ha^{-1} glufosinate) in a study conducted by Eberlein et al. (1993).

Alternative POST Herbicides for Gly-R Kochia Control. *Visual Assessment of Control.* The interaction of accession by treatment was significant

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Table 8. Control and shoot dry weight (percentage of nontreated) of Gly-S and Gly-R kochia accessions from Montana 3 wk after treatment with various POST herbicides labeled for corn or soybean.[a,b]

Herbicide(s)	Rate(s)	Gly-S[c]	GIL01	CHES01	CHES02	JOP01	P value
	(kg ai or ae ha^{-1})	Control (%)					
Cloransulam-methyl[d]	0.017	93 a	37 c	29 e	12 e	12 d	0.0002
Fomesafen[d]	0.459	87 bc	88 a	84 b	71 b	73 ab	<0.0001
Lactofen[e]	0.218	91 ab	89 a	89 ab	84 a	74 ab	0.0007
S-metolachlor + mesotrione[d]	1.866 + 0.184	78 d	64 b	77 c	64 c	71 b	0.0018
Tembotrione[e]	0.089	56 e	41 c	38 d	34 d	33 c	<0.0001
Tembotrione + atrazine[e]	0.089 + 0.560	94 a	88 a	88 ab	76 b	78 a	<0.0001
Topramezone[e]	0.018	11 f	11 d	28 e	33 d	16 d	0.0004
Topramezone + atrazine[e]	0.018 + 0.560	84 c	88 a	91 a	75 b	72 b	0.0001
		Dry weight (% of nontreated)					
Cloransulam-methyl[d]	0.017	8 f	66 b	77 a	86 a	76 a	<0.0001
Fomesafen[d]	0.459	19 d	25 d	27 c	38 c	35 d	0.0057
Lactofen[e]	0.218	17 de	28 d	21 d	29 d	36 cd	0.0223
S-metolachlor + mesotrione[d]	1.866 + 0.184	34 c	44 c	30 c	42 c	43 c	0.0399
Tembotrione	0.089	60 b	60 b	58 b	74 b	54 b	0.0357
Tembotrione + atrazine[e]	0.089 + 0.560	11 ef	21 d	20 d	34 cd	36 d	<0.0001
Topramezone	0.018	88 a	88 a	77 a	74 b	69 a	0.0143
Topramezone + atrazine[e]	0.018 + 0.560	17 de	23 d	18 d	36 cd	41 d	<0.0001

[a] Abbreviations: Gly-S, glyphosate-susceptible accession, Huntley, MT; Gly-R, glyphosate-resistant; GIL01, Gly-R accession, Gildford, MT; JOP01, Gly-R accession, Joplin, MT; CHES01, Gly-R accession 1, Chester, MT; CHES02, Gly-R accession 2, Chester, MT.

[b] Herbicide treatments were applied to 8- to 10-cm-tall kochia plants.

[c] For percent control and shoot dry weight, means for a kochia accession within a column followed by similar lowercase letters are not significantly different based on Fisher's protected LSD test at $P < 0.05$.

[d] Nonionic surfactant (NIS) at 0.25% (v/v) was included.

[e] Methylated seed oil (MSO) at 1% (v/v) was included.

($P < 0.0005$), indicating that kochia accessions showed differential response to POST herbicides (labeled for corn/soybean) evaluated in the study. The differential response of the accessions might be attributed to the high genetic diversity of kochia (Kumar et al. 2014; Mengistu and Messersmith 2002).

For the Gly-S kochia accession tested, cloransulam-methyl, lactofen, and tembotrione + atrazine provided 91 to 94% control 3 WAT (Table 8). Control with fomesafen (87%) did not differ from control with lactofen (91%). The addition of atrazine to tembotrione or topramezone improved kochia control by 38 and 73%, respectively, compared with tembotrione or topramezone alone 3 WAT. Control of the Gly-S accession with *S*-metolachlor + mesotrione was 78% 3 WAT.

Besides modest differences in response to herbicides across accessions, control of Gly-R kochia was 71 to 91% at 3 WAT with lactofen, fomesafen, tembotrione + atrazine, or topramezone + atrazine (Table 8). Control of the four Gly-R kochia accessions with *S*-metolachlor + mesotrione was 64 to 77%. Gly-R kochia control with cloransulam-methyl, tembotrione alone, or topramezone alone was poor (≤41 %). The lower control of the Gly-R accessions compared with the Gly-S accession observed with cloransulam-methyl was because the Gly-R accessions were also resistant to the ALS-inhibitor herbicide (data not shown).

Shoot Dry Weight Response. The interaction of accession by treatment was significant ($P < 0.0001$). In general, shoot dry weight reductions of treated kochia accessions were consistent with the control ratings for the herbicides tested. For the Gly-S accession, cloransulam-methyl and tembotrione + atrazine reduced kochia shoot dry weight by 89 to 92% 3 WAT followed by fomesafen, lactofen, and topramezone + atrazine treatments (82% average reduction in shoot dry weight) (Table 8). For the Gly-R accessions, lactofen, fomesafen, tembotrione + atrazine, or

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topramezone + atrazine were the best treatments tested, and reduced shoot dry weight up to 82% 3 WAT. *S*-metolachlor + mesotrione reduced shoot dry weight of Gly-R accessions up to 70%. Consistent with poor control, cloransulam-methyl, tembotrione-, and topramezone-treated Gly-R plants produced greater shoot dry weight among all treatments (Table 8).

In summary, the PRE herbicide field trials suggest that acetochlor + atrazine, pyroxasulfone + atrazine, and *S*-metolachlor + atrazine + mesotrione would provide effective season-long kochia control in corn/grain sorghum. Sulfentrazone and metribuzin would provide effective residual control of kochia in soybean. Evident from the POST herbicide field trials, paraquat plus atrazine, paraquat plus linuron, and paraquat plus metribuzin would be effective burndown programs for kochia control in corn/grain sorghum, corn/fallow, and soybean, respectively. POST kochia control with glyphosate was 88% 5 WAT, and did not differ from bromoxynil + fluroxypyr (labeled in wheat/barley), tembotrione + atrazine (labeled in corn), and topramezone + atrazine (labeled in corn) programs.

Results from the greenhouse experiments suggest that atrazine + tembotrione or atrazine + topramezone would be an effective POST option for Gly-R kochia control in Gly-R corn. Lactofen or fomesafen could potentially provide effective control of Gly-R kochia in Gly-R soybean. Additionally, cloransulam-methyl would be an effective alternative product for Gly-R kochia control in Gly-R soybean, unless kochia plants are resistant to the ALS-inhibitor herbicide.

In conclusion, PRE soil-residual herbicide should serve as a foundation for kochia control programs. As kochia accessions with resistance to group 9 (glyphosate), group 2 (sulfonylureas and imidazolinones), group 5 (atrazine), or group 4 herbicides (dicamba, fluroxypyr) continue to spread and impact larger acreages in the northwestern and north central United States, incorporation of additional effective modes of action (investigated in this research) will be needed to control kochia. Kochia is a highly variable species, and the results reported in this article may not be consistent for all accessions. Growers managing kochia in their fields should pay greater attention to the response of kochia to the herbicides they use, and use a diversity of herbicides and other weed management techniques to avoid selecting for additional herbicide resistance in kochia accessions on their farms.

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