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Comparison of Herbicide Programs for Season-Long Control of Glyphosate-Resistant Common Waterhemp (*Amaranthus rudis*) in Soybean

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The evolution of glyphosate and acetolactate synthase (ALS) inhibitor-resistant common waterhemp in the Midwestern United States has reduced the number of effective POST herbicide options for management of this problem weed in glyphosate-resistant soybean. Moreover, common waterhemp emerges throughout the crop growing season, justifying the need to evaluate herbicide programs that provide season-long control. The objectives of this study were to compare POST-only and PRE followed by (fb) POST herbicide programs for control of glyphosate-resistant common waterhemp in glyphosate-resistant soybean. Field experiments were conducted in 2013 and 2014 in Dodge County, NE, in a field infested with glyphosate-resistant common waterhemp. Programs containing PRE herbicides resulted in ≥83% control of common waterhemp and densities of ≤35 plants m^{-2} at 21 d after PRE (DAPRE). Post-only herbicide programs resulted in <70% control and densities of 107 to 215 plants m^{-2} at 14 d after early-POST (DAEPOST) treatment. PRE fb POST herbicide programs, including saflufenacil plus imazethapyr plus dimethenamid-P, sulfentrazone plus cloransulam, or *S*-metolachlor plus metribuzin, fb fomesafen plus glyphosate; *S*-metolachlor plus fomesafen fb acifluorfen plus glyphosate resulted in >90% control of glyphosate-resistant common waterhemp throughout the growing season, reduced density to ≤7 plants m^{-2}, ≥92% biomass reduction, and soybean yield >2,200 kg ha^{-1}. Averaged across herbicide programs, common waterhemp control was 84%, and density was 15 plants m^{-2} with PRE fb POST herbicide programs compared with 42% control, and density of 101 plants m^{-2} with POST-only herbicide programs at harvest. Results of this study indicated that PRE fb POST herbicide programs with effective modes of action exist for season-long control of glyphosate-resistant common waterhemp in glyphosate-resistant soybean.

Nomenclature: Acetochlor; acifluorfen; chlorimuron-ethyl; cloransulam-methyl; dimethenamid-P; flumioxazin; fomesafen; glyphosate; imazethapyr; lactofen; saflufenacil; *S*-metolachlor; sulfentrazone; thifensulfuron-methyl; common waterhemp, *Amaranthus rudis* Sauer; soybean, *Glycine max* (L.) Merr.
Key words: Biomass reduction, PRE followed by POST, resistance management, soybean yield.

La evolución de *Amaranthus rudis* resistente a glyphosate y a inhibidores de acetolactate synthase en el medio oeste de los Estados Unidos ha reducido el número de opciones efectivas de herbicidas POST para el manejo de esta problemática maleza en soja resistente a glyphosate. Además, *A. rudis* emerge a lo largo de la temporada de crecimiento del cultivo, lo que justifica la necesidad de evaluar programas de herbicidas que brinden control durante toda la temporada. Los objetivos de este estudio fueron comparar programas con sólo herbicidas POST y con herbicidas PRE seguidos por (fb) herbicidas POST para el control de *A. rudis* resistente a glyphosate en soja resistente a glyphosate. Se realizaron experimentos de campo en 2013 y 2014 en el condado Dodge, en Nebraska, en campos infestados con *A. rudis* resistente a glyphosate. Los programas que contenían herbicidas PRE resultaron en ≥83% de control de *A. rudis* y en densidades de ≤35 plantas m^{-2} a 21 d después de PRE (DAPRE). Programas con sólo herbicidas POST resultaron en <70% de control y densidades de 107 a 215 plantas m^{-2} a 14 d después del tratamiento POST temprano (DAEPOST). Programas de herbicidas PRE fb POST, incluyendo saflufenacil más imazethapyr más dimethenamid-P, sulfentrazone más cloransulam, o *S*-metolachlor más metribuzin, fb fomesafen más glyphosate; *S*-metolachlor más fomesafen fb acifluorfen más glyphosate resultaron en >90% de control de *A. rudis* resistente a glyphosate a lo largo de la temporada, densidad reducida a ≤7 plantas m^{-2}, reducción de biomasa ≥92%, y rendimiento de

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soja >2,200 kg ha^{-1}. Promediando los programas de herbicidas, el control de *A. rudis* al momento de la cosecha fue 84%, y la densidad fue 15 plantas m^{-2} con programas de herbicidas PRE fb POST en comparación con 42% de control y densidad de 101 plantas m^{-2} con programas de sólo herbicidas POST. Los resultados de este estudio indicaron que existen programas de herbicidas PRE fb POST con modos de acción efectivos para el control de *A. rudis* resistente a glyphosate durante toda la temporada de crecimiento en soja resistente a glyphosate.

The widespread adoption of glyphosate-resistant crops has increased rates of glyphosate application and reduced the use of soil-applied herbicides, thus reducing the cost of weed control programs (Prince et al. 2012a; Young 2006). Consequently, glyphosate has become the most commonly used herbicide in agriculture worldwide (Dill et al. 2010; Duke and Powles 2008). Moreover, glyphosate-resistant crop technology has encouraged no-till or conservation tillage practices where weed control is primarily based on the application of herbicides (Coffman and Frank 1991; Gianessi 2005; Jhala et al. 2014a; Norsworthy et al. 2012), which is believed to aid in the shift towards small-seeded broadleaf weed species such as common waterhemp (Culpepper 2006; Legleiter and Bradley 2008; Owen 2008).

The continuous use of glyphosate in glyphosate-resistant crops for the past several years has created the unintended consequence of selection pressure on weed communities, resulting in the evolution of glyphosate-resistant weeds (Owen and Zelaya 2005). Horseweed [*Conyza canadensis* (L.) Cronq.] was the first glyphosate-resistant weed reported in the United States (VanGessel 2001), and currently, 35 weed species have evolved resistance to glyphosate in 25 countries worldwide, including 16 species in the United States (Heap 2016a). Six weed species in Nebraska, including common waterhemp, have been shown to be resistant to glyphosate (Jhala 2016; Sarangi et al. 2015). Management of glyphosate-resistant weeds has become the greatest challenge for Nebraska corn (*Zea mays* L.) and soybean growers (Chahal and Jhala 2015; Ganie et al. 2016; Jhala et al. 2014b; Kaur et al. 2014).

Common waterhemp, a summer annual broadleaf weed, is native to the northern United States (Waselkov and Olsen 2014). It can thrive under a wide range of climatic gradients and can be found from arid regions in Texas to humid/semi humid regions of Maine (Costea et al. 2005; Nordby et al. 2007; Sarangi et al. 2016). Surveys conducted in the past few years have listed common waterhemp as one of the most commonly encountered and troublesome weeds in agricultural fields (Prince et al. 2012b; Rosenbaum and Bradley 2013). It is a highly competitive weed, causing significant economic damage to many crops, including corn and soybean (Bensch et al. 2003; Steckel and Sprague 2004). In Illinois, common waterhemp reduced soybean yield by 43% when allowed to compete up to 10 wk after soybean unifoliate expansion, with a density of up to 362 plants m^{-2} (Hager et al. 2002b). Favorable biological attributes of common waterhemp, including its rapid growth (Horak and Loughin 2000) and prolific seed production potential (Steckel et al. 2003) favor its persistence as a successful weed in row-crop production systems in the midwestern United States (Owen 2008).

Common waterhemp is a dioecious species, and the rapid evolution of herbicide resistance in common waterhemp is partially due to the high genetic diversity present in the species and the potential for gene flow (Liu et al. 2012; Sarangi 2016). Legleiter and Bradley (2008) reported the first occurrence of glyphosate-resistant common waterhemp in Missouri, and it has now been confirmed in 18 states (Heap 2016b). In addition, common waterhemp biotypes resistant to acetolactate synthase (ALS) inhibitors (Horak and Peterson 1995), photosystem II inhibitors (Anderson et al. 1996), protoporphyrinogen oxidase (PPO) inhibitors (Shoup et al. 2003), 4-hydroxyphenylpyruvate dioxygenase inhibitors (Hausman et al. 2011), and synthetic auxins (Bernards et al. 2012) have already been confirmed in the United States.

In the midwestern United States, soybean growers are mostly relying on POST herbicides in no-till systems to control troublesome weeds, including pigweed (Amaranthaceae) species (Legleiter et al. 2009; Prince et al. 2012a). Widespread resistance in common waterhemp against ALS-inhibiting herbicides and glyphosate is compelling soybean growers to depend mostly on PPO-inhibiting herbicides such as acifluorfen, fomesafen, or lactofen (Shoup et al. 2003; Shoup and Al-Khatib 2004). Hartzler et al. (1999) reported that common waterhemp has an extended period of emergence compared to other summer annual weed species, and Werle et al. (2014)

considered this weed as a late-emerging species. The PRE (soil-applied) herbicides may lose their residual activity later in the growing season; therefore, the application of POST herbicide is necessary to control late-emerging common waterhemp flushes (Hager et al. 2002a). Conversely, most POST herbicides have limited or no residual activity, meaning that they can control common waterhemp present at the time of herbicide application, but cannot control later-emerging plants. Additionally, herbicide selection and application rates and weed height are important factors to be considered for the effective control of common waterhemp with POST herbicide programs (Chahal et al. 2015; Falk et al. 2006; Ganie et al. 2015; Hager et al. 2003).

Several PRE herbicides have been registered for weed control in soybean, and several reports have confirmed excellent control of pigweeds with certain PRE herbicides. For example, sulfentrazone applied PRE alone or tank-mixed with other residual herbicides such as *S*-metolachlor, chlorimuron, or cloransulam resulted in >90% control of common waterhemp up to 56 d after application (Hager et al. 2002a; Krausz and Young 2003). Legleiter et al. (2009) reported that alachlor, flumioxazin, *S*-metolachlor plus metribuzin, or sulfentrazone followed by (fb) POST application of lactofen or acifluorfen provided ≥85% control of glyphosate-resistant common waterhemp at 90 d after PRE (DAPRE). Similarly, a study conducted in Virginia showed that PRE applications of flumioxazin plus chlorimuron, and saflufenacil plus imazethapyr resulted in ≥89% control of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri* S. Wats), a species closely related to common waterhemp, at 2 wk after herbicide application (Ahmed and Holshouser 2012).

Limited scientific literature is available for comparison of POST-only programs with PRE fb POST programs for controlling glyphosate-resistant common waterhemp in glyphosate-resistant soybean. Moreover, this information would be beneficial for soybean growers in developing season-long effective plans for controlling glyphosate-resistant common waterhemp. The objectives of this study were to compare POST-only herbicide programs with PRE fb POST programs to control glyphosate-resistant common waterhemp and to evaluate their effect on soybean injury and yield. We hypothesized that PRE fb POST herbicide programs would provide better control of glyphosate-resistant common waterhemp and higher soybean yield compared to POST-only programs.

Materials and Methods

Site Description. Field experiments were conducted in Dodge County, NE (41.47°N, 96.46°W) in 2013 and 2014 in a grower's field infested with glyphosate-resistant common waterhemp. The site was selected for having a uniform density of >300 common waterhemp plants m^{-2}. The field had been under glyphosate-resistant corn or soybean production with reliance on glyphosate for weed control for at least 8 yr. Greenhouse dose-response studies confirmed that the level of glyphosate-resistance in the biotype collected from the experimental site was 24-fold compared to a known glyphosate-susceptible common waterhemp biotype (Sarangi et al. 2015). The soil texture at the experiment site was determined as clay with a pH of 6.7, with 29% sand, 30% silt, 41% clay, and 4% organic matter. Glyphosate-resistant soybean (Cv. "Pioneer 93Y12") was planted into a conventionally tilled seedbed at 346,000 seeds ha^{-1} in rows spaced 76.2 cm apart. Soybean planting was delayed (June 11) in 2013 due to adverse weather conditions in May, though the planting date was May 20 in 2014. The plots were 3 m wide by 9 m long. The experimental site was under rainfed/dryland environment with no supplemental irrigation. Fertilizer applications were made based on soil test recommendations. During both years, precipitation was adequate to activate the residual herbicides applied in this study (Table 1).

Field experiments were arranged in a randomized complete block design with each treatment replicated four times. The herbicide programs evaluated to control glyphosate-resistant common waterhemp consisted of early-POST fb late-POST (i.e. POST-only) and PRE fb POST herbicide programs (Table 2). A nontreated control was included for comparison. Herbicides were applied with a handheld CO_2-pressurized backpack sprayer equipped with AIXR 110015 flat fan nozzles (TeeJet® Technologies, Spraying Systems Co., P.O. Box 7900, Wheaton, IL 60187) calibrated to deliver 140 L ha^{-1} at 276 kPa at a constant speed of 4.8 km h^{-1}. The PRE herbicides were applied on the day of or day following soybean planting, whereas early-POST (E-POST) herbicides were

Table 1. Monthly mean air temperature and total precipitation during the 2013 and 2014 growing seasons and 30 yr average at Fremont, NE.[a]

	Mean temperature			Total precipitation		
Month	2013	2014	30 yr average	2013	2014	30 yr average
	C			mm		
March	0.1	1.1	4.1	47.5	10.7	43.7
April	7.0	10.3	10.9	120.0	51.8	77.5
May	15.5	16.6	17.2	171.5	120.0	105.2
June	21.6	22.2	22.6	83.8	317.8	125.0
July	23.8	22.0	24.7	14.2	18.8	85.1
August	23.7	23.2	23.4	73.2	154.2	87.4
September	20.9	17.7	18.7	23.9	153.4	77.5
October	11.2	12.6	11.8	145.5	66.0	55.6
Annual	9.4	9.3	10.7	734.6	961.6	752.1

[a] Mean air temperature and total precipitation data were obtained from National Oceanic and Atmospheric Administration (2015).

applied at 21 DAPRE (July 1 2013 and June 9 2014), when common waterhemp was 8- to 12-cm tall and soybean was at the V2 to V3 stage. Late-POST (L-POST) herbicide applications were made 14 d after E-POST (DAEPOST) applications (July 15 2013 and June 24 2014), when common waterhemp plants were 15- to 20-cm tall and soybean was at the V4 to V5 stage.

Data Collection. Common waterhemp control was assessed visually at 21 DAPRE, 14 DAEPOST, 14 d after late POST (DALPOST), 28 DALPOST, and at soybean harvest on a scale of 0% to 100%, with 0% meaning no control of common waterhemp and 100% meaning complete control. Common waterhemp densities were also recorded on the same dates mentioned for the visual control, by counting the number of common waterhemp plants in two $0.25\,\mathrm{m}^2$ quadrats placed randomly between the center two soybean rows in each plot and are presented as number of plants m^{-2}. At 28 DALPOST, common waterhemp plants surviving herbicide treatments were cut at the soil surface from two randomly selected $0.25\,\mathrm{m}^2$ quadrats per plot and oven-dried at 65 C until they reached a constant weight. Aboveground dry biomass was recorded and converted into percent biomass reduction compared to the nontreated control:

$$\%\,\text{biomass reduction} = [(C - B)/C] \times 100 \qquad [1]$$

where C is the biomass of the nontreated control plot, and B is the biomass of an individual treated plot. Soybean injury data were recorded at 14 DAPRE, 7 DAEPOST, 7 DALPOST, and 28 DALPOST on a scale of 0% to 100%, with 0% meaning no soybean injury and 100% meaning death of the soybean plants. Soybeans were harvested from the center two rows in each plot using a plot combine, and grain yield was adjusted to 13% moisture content.

Statistical Analysis. Data were subjected to ANOVA using the PROC GLIMMIX procedure in SAS® version 9.3 (SAS Institute Inc., 100 SAS Campus Drive, Cary, NC 27513-2414). In the model, years (experimental runs) and treatments were considered fixed effects, whereas blocks (nested within year) were considered random effects. Data were tested for normality with PROC UNIVARIATE. Visual control estimates, percent biomass reduction, and soybean injury data were arcsine square root transformed before analysis; however, back-transformed data are presented with mean separation based on transformed data. Individual treatment means were separated at the 5% level of significance using Fisher's protected LSD test. To determine relative treatment efficacy for common waterhemp control, density, biomass reduction, and soybean yield *a priori* orthogonal contrasts (single degree of freedom contrasts) were performed.

Results and Discussion

Year-by-treatment interactions for glyphosate-resistant common waterhemp control, density, and

Table 2. Details of herbicide treatments, application timing, and rates used for control of glyphosate-resistant common waterhemp in soybean in field experiments conducted in Nebraska in 2013 and 2014.[a]

Herbicide	Trade name	Application timing	Rate	Manufacturer	Adjuvants[b]
			— $\text{g ae or ai ha}^{-1}$ —		
Glyphosate fb Glyphosate	Roundup PowerMax fb Roundup PowerMax	Early POST fb Late POST	1,730 870	Monsanto Company, St. Louis, MO 63167 Monsanto Co.	AMS fb AMS
Imazethapyr + Glyphosate fb Glyphosate	Extreme fb Roundup PowerMax	Early POST fb Late POST	910 870	BASF Corporation, Research Triangle Park, NC 27709 Monsanto Co.	NIS + AMS fb AMS
Imazethapyr + Glyphosate + Acetochlor fb Glyphosate	Extreme + Warrant fb Roundup PowerMax	Early POST fb Late POST	910 + 1,680 870	BASF Corp. + Monsanto Co. Monsanto Co.	NIS + AMS fb AMS
Imazethapyr + Fomesafen + Glyphosate + Acetochlor fb Glyphosate	Extreme + Flexstar GT + Warrant fb Roundup PowerMax	Early POST fb Late POST	910 + 1,380 + 1,680 870	BASF Corp. + Syngenta Crop Protection, Inc., Greensboro, NC 27419 + Monsanto Co. Monsanto Co.	NIS + AMS fb AMS
Imazethapyr + Fomesafen + Glyphosate + Acetochlor fb Lactofen + Glyphosate	Extreme + Flexstar GT + Warrant fb Cobra + Roundup PowerMax	Early POST fb Late POST	910 + 1,380 + 1,680 220 + 870	BASF Corp. + Syngenta Crop Protec., Inc. + Monsanto Co. Valent U.S.A. Corporation, Walnut Creek, CA 94596 + Monsanto Co.	NIS + AMS fb COC + AMS
Flumioxazin + Chlorimuron fb Fomesafen + Glyphosate	Valor XLT fb Flexstar GT	PRE fb Late POST	113 1380	Valent U.S.A. Corp. Syngenta Crop Protec., Inc.	No Adjuvants fb COC + AMS
Saflufenacil + Imazethapyr fb Fomesafen + Glyphosate	Optill fb Flexstar GT	PRE fb Late POST	95 1,380	BASF Corp. Syngenta Crop Protec., Inc.	No Adjuvants fb COC + AMS
Saflufenacil + Imazethapyr + Dimethenamid-P fb Fomesafen + Glyphosate	Optill + Outlook fb Flexstar GT	PRE fb Late POST	95 + 525 1,380	BASF Corp. + BASF Corp. Syngenta Crop Protec., Inc.	No Adjuvants fb COC + AMS
Sulfentrazone + Imazethapyr fb Fomesafen + Glyphosate	Authority Assist fb Flexstar GT	PRE fb Late POST	420 1,380	FMC Corporation, Philadelphia, PA 19103 Syngenta Crop Protec., Inc.	No Adjuvants fb COC + AMS
Sulfentrazone + Chlorimuron fb Fomesafen + Glyphosate	Authority XL fb Flexstar GT	PRE fb Late POST	392 1380	FMC Corp. Syngenta Crop Protec., Inc.	No Adjuvants fb COC + AMS
Sulfentrazone + Cloransulam fb Fomesafen + Glyphosate	Sonic fb Flexstar GT	PRE fb Late POST	392 1380	Dow AgroSciences LLC, Indianapolis, IN 46268 Syngenta Crop Protec., Inc.	No Adjuvants fb COC + AMS
Chlorimuron + Thifensulfuron + Flumioxazin fb Fomesafen + Glyphosate	Enlite fb Flexstar GT	PRE fb Late POST	94 1,380	E. I. du Pont de Nemours and Company, Wilmington, DE 19898 Syngenta Crop Protec., Inc.	No Adjuvants fb COC + AMS
S-metolachlor fb Fomesafen + Glyphosate	Dual II Magnum fb Flexstar GT	PRE fb Late POST	1,420 1,380	Syngenta Crop Protec., Inc. Syngenta Crop Protec., Inc.	No Adjuvants fb COC + AMS
S-metolachlor + Fomesafen fb Acifluorfen + Glyphosate	Prefix fb Ultra Blazer + Roundup PowerMax	PRE fb Late POST	1,480 560 + 870	Syngenta Crop Protec., Inc. United Phosphorus, Inc. King of Prussia, PA 19406 + Monsanto Co.	No Adjuvants fb COC + AMS
Flumioxazin + Pyroxasulfone fb Fomesafen + Glyphosate	Fierce fb Flexstar GT	PRE fb Late POST	200 1,380	Valent U.S.A. Corp. Syngenta Crop Protec., Inc.	No Adjuvants fb COC + AMS
Pyroxasulfone fb Fomesafen + Glyphosate	Zidua fb Flexstar GT	PRE fb Late POST	208 1,380	BASF Corp. Syngenta Crop Protec., Inc.	No Adjuvants fb COC + AMS

Table 2. (*Continued*)

Herbicide	Trade name	Application timing	Rate	Manufacturer	Adjuvants[b]
S-metolachlor + Metribuzin fb	Boundary fb	PRE fb	2,050	Syngenta Crop Protec., Inc.	No Adjuvants fb COC + AMS
Fomesafen + Glyphosate	Flexstar GT	Late POST	1380	Syngenta Crop Protec., Inc.	
Pendimethalin + Metribuzin fb	Prowl H_2O + Sencor fb	PRE fb	1,920 + 420	BASF Corp. + Bayer CropScience LP, Research Triangle Park, NC 27709	No Adjuvants fb COC + AMS
Fomesafen + Glyphosate	Flexstar GT	Late POST	1380	Syngenta Crop Protec., Inc.	

[a] Abbreviations: AMS, ammonium sulfate (DSM Chemicals North America Inc., Augusta, GA); COC, crop oil concentrate (Agridex, Helena Chemical Co., Collierville, TN); fb, followed by; NIS, nonionic surfactant (Induce, Helena Chemical Co., Collierville, TN).

[b] AMS was mixed at 2.5% wt/v; COC was mixed at 1% v/v; NIS was mixed at 0.25% v/v.

biomass were not significant; therefore data were combined across the two years.

Common Waterhemp Control. The PRE herbicide programs provided ≥83% control of glyphosate-resistant common waterhemp at 21 DAPRE, indicating the importance of early season control of common waterhemp using residual PRE herbicides (Table 3). Among PRE herbicides, sulfentrazone-based tank mixtures, pyroxasulfone [5-(difluoromethoxy)-1-methyl-3-(trifluoromethyl)pyrazol-4-ylmethyl 4,5-dihydro-5,5-dimethyl-1,2-oxazol-3-yl sulfone], alone or tank-mixed with flumioxazin, *S*-metolachlor plus fomesafen/metribuzin, and saflufenacil plus imazethapyr plus dimethenamid-P provided 94% to 97% control at 21 DAPRE. Several studies reported application of PRE herbicides as one of the most effective methods for early-season control of common waterhemp; for example, Johnson et al. (2012) reported that the PRE application of sulfentrazone tank-mixed with cloransulam or imazethapyr, *S*-metolachlor plus fomesafen provided 96% to 99% control of common waterhemp at 27 d after planting. Aulakh and Jhala (2015) reported that the application of PRE herbicides resulted in ≥92% control of common waterhemp at 15 DAPRE. Similarly, Meyer et al. (2015) reported that PRE herbicide programs provided at least 95% control of common waterhemp at 3 to 4 wk after herbicide application.

Due to decline in residual activity of pyroxasulfone applied alone or tank-mixed with flumioxazin, common waterhemp control reduced to ≤86% at 14 DAEPOST (Table 3). Similarly, Knezevic et al. (2009) reported that pyroxasulfone applied at 152 g ai ha^{-1} provided 90% control of tall waterhemp [*Amaranthus tuberculatus* (Moq.) Sauer] at 28 d after treatment (DAT), though higher rates (≥198 g ai ha^{-1}) were needed to achieve the same level of control at 45 and 65 DAT. The POST-only herbicide programs resulted in ≤70% control at 14 DAEPOST, which was lower than PRE fb POST herbicide programs (≥83%), except for *S*-metolachlor or pendimethalin plus metribuzin fb fomesafen plus glyphosate, which resulted in <80% control (Table 3). Averaged across herbicide treatments, control of glyphosate-resistant common waterhemp was 87% at 14 DAEPOST compared to 57% with only E-POST application of herbicides.

The POST-only herbicide programs resulted in <82% control of glyphosate-resistant common waterhemp compared to up to 97% control with PRE fb

Table 3. Control of glyphosate-resistant common waterhemp in glyphosate-resistant soybean at 21 days after preemergence (DAPRE), 14 days after early postemergence (DAEPOST), 14 days after late postemergence (DALPOST), and at harvest in field experiments conducted in Dodge County, NE in 2013 and 2014.

			Common waterhemp control [b,c]			
Herbicide[a]	Application timing[a]	Rate	21 DAPRE[d]	14 DAEPOST	14 DALPOST	At harvest
		— g ae or ai ha^{-1} —		%		
Glyphosate fb glyphosate	Early POST fb Late POST	1,730 870	—	26 i	56 g	23 i
Imazethapyr + glyphosate fb glyphosate	Early POST fb Late POST	910 870	—	56 h	59 g	37 h
Imazethapyr + glyphosate + acetochlor fb glyphosate	Early POST fb Late POST	910 + 1,680 870	—	69 fg	61 f	42 gh
Imazethapyr + fomesafen + glyphosate + acetochlor fb glyphosate	Early POST fb Late POST	910 + 1,380 + 1,680 870	—	70 fg	60 g	49 fg
Imazethapyr + fomesafen + glyphosate + acetochlor fb lactofen + glyphosate	Early POST fb Late POST	910 + 1,380 + 1,680 220 + 870	—	64 gh	82 e	59 f
Flumioxazin + chlorimuron fb fomesafen + glyphosate	PRE fb Late POST	113 1,380	92 bcd	85 cd	90 bcd	83 cd
Saflufenacil + imazethapyr fb fomesafen + glyphosate	PRE fb Late POST	95 1,380	91 cd	87 bcd	89 cde	84 bcd
Saflufenacil + imazethapyr + dimethenamid-P fb fomesafen + glyphosate	PRE fb Late POST	95 + 525 1,380	97 a	93 ab	97 a	96 a
Sulfentrazone + imazethapyr fb fomesafen + glyphosate	PRE fb Late POST	420 1,380	97 a	94 a	90 bcd	83 cd
Sulfentrazone + chlorimuron fb fomesafen + glyphosate	PRE fb Late POST	392 1,380	95 abc	91 abc	94 abc	86 bc
Sulfentrazone + cloransulam fb fomesafen + glyphosate	PRE fb Late POST	392 1,380	96 ab	94 a	95 ab	91 ab
Chlorimuron + thifensulfuron + flumioxazin fb fomesafen + glyphosate	PRE fb Late POST	94 1,380	88 de	83 de	86 de	72 e
S-metolachlor fb fomesafen + glyphosate	PRE fb Late POST	1,420 1,380	83 e	66 g	72 f	61 f
S-metolachlor + fomesafen fb acifluorfen + glyphosate	PRE fb Late POST	1,480 560 + 870	96 ab	93 ab	97 a	96 a
Flumioxazin + pyroxasulfone fb fomesafen + glyphosate	PRE fb Late POST	200 1,380	94 abc	86 cd	90 bcd	88 bc
Pyroxasulfone fb fomesafen + glyphosate	PRE fb Late POST	208 1,380	95 abc	83 de	88 de	83 cd
S-metolachlor + metribuzin fb fomesafen + glyphosate	PRE fb Late POST	2,050 1,380	97 a	94 a	96 a	91 ab
Pendimethalin + metribuzin fb fomesafen + glyphosate	PRE fb Late POST	1,920 + 420 1,380	92 bcd	77 ef	86 de	75 de
p-value			<0.0001	<0.0001	<0.0001	<0.0001
Contrasts [e]						
POST-only vs. PRE fb POST			—	57 vs. 87 *	64 vs. 90 *	42 vs. 84 *

[a] Abbreviations: fb, followed by.

[b] Data were arc-sine square-root transformed before analysis; however, back-transformed original mean values are presented based on the interpretation from the transformed data.

[c] Means presented within each column with no common letter(s) are significantly different according to Fisher's protected LSD where $\alpha = 0.05$.

[d] Early-POST herbicides were not applied at this time; therefore, control in POST-only treatments were zero. Data from POST-only treatments were not included in analysis at 21 DAPRE.

[e] *a priori* orthogonal contrasts; * = Significant ($p < 0.05$).

POST programs at 14 DALPOST (Table 3). Relatively lower control of common waterhemp in POST herbicide program can be attributed to the larger plant size at the time of herbicide applications and lower herbicide coverage due to dense population, especially L-POST herbicides that were applied at the plant height of 15- to 20-cm and a density of >100 plants m^{-2} in the POST-only herbicide programs. Similarly, Hager et al. (2003) reported that common waterhemp control was dependent on the height of the plants; therefore, L-POST herbicide applications with acifluorfen, fomesafen, or lactofen showed ≤86% control of common waterhemp, whereas control was up to 91% at 21 DAT with E-POST applications. The PPO-inhibitors are contact herbicides that require adequate spray coverage to provide optimum weed control, especially in dense foliage (Anonymous 2012; Creech et al. 2015). At 14 DALPOST, control of glyphosate-resistant common waterhemp was ≥94% with several PRE fb POST herbicide programs (Table 3). Similarly, Patton (2013) reported that the application of sulfentrazone-based PRE herbicides fb POST application of fomesafen and glyphosate, saflufenacil fb fomesafen plus glyphosate, *S*-metolachlor plus metribuzin fb fomesafen plus glyphosate provided ≥98% control of common waterhemp throughout the growing season. Owen et al. (2010) also reported that the application of saflufenacil plus imazethapyr fb glyphosate provided 96% and 91% control of common waterhemp at 3 and 7 wk after POST herbicide application, respectively.

Later in the season (at soybean harvest), control of glyphosate-resistant common waterhemp showed trends similar to earlier observations. Averaged across herbicide programs, control was 84% with PRE fb POST herbicide programs compared with 42% control under POST-only herbicide programs (Table 3). Results of this study showed that control of glyphosate-resistant common waterhemp was consistently higher with PRE fb POST herbicide programs compared to the POST-only programs. Similar results were reported by Johnson et al. (2012), Legleiter et al. (2009), and Schuster and Smeda (2007), where PRE fb POST herbicide programs resulted in higher control of common waterhemp compared to POST-only programs.

Common Waterhemp Density and Biomass. The results of common waterhemp control were reflected in common waterhemp density and biomass (Table 4). Application of PRE herbicides reduced common waterhemp density to ≤35 plants m^{-2} compared with >300 plants m^{-2} without any herbicide application at 21 DAPRE. At 14 DAEPOST, the nontreated control had the highest number of common waterhemp plants (242 m^{-2}), which was comparable with the sequential glyphosate treatments (215 plants m^{-2}), indicating the presence of glyphosate-resistant common waterhemp at the experimental site. Averaged across the PRE fb POST herbicide programs, common waterhemp density increased (13 plants m^{-2}) at 14 DAEPOST compared to 6 plants m^{-2} at 21 DAPRE; mainly due to reduction in residual activity of soil-applied PRE herbicides and the continuous new emergence of common waterhemp (Table 4). At 14 DALPOST, POST-only treatments of imazethapyr plus fomesafen plus glyphosate plus acetochlor fb lactofen plus glyphosate reduced common waterhemp density to 30 plants m^{-2}, which was comparable to several PRE fb POST herbicide programs, including saflufenacil plus imazethapyr, *S*-metolachlor, or pendimethalin plus metribuzin fb fomesafen plus glyphosate (Table 4). The residual activity of microencapsulated acetochlor tank-mixed with other herbicides in POST herbicide programs can suppress common waterhemp emergence later in the growing season (Jhala et al. 2015). Similarly, Cahoon et al. (2015) and Sarangi et al. (2013) reported that microencapsulated acetochlor applied alone or tank-mixed with other residual herbicides showed >90% control of common waterhemp and Palmer amaranth, reducing plant density significantly.

The precipitation in early August during 2013 and 2014 (Table 1) triggered the late emergence of common waterhemp that resulted in slightly higher density at harvest and the overall increase in density from 14 DALPOST was estimated as 16% and 25% in POST-only and PRE fb POST treatments, respectively (Table 4). Hartzler et al. (1999) reported that common waterhemp emergence can be enhanced after substantial amounts of rainfall. At harvest, lower common waterhemp densities (≤12 plants m^{-2}) were observed with herbicide programs including saflufenacil plus imazethapyr plus dimethenamid-P fb fomesafen plus glyphosate, sulfentrazone plus cloransulam fb fomesafen plus glyphosate, *S*-metolachlor plus fomesafen fb acifluorfen plus glyphosate, flumioxazin plus pyroxasulfone fb fomesafen plus glyphosate, and

Table 4. Effect of herbicide programs on glyphosate-resistant common waterhemp density at 21 days after preemergence (DAPRE), 14 days after early postemergence (DAEPOST), 14 days after late postemergence (DALPOST), and at harvest, and on biomass reduction in glyphosate-resistant soybean in field experiments conducted in Dodge County, NE in 2013 and 2014.

			Common waterhemp density [b]				
Herbicide[a]	Application timing[a]	Rate	21 DAPRE	14 DAEPOST	14 DALPOST	At harvest	Biomass reduction[b,c]
		— g ae or ai ha^{-1} —	#plants m^{-2}				— % —
Nontreated control	—	—	307 b	242 a	186 a	162 a	0
Glyphosate fb	Early POST fb	1,730	391 a	215 a	107 b	135 b	23 g
glyphosate	Late POST	870					
Imazethapyr + glyphosate fb	Early POST fb	910	313 b	147 b	100 b	118 c	25 g
glyphosate	Late POST	870					
Imazethapyr + glyphosate + acetochlor fb	Early POST fb	910 + 1,680	333 ab	116 bc	100 b	93 d	30 fg
glyphosate	Late POST	870					
Imazethapyr + fomesafen + glyphosate + acetochlor fb	Early POST fb	910 + 1,380 + 1,680	335 ab	107 c	100 b	80 e	40 efg
glyphosate	Late POST	870					
Imazethapyr + fomesafen + glyphosate + acetochlor fb	Early POST fb	910 + 1,380 + 1,680	323 b	133 bc	30 c	79 e	48 def
lactofen + glyphosate	Late POST	220 + 870					
Flumioxazin + chlorimuron fb	PRE fb	113	7 c	17 de	13 def	19 fg	89 ab
fomesafen + glyphosate	Late POST	1,380					
Saflufenacil + imazethapyr fb	PRE fb	95	6 c	11 de	19 cde	16 ghi	82 bc
fomesafen + glyphosate	Late POST	1,380					
Saflufenacil + imazethapyr + dimethenamid-P fb	PRE fb	95 + 525	1 c	4 e	2 f	2 j	97 a
fomesafen + glyphosate	Late POST	1,380					
Sulfentrazone + imazethapyr fb	PRE fb	420	1 c	2 e	12 def	22 fg	93 ab
fomesafen + glyphosate	Late POST	1,380					
Sulfentrazone + chlorimuron fb	PRE fb	392	2 c	2 e	4 f	20 fg	88 ab
fomesafen + glyphosate	Late POST	1,380					
Sulfentrazone + cloransulam fb	PRE fb	392	1 c	2 e	6 ef	6 ij	92 ab
fomesafen + flyphosate	Late POST	1,380					
Chlorimuron + thifensulfuron + flumioxazin fb	PRE fb	94	10 c	27 de	13 def	20 fg	69 cd
fomesafen + glyphosate	Late POST	1,380					
S-metolachlor fb	PRE fb	1,420	35 c	37 d	34 c	29 f	57 de
fomesafen + glyphosate	Late POST	1,380					
S-metolachlor + fomesafen fb	PRE fb	1,480	1 c	3 e	2 f	2 j	97 a
acifluorfen + glyphosate	Late POST	560 + 870					
Flumioxazin + pyroxasulfone fb	PRE fb	200	2 c	21 de	8 def	12 ghij	89 ab
fomesafen + glyphosate	Late POST	1,380					
Pyroxasulfone fb	PRE fb	208	6 c	17 de	13 def	18 fgh	87 ab
fomesafen + glyphosate	Late POST	1,380					
S-metolachlor + metribuzin fb	PRE fb	2,050	1 c	5 e	3 f	7 hij	97 a
fomesafen + glyphosate	Late POST	1,380					
Pendimethalin + metribuzin fb	PRE fb	1,920 + 420	9 c	26 de	21 cd	21 fg	78 bc
fomesafen + glyphosate	Late POST	1,380					
p-value			<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Contrasts [d]							
POST-only vs. PRE fb POST			—	144 vs. 13 *	87 vs. 12 *	101 vs. 15 *	33 vs. 86 *

[a] Abbreviations: fb, followed by.

[b] Means presented within each column with no common letter(s) are significantly different according to Fisher's protected LSD where $\alpha = 0.05$.

[c] Data were arc-sine square root transformed before analysis; however, back-transformed original mean values are presented based on the interpretation from the transformed data.

[d] *a priori* orthogonal contrasts; *, significant ($p < 0.05$); NS, non-significant.

S-metolachlor plus metribuzin fb fomesafen plus glyphosate (Table 4). Legleiter et al. (2009) also reported that PRE fb POST herbicide programs reduced common waterhemp density up to 1 plant m^{-2} at 8 wk after POST herbicide treatments.

Common waterhemp biomass followed the same trend as common waterhemp control and density (Table 4). More than 85% reduction in biomass was observed in the PRE fb POST treatments including flumioxazin plus chlorimuron/pyroxasulfone, saflufenacil plus imazethapyr plus dimethenamid-P, sulfentrazone plus imazethapyr/chlorimuron/cloransulam, pyroxasulfone, *S*-metolachlor plus metribuzin, and all followed by fomesafen plus glyphosate and with *S*-metolachlor plus fomesafen fb acifluorfen plus glyphosate. The contrast analysis suggested that PRE fb POST herbicide programs provided 86% reduction in common waterhemp biomass compared with 33% reduction with POST-only programs.

Soybean Injury and Yield. Soybean injury at 14 DAPRE and at 7 DAEPOST was minimal (<6%); therefore, only injury at 7 DALPOST is presented (Table 5). The late-POST application of lactofen plus glyphosate resulted in 24% injury at 7 DALPOST compared with 15% and ≤6% injury when glyphosate was tank-mixed with acifluorfen or fomesafen, respectively. However, soybean plants were resilient enough to overcome injury at 28 DALPOST (data not shown). POST-application of PPO inhibitors during hot and humid weather may cause soybean injury at 7 to 14 DAT (Sarangi and Jhala 2015). Several other studies reported similar level of soybean injury due to POST application of PPO inhibitors, without affecting soybean yield (Legleiter and Bradley 2008; Patton 2013; Riley and Bradley 2014).

Year-by-treatment interaction was significant for soybean yield; therefore, data from 2013 and 2014 were analyzed separately (Table 5). The difference in soybean yield might be due to the substantial amount of rainfall (>150 mm) received during August and September in 2014, which resulted in stagnant water conditions for several days, affecting soybean growth and yield (Table 1). Saflufenacil plus imazethapyr plus dimethenamid-P fb fomesafen plus glyphosate resulted in 2,559 and 2,404 kg ha^{-1} soybean yields in 2013 and 2014, respectively, which were comparable to soybean yields obtained in herbicide programs including sulfentrazone plus cloransulam fb fomesafen plus glyphosate, *S*-metolachlor plus fomesafen fb acifluorfen plus glyphosate, *S*-metolachlor plus metribuzin fb fomesafen plus glyphosate (Table 5). Similarly, Legleiter et al. (2009) reported the highest soybean yield (≥3,100 kg ha^{-1}) with *S*-metolachlor plus metribuzin fb lactofen/acifluorfen plus glyphosate compared to other PRE fb POST and POST-only herbicide programs.

Averaged across PRE fb POST herbicide programs, soybean yield was 2,053 and 1,974 kg ha^{-1} in 2013 and 2014, respectively, whereas the average yield in the POST-only programs was 1,537 and 1,048 kg ha^{-1} in 2013 and 2014, respectively. Results of this study indicate that early-season common waterhemp control using PRE residual herbicides is important to avoid soybean yield reduction. Though common waterhemp can emerge throughout the crop growing season, it is essential to control weed species effectively during the critical period of weed control in soybean, which ranges from the V1 (first trifoliate stage) to the V4 stage of soybean development, depending on the climate, row spacing, and weed species and density (Knezevic et al. 2003; Meyer et al. 2015). In a previous study conducted in Illinois, Hager et al. (2002b) reported that removal of common waterhemp no later than 2 wk after soybean unifoliate leaf expansion is extremely important in preventing yield reduction.

Practical Implications. Results of this study indicated that few PRE fb POST herbicide programs evaluated in this study resulted in >90% season-long common waterhemp control, significant reduction in density and biomass, and high soybean yields. In fact, averaged across programs, PRE fb POST programs provided >80% control throughout the growing season compared to POST-only programs (<65%). Effective control of glyphosate-resistant common waterhemp means less seed production per unit area, which reduces the weed seed bank (Buhler and Hartzler 2001; Legleiter et al. 2009). The application of soil-residual herbicides applied PRE is essential for providing early-season control of common waterhemp. PRE applications of very-long-chain fatty acid–inhibiting herbicides, including acetochlor, *S*-metolachlor, or pyroxasulfone are effective initially (25 to 35 DAT) for controlling common waterhemp, depending upon environmental conditions; however, POST herbicide

Table 5. Effect of herbicide programs on soybean injury and yield in field experiments conducted in Dodge County, NE in 2013 and 2014.

Herbicide[a]	Application timing[a]	Rate	Soybean injury [b,c]	Soybean yield [b,d]	
				2013	2014
		— g ae or ai ha^{-1} —	— % —	— kg ha^{-1} —	
Nontreated control	—	—	0	926 g	852 i
Glyphosate fb	Early POST fb	1,730	0 d	1,289 fg	879 i
glyphosate	Late POST	870			
Imazethapyr + glyphosate fb	Early POST fb	910	0 d	1,403 ef	966 i
glyphosate	Late POST	870			
Imazethapyr + glyphosate + acetochlor fb	Early POST fb	910 + 1,680	0 d	1,687 de	1,077 hi
glyphosate	Late POST	870			
Imazethapyr + fomesafen + glyphosate + acetochlor fb	Early POST fb	910 + 1,380 + 1,680	0 d	1,649 def	985 i
glyphosate	Late POST	870			
Imazethapyr + fomesafen + glyphosate + acetochlor fb	Early POST fb	910 + 1,380 + 1,680	24 a	1,655 def	1,334 gh
lactofen + glyphosate	Late POST	220 + 870			
Flumioxazin + chlorimuron fb	PRE fb	113	3 cd	1,993 cd	1,938 cde
fomesafen + glyphosate	Late POST	1,380			
Saflufenacil + Imazethapyr fb	PRE fb	95	2 cd	2,034 bcd	1,910 cde
fomesafen + glyphosate	Late POST	1,380			
Saflufenacil + imazethapyr + dimethenamid-P fb	PRE fb	95 + 525	3 cd	2,559 a	2,404 a
fomesafen + glyphosate	Late POST	1,380			
Sulfentrazone + imazethapyr fb	PRE fb	420	4 cd	1,898 d	1,870 de
fomesafen + glyphosate	Late POST	1,380			
Sulfentrazone + chlorimuron fb	PRE fb	392	5 c	1,927 d	1,978 cde
fomesafen + glyphosate	Late POST	1,380			
Sulfentrazone + cloransulam fb	PRE fb	392	3 cd	2,335 abc	2,235 abc
fomesafen + glyphosate	Late POST	1,380			
Chlorimuron + thifensulfuron + flumioxazin fb	PRE fb	94	4 cd	1,717 de	1,736 ef
fomesafen + glyphosate	Late POST	1,380			
S-metolachlor fb	PRE fb	1,420	6 c	1,684 def	1,431 fg
fomesafen + glyphosate	Late POST	1,380			
S-metolachlor + fomesafen fb	PRE fb	1,480	15 b	2,584 a	2,345 ab
acifluorfen + glyphosate	Late POST	560 + 870			
Flumioxazin + pyroxasulfone fb	PRE fb	200	6 c	1,885 d	2,014 bcde
fomesafen + glyphosate	Late POST	1,380			
Pyroxasulfone fb	PRE fb	208	5 c	1,890 d	1,796 e
fomesafen + glyphosate	Late POST	1,380			
S-metolachlor + metribuzin fb	PRE fb	2,050	3 cd	2,430 ab	2,201 abcd
fomesafen + glyphosate	Late POST	1,380			
Pendimethalin + metribuzin fb	PRE fb	1,920 + 420	6 c	1,759 de	1,798 e
fomesafen + glyphosate	Late POST	1,380			
p-value				<0.0001	<0.0001
Contrasts [e]					
POST-only vs. PRE fb POST			—	1,537 vs. 2,053 *	1,048 vs. 1,974 *

[a] Abbreviations: fb, followed by.

[b] Means presented within each column with no common letter(s) are significantly different according to Fisher's protected LSD where $\alpha = 0.05$.

[c] Soybean injury was evaluated at 7 days after late postemergence DALPOST and the data were arc-sine square root transformed before analysis; however, back-transformed original mean values are presented based on the interpretation from the transformed data.

[d] Year-by-treatment interaction was significant for soybean yield; therefore, data from both the years were not combined.

[e] *a priori* orthogonal contrasts; *, significant ($p < 0.05$); NS, non-significant.

applications following PRE are necessary to obtain season-long control of common waterhemp. The results from this study revealed that relying on POST-only herbicide programs would not provide economically acceptable control of common waterhemp, even if it includes herbicides with multiple modes of action; so, application of the residual PRE herbicide is important. Few herbicide premixes with multiple effective modes of action that can control glyphosate-resistant common waterhemp effectively have been registered as PRE in soybean.

Weed management programs relying on herbicide(s) with the same mode of action increase the likelihood of resistance evolving (Norsworthy et al. 2012; Wrubel and Gressel 1994); therefore, it is important to select programs that include herbicides with disparate modes of action to minimize selection pressure of a single herbicide or herbicides with similar modes of action. The evolution of multiple herbicide-resistant weeds has reduced the number of POST herbicide options for soybean growers. In fact, a common waterhemp biotype in Illinois was confirmed resistant to ALS inhibitors, glyphosate, PPO inhibitors, and triazine herbicides, leaving no POST herbicide option for glyphosate-resistant soybean growers (Bell et al. 2013). Soybean cultivars resistant to 2,4-D or dicamba will be commercialized in the near future and will provide soybean growers with additional POST herbicide options for controlling glyphosate-resistant and hard-to-control weeds (Chahal et al. 2015; Craigmyle et al. 2013a, 2013b; Soltani et al. 2015; Spaunhorst et al. 2014). Management strategies for glyphosate-resistant common waterhemp must include long-term integrated strategies such as crop rotation, rotational use of herbicide-resistant crop technologies, residual herbicides, and the use of herbicides with different modes of action.

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