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Control of Glyphosate-Resistant Common Waterhemp (*Amaranthus rudis*) in Glufosinate-Resistant Soybean

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Glyphosate-resistant (GR) common waterhemp has become a significant problem weed in Nebraska and several Midwestern states. Several populations of GR common waterhemp are also resistant to acetolactate synthase (ALS)-inhibiting herbicides, making them difficult to control with POST herbicides in GR soybean. Glufosinate-resistant (GFR) soybean is an alternate system for controlling GR common waterhemp, justifying the need for evaluating glufosinate-based herbicide programs. The objectives of this study were to compare POST-only herbicide programs (including one-pass and two-pass POST programs) with PRE followed by (fb) POST herbicide programs for control of GR common waterhemp in GFR soybean and their effect on common waterhemp density, biomass, and soybean yield. Field experiments were conducted in 2013 and 2014 near Fremont, NE in a grower's field infested with GR common waterhemp. Glufosinate applied early- and late-POST provided 76% control of GR common waterhemp at 14 d after late-POST (DALPOST) compared with 93% control with a PRE fb POST program when averaged across treatments. The PRE application of chlorimuron plus thifensulfuron plus flumioxazin, *S*-metolachlor plus fomesafen or metribuzin, saflufenacil plus dimethenamid-P fb glufosinate provided ≥95% control of common waterhemp throughout the growing season, reduced common waterhemp density to ≤2.0 plants m^{-2}, caused ≥94% biomass reduction, and led to 1,984 to 2,210 kg ha^{-1} soybean yield. Averaged across treatments, the PRE fb POST program provided 82% common waterhemp control at soybean harvest, reduced density to 23 plants m^{-2} at 14 DALPOST, and caused 86% biomass reduction and 1,803 kg ha^{-1} soybean yield compared with 77% control, 99 plants m^{-2}, 53% biomass reduction, and 1,190 kg ha^{-1} yield with POST-only program. It is concluded that PRE fb POST programs with multiple effective modes of action are available for control of GR common waterhemp in GFR soybean.
Nomenclature: Acetochlor, alachlor, cloransulam, chlorimuron, dimethenamid, flumioxazin, fomesafen, glufosinate, glyphosate, imazethapyr, metribuzin, saflufenacil, *S*-metolachlor, sulfentrazone, thifensulfuron, common waterhemp, *Amaranthus rudis* Sauer, soybean, *Glycine max* (L.) Merr.
Key words: Biomass reduction, POST-only program, PRE followed by POST, resistance management, soybean yield.

Amaranthus rudis resistente a glyphosate (GR) se ha convertido en un problema de malezas significativo en Nebraska y en varios estados del Medio Oeste. Varias poblaciones de *A. rudis* GR también son resistentes a herbicidas inhibidores de acetolactate synthase, lo que las hace difíciles de controlar con herbicidas POST en soja GR. Soja resistente a glufosinate es un sistema alternativo para el control de *A. rudis* GR, lo que justifica la necesidad de evaluar programas de herbicidas basados en glufosinate. Los objetivos de este estudio fueron comparar programas con sólo herbicidas POST (incluyendo programas POST con uno y dos pases) con programas de herbicidas PRE seguidos por (fb) POST para el control de *A. rudis* GR en soja GFR y sus efectos sobre la densidad y biomasa de *A. rudis* y el rendimiento de la soja. En 2013 y 2014, se realizaron experimentos de campo cerca de Fremont, Nebraska en un campo comercial infestado con *A. rudis* GR. Glufosinate aplicado en POST temprano y tardío brindó 76% de control de *A. rudis* GR a 14 d después del POST tardío (DALPOST), comparado con 93% de control con un programa PRE fb POST, cuando se promediaron los tratamientos. Las aplicaciones PRE de chlorimuron más thifensulturon más flumioxazin, *S*-metolachlor más fomesafen o metribuzin, saflufenacil más dimethenamid-P fb glufosinate brindaron ≥95% de control de *A. rudis* a lo largo de la temporada de crecimiento, redujeron la densidad de *A. rudis* a ≤2 plantas m^{-2}, causaron ≥94% de reducción de biomasa, y permitieron

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un rendimiento de soja de 1,984 a 2,210 kg ha^{-1}. Al promediarse los tratamientos, el programa PRE fb POST brindó 82% de control de *A. rudis* al momento de la cosecha, redujo la densidad a 23 plantas m^{-2} a 14 DALPOST, causó 86% de reducción de biomasa, y el rendimiento de la soja fue 1,803 kg ha^{-1}, comparado con 77% de control, 99 plantas m^{-2}, 53% de reducción de biomasa, y un rendimiento de 1,190 kg ha^{-1} con el programa de sólo herbicidas POST. Se concluyó que hay programas de herbicidas PRE fb POST disponibles con modos de acción efectivos para el control de *A. rudis* GR en soja GFR.

Common waterhemp, a native to the Great Plains region of the United States, is a problem C_4 broadleaf weed species in Nebraska and several other states in the Midwestern United States (Rosenbaum and Bradley 2013; Waselkov and Olsen 2014). Common waterhemp is a prolific seed producer. On average, a single female plant produces 250,000 seeds, though some plants can produce more than 1 million seeds when allowed to grow without competition (Sellers et al. 2003). Common waterhemp is a highly competitive weed that causes significant yield losses in many crops, including corn (*Zea mays* L.) and soybean (Bensch et al. 2003; Steckel and Sprague 2004). For example, Hager et al. (2002a) reported that when common waterhemp plants were allowed to interfere up to 10 wk after soybean unifoliate expansion, there was a 43% yield loss in soybean compared with the weed-free control. Steckel and Sprague (2004) reported 74% corn yield reduction due to season-long common waterhemp interference. Common waterhemp has a prolonged emergence pattern (Refsell and Hartzler 2009), and even late-emerging cohorts have strong seed production potential (Wu and Owen 2014). The species' ability to compete with crops, rapid growth rate, prolific seed production, extended emergence pattern, and ability to thrive under a wide range of stress conditions have established common waterhemp as a successful weed in conventional and no-till crop production systems in the Midwest (Horak and Loughin 2000; Owen 2008; Rosenbaum and Bradley 2013; Sarangi et al. 2016; Steckel et al. 2003; Wu and Owen 2014; 2015).

Since the commercialization of glyphosate-resistant (GR) crops, the continuous use of glyphosate in GR corn and soybean cropping systems and a decline in the use of residual herbicides in the Midwest has resulted in the evolution of GR weeds (Beckie 2006; Culpepper 2006; Young 2006). The first report of a GR weed in the United States was horseweed [*Conyza canadensis* (L.) Cronq.] in Delaware (VanGessel 2001). As of June 2016, 35 weed species worldwide have been confirmed resistant to glyphosate, including 16 species in the United States (Heap 2016a) and six in Nebraska (Jhala 2016). The first report of GR common waterhemp was in Missouri in 2008 (Legleiter and Bradley 2008), and as of 2016, it has been confirmed in 17 states in the United States (Heap 2016b) and in Ontario, Canada (P. Sikkema, personal communication). Common waterhemp biotypes resistant to herbicides belonging to other mode of action groups have also been confirmed. For example, common waterhemp populations 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 (HPPD)-inhibitors (Hausman et al. 2011), and synthetic auxins (Bernards et al. 2012) have been reported. Common waterhemp resistant to multiple herbicides has also been reported (Bell et al. 2013; Legleiter and Bradley 2008). Glyphosate-resistant common waterhemp has recently been confirmed in several eastern Nebraska counties (Sarangi et al. 2015), and management of GR common waterhemp has become a challenge for Nebraska corn and soybean growers. Additionally, the majority of GR common waterhemp biotypes in eastern Nebraska have decreased sensitivity to ALS-inhibiting herbicides, further lowering the number of effective POST herbicide options for management in GR soybean (Sarangi et al. 2015).

Glufosinate is a contact, POST herbicide for control of a broad spectrum of emerged broadleaf and grassy weeds. It is a non-selective herbicide historically used for weed control in fruit and nut orchards and non-crop areas; however, after the commercialization of glufosinate-resistant (GFR) crops in 1999, glufosinate has been used POST in crops resistant to glufosinate, including soybean (Wiesbrook et al. 2001). Glufosinate inhibits glutamine synthetase, an enzyme that is essential for nitrogen metabolism in plants (Logusch et al. 1991). Glutamine synthetase is involved in the assimilation of ammonium, and inhibition of this enzyme results in the buildup of ammonium in plant tissue, indirectly inhibiting photorespiration and photosynthesis in the plant and thus causing plant death (Wild and Manderscheid 1984). Though the

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adoption of GFR crops has been slow, the evolution of GR weeds is causing growers to search for alternative herbicide-resistant cropping technologies (Aulakh and Jhala 2015). For example, growers began to adopt GFR soybean in the Mid-South as an option for controlling GR Palmer amaranth (*Amaranthus palmeri* S. Wats) (Riar et al. 2013). It is possible that GFR soybean will be adopted on a relatively large scale in the Midwest in the near future for the control of GR weeds, including common waterhemp. Research conducted in Nebraska reported excellent control of GR giant ragweed (*Ambrosia trifida* L.) and GR volunteer corn in GFR soybean (Chahal and Jhala 2015; Kaur et al. 2014). More information is needed to develop recommendations for herbicide programs that can provide effective control of GR common waterhemp and other difficult-to-control weeds in GFR soybean.

Glufosinate can be applied in a single application or sequentially, though its maximum cumulative total may not exceed 1,329 g ai ha^{-1} per growing season in GFR soybean (Anonymous 2016). If applied in a burndown (before planting) program, the application rate can be 593 to 736 g ai ha^{-1}, with an additional in-season application of 593 g ai ha^{-1} before but not during the bloom growth stage of GFR soybean (Anonymous 2016). Sequential applications of glufosinate should be made at least five days apart. Aulakh and Jhala (2015) reported <82% control of common waterhemp, common lambsquarters (*Chenopodium album* L.), and eastern black nightshade (*Solanum ptychanthum* Dunal) with glufosinate applied early and late POST, compared with ≥95% control with sulfentrazone plus metribuzin applied PRE followed by (fb) glufosinate plus pyroxasulfone (3-[[5-(difluoromethoxy)-1-methyl-3-(trifluoromethyl)pyrazol-4-yl]methylsulfonyl]-5,5-dimethyl-4H-1,2-oxazole) or acetochlor applied POST. Similarly, Bell et al. (2016) reported 98% control of GR Palmer amaranth in GFR soybean with flumioxazin plus pyroxasulfone applied PRE fb glufosinate, but <70% control with glufosinate applied sequentially. Therefore, it is important to incorporate residual herbicides with different modes of action in glufosinate-based herbicide programs to achieve season-long control of GR weeds such as common waterhemp.

Scientific literature comparing one- and two-pass POST herbicide programs to PRE fb POST programs for controlling GR common waterhemp in GFR soybean is limited. The objective of this study was to compare glufosinate-based one- or two-pass POST herbicide (POST-only) programs to PRE fb POST programs for the management of GR common waterhemp. We evaluated the effect of each treatment on common waterhemp density and biomass and GFR soybean injury and yield. We hypothesized that residual PRE herbicides applied at planting fb glufosinate would provide better control of GR common waterhemp and higher soybean yield than POST-only programs.

Materials and Methods

Field Experiments. Field experiments were conducted during the summers of 2013 and 2014 in a grower's field near Fremont, NE (41.47°N, 96.46°W) that was infested with GR common waterhemp. The level of glyphosate resistance in the common waterhemp biotype from this site was 16- to 24-fold that of known susceptible biotypes, and it also had a reduced susceptibility to ALS-inhibiting herbicides (Sarangi et al. 2015). Common waterhemp was the dominant weed at the research site, with an average density of 250 to 300 plants m^{-2}. The field had been under GR corn or soybean production systems with a reliance on glyphosate for weed control for at least 8 yr. The soil at the experimental site was clay (Luton series) with a pH of 6.7, and comprised 29% sand, 30% silt, 41% clay, and 4% organic matter. A soybean cultivar resistant to glufosinate was planted in a conventionally-tilled seedbed at 345,000 seeds ha^{-1} in rows spaced 76.2 cm apart. Soybean was planted on June 11 in 2013, due to adverse weather conditions early in the season, and on May 20 in 2014. Individual plots measured 3 m wide by 9 m long. The experimental site was located in a rainfed, dryland environment with no supplemental irrigation; however, precipitation was adequate to activate the residual herbicides (Table 1).

Field experiments were arranged in a randomized complete block design with four replications for each treatment. The herbicide programs evaluated to control GR common waterhemp consisted of one-pass POST, two-pass POST, and PRE fb POST programs (Table 2). A non-treated 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}. To improve efficacy,

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

Month	Mean temperature			Total precipitation		
	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] Data were obtained from National Oceanic and Atmospheric Administration (NOAA 2015).

each treatment with glufosinate was mixed with ammonium sulfate at 3.4 kg ha^{-1}, as recommended on the label (Anonymous 2016). PRE herbicides were applied on the day of soybean planting, whereas early-POST herbicides were applied 21 d after PRE (DAPRE), at which time the common waterhemp was 8 to 18 cm tall (depending on treatment), and soybean was at the first to second trifoliate stage. Late-POST herbicide applications were made 14 d after the early-POST herbicide applications (DAEPOST), when common waterhemp plants were 5 to 20 cm tall. Common waterhemp plant height at the time of late-POST herbicide application was variable because some new plants had emerged and some plants had been partially controlled by the early-POST herbicide applications.

Data Collection. Common waterhemp control was assessed visually at 14 DAPRE, 14 DAEPOST, 14 d after late-POST (DALPOST) herbicide applications, and at soybean harvest, on a scale of 0% to 100%, with 0% meaning no control or injury symptoms on common waterhemp plants, and 100% meaning complete control. Common waterhemp densities were recorded at 14 DAPRE and 14 DAL-POST by counting the number of common water-hemp plants in two 0.25 m^2 quadrats placed randomly between the center two soybean rows in each plot and were reported as the number of plants per square meter. At 28 DALPOST, common waterhemp plants that survived the herbicide treatments were cut at the soil surface from two randomly selected 0.25 m^2 quadrats per plot and oven-dried at 65 C until they reached a constant weight. Aboveground biomass was converted into percent biomass reduction compared with the non-treated control using the following equation (Wortman 2014):

$$\%\ \text{biomass reduction} = \left[\left(\overline{C} - B\right) / \overline{C}\right] \times 100 \quad [1]$$

where $\overline{C}$ is the biomass of the non-treated control 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% indicating no soybean injury and 100% indicating death of soybean plants. Soybean was harvested from the center two rows in each plot using a plot combine (Gleaner K2; AGCO, 4205 River Green Parkway, Duluth, GA). The combine had a row-crop header that can harvest two rows that are 76 cm apart, and included the HarvestMaster System equipped with Mirus Data collection software (Juniper Systems & HarvestMaster, Logan, UT) for determining seed weight. 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., Cary, NC). In the model, years and treatments were considered fixed effects, whereas blocks, which were nested within years, were considered random effects. Data were tested for normality using PROC UNIVARIATE. Common waterhemp visual control estimates and percent biomass reduction 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

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

Herbicide program[a]	Trade name	Application timing	Rate	Manufacturer
			g ae or ai ha^{-1}	
Glufosinate + fomesafen + imazethapyr + acetochlor	Liberty + Flexstar + Pursuit + Warrant	Early POST	594 + 263 + 70 + 1,680	Bayer CropScience, Research Triangle Park, NC + Syngenta Crop Protection, Greensboro, NC + BASF Corporation, Research Triangle Park, NC + Monsanto Company, St. Louis, MO
Glufosinate fb	Liberty fb	Early POST fb	594	Bayer CropScience
glufosinate	Liberty	late POST	594	Bayer CropScience
Glufosinate + acetochlor fb	Liberty + Warrant fb	Early POST fb	594 + 1,680	Bayer CropScience + Monsanto Company,
glufosinate	Liberty	late POST	594	Bayer CropScience
Glufosinate + acetochlor + imazethapyr fb	Liberty + Warrant + Pursuit fb	Early POST fb	594 + 1,680 + 70	Bayer CropScience + Monsanto Company +
glufosinate	Liberty	late POST	594	BASF Corporation fb Bayer CropScience
Glufosinate + fomesafen fb	Liberty + Flexstar fb	Early POST fb	594 + 263	Bayer CropScience + Syngenta Crop
glufosinate	Liberty	late POST	594	Protection, Bayer CropScience
Glufosinate + fomesafen + acetochlor fb	Liberty + Flexstar + Warrant fb	Early POST fb	594 + 263 + 1,680	Bayer CropScience + Syngenta Crop
glufosinate	Liberty	late POST	594	Protection + Monsanto Company fb Bayer CropScience LP
Glufosinate + fomesafen + imazethapyr + acetochlor fb	Liberty + Flexstar + Pursuit + Warrant fb	Early POST fb	594 + 263 + 70 + 1,680	Bayer CropScience + Syngenta Crop Protection + BASF Corporation +
glufosinate	Liberty	late POST	594	Monsanto Company fb Bayer CropScience
Flumioxazin fb	Valor fb	PRE fb	107	Valent USA Corporation, Walnut Creek, CA
glufosinate	Liberty	late POST	594	Bayer CropScience
Flumioxazin + cloransulam-methyl fb	Valor + FirstRate fb	PRE fb	107 + 35.3	Valent + Dow AgroSciences, Indianapolis, IN
glufosinate	Liberty	late POST	594	Bayer CropScience
Chlorimuron-ethyl + thifensulfuron-methyl + flumioxazin fb	Envive fb	PRE fb	153	E. I. du Pont de Nemours and Company, Wilmington, DE
glufosinate	Liberty	late POST	594	Bayer CropScience
Alachlor fb	Intrro fb	PRE fb	3,360	Monsanto Company fb
glufosinate	Liberty	late POST	594	Bayer CropScience
S-metolachlor fb	Dual II Magnum fb	PRE fb	1420	Syngenta Crop Protection
glufosinate	Liberty	late POST	594	Bayer CropScience
S-metolachlor + imazethapyr fb	Dual II Magnum + Pursuit fb	PRE fb	1,420 + 70	Syngenta Crop Protection + BASF Corporation
glufosinate	Liberty	late POST	594	Bayer CropScience
S-metolachlor + fomesafen fb	Prefix fb	PRE fb	1,480	Syngenta Crop Protection
glufosinate	Liberty	late POST	594	Bayer CropScience
S-metolachlor + metribuzin fb	Boundary fb	PRE fb	2,050	Syngenta Crop Protection
glufosinate	Liberty	late POST	594	Bayer CropScience

Sulfentrazone + metribuzin fb	Authority MTZ fb	PRE fb	570	FMC Corporation, Philadelphia, PA
glufosinate	Liberty	late POST	594	Bayer CropScience
Saflufenacil fb	Sharpen fb	PRE fb	25	BASF Corporation
glufosinate	Liberty	late POST	594	Bayer CropScience
Saflufenacil + dimethenamid-P fb	Sharpen + Outlook fb	PRE fb	25 + 950	BASF Corporation + BASF Corporation fb
glufosinate	Liberty	late POST	594	Bayer CropScience

[a] Each treatment with glufosinate was mixed with ammonium sulfate (DSM Chemicals North America Inc., Augusta, GA) at 3.4 kg ha^{-1}.

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) were performed. Preplanned contrasts were conducted to compare one-pass POST to two-pass POST, and to compare POST-only to the PRE fb POST programs.

Results and Discussion

Year-by-treatment interactions for GR common waterhemp control estimates, density, and biomass, and soybean yield were not significant; therefore, data from both years were combined.

Common Waterhemp Control. Two-pass herbicide programs provided 78% control of common waterhemp, compared with 93% control with PRE fb POST programs, when averaged across treatments at 14 DALPOST (Table 3), indicating the importance of residual herbicides fb a late-POST glufosinate application for common waterhemp control. Two-pass POST herbicide programs provided 77% control, while the PRE fb POST program provided 90% control, when averaged across treatments at 14 DAEPOST. This is due to the excellent control of common waterhemp that can be achieved with residual herbicides applied PRE with a follow-up application of glufosinate when plants are less than 12 cm tall. Krausz and Young (2003) also reported 89% to 99% control of common waterhemp with sulfentrazone-based tank-mixtures applied PRE fb glyphosate in GR soybean.

Herbicides applied PRE resulted in 76% to 99% control of GR common waterhemp at 14 DAPRE (Table 4). Similarly, Aulakh and Jhala (2015) reported ≥ 92% control of common waterhemp and common lambsquarters at 15 DAPRE, but no control using a POST-only herbicide program. Among PRE herbicides, flumioxazin plus cloransulam, chlorimuron plus thifensulfuron plus flumioxazin, *S*-metolachlor plus fomesafen, *S*-metolachlor or sulfentrazone plus metribuzin, and saflufenacil plus dimethenamid provided ≥98% control. Similar to the results of this study, Bell et al. (2015) reported >99% control of Palmer amaranth 21 d after soybean planting when *S*-metolachlor plus metribuzin was applied PRE at the time of planting.

At 14 DAEPOST, the POST-only programs that we tested provided 71% to 82% control of common waterhemp (Table 5), while the PRE fb POST herbicide programs provided 71% to 99% control.

Table 3. Orthogonal contrasts[a] for comparison of herbicide programs for glyphosate-resistant common waterhemp control, density, and biomass reduction and soybean yield in field experiments conducted near Fremont, Nebraska in 2013 and 2014.[b]

Herbicide program	Common waterhemp control 14 DAPRE	14 DAEPOST	14 DALPOST	At harvest	Weed density 14 DAPRE	28 DALPOST	Biomass reduction	Soybean yield
	%				Plants m^{-2}		%	kg ha^{-1}
POST-only v. PRE fb POST	0 v. 93**	77 v. 90**	78 v. 93**	45 v. 82**	342 v. 8**	99 v. 23**	53 v. 86**	1,190 v. 1,803**
One-pass POST v. two-pass POST	–	81 v. 77*	58 v. 81**	19 v. 50**	–	124 v. 95**	25 v. 59**	975 v. 1,226*

[a] *a priori* orthogonal contrasts.

[b] Abbreviations: DAEPOST, days after early-post-emergence herbicide treatment; DAPRE, days after pre-emergence herbicide treatment; DALPOST, days after late-post-emergence herbicide treatment; v., versus.

*Significant at $P<0.05$; ** significant at $P<0.01$.

This is likely due to the fact that when early-POST herbicides were applied, common waterhemp plants were 8 to 18 cm tall with a density of approximately 300 plants m^{-2}, and therefore were less likely to be effectively controlled with a glufosinate-based herbicide program because the efficacy of glufosinate can be affected by weed height and density. For instance, Barnett et al. (2013) reported >90% control of Palmer amaranth when glufosinate was applied to 13-cm-tall plants, but <60% control when glufosinate was applied to 26-cm-tall plants. In a bare-ground study in Illinois, Steckel et al. (1997) reported >80% control of giant foxtail (*Setaria faberi* Herrm.), common lambsquarters, common cocklebur (*Xanthium strumarium* L.), and Pennsylvania smartweed (*Polygonum pensylvanicum* L.) when glufosinate was applied at the 10-cm weed height, but <70% control at the 15-cm weed height. In contrast, Coetzer et al. (2002) reported 82% to 87% control at 4 wk after treatment with glufosinate applied alone at 410 g ai ha^{-1} when common waterhemp plants ranged from 2 to 18 cm tall.

Glufosinate applied alone resulted in 71% control, while glufosinate tank-mixed with acetochlor, imazethapyr, and/or fomesafen resulted in 75% to 82% control (Table 5). Similarly, Chahal and Johnson (2012) reported 78% to 84% control of GR common lambsquarters with glufosinate tank-mixed with 2,4-D or dicamba, but only 44% control with glufosinate applied alone. Aulakh and Jhala (2015) reported <73% control of common waterhemp with glufosinate applied alone in GFR soybean. Among POST-only herbicide programs, a one-pass POST application of glufosinate plus fomesafen plus acetochlor plus imazethapyr, a program with four distinct modes of action, provided 58% control at 14 DALPOST, while two-pass POST herbicide programs provided 76% to 83% control (Table 5). These data suggest that including herbicides with multiple modes of action is not sufficient to achieve a high level of common waterhemp control, and that the application timing is critical. For example, at least five PRE fb POST herbicide programs with multiple modes of action provided 97% to 99% control at 14 DALPOST in this study (Table 4). Similarly, Bell et al. (2016) reported ≥95% control of Palmer amaranth with flumioxazin plus pyroxasulfone applied PRE in GR and GFR soybean. Flumioxazin applied alone and *S*-metolachlor plus imazethapyr provided <62% control at harvest.

Averaged across treatments, a two-pass POST program provided 50% control of GR common waterhemp at harvest, while a one-pass POST program provided 19% control, indicating the failure of one- or two-pass POST herbicide programs to effectively control GR common waterhemp (Table 3). Aulakh and Jhala (2015) also reported 65% to 81% control of common waterhemp with glufosinate-based one- or two-pass POST programs in GFR soybean. Contrast analysis of common waterhemp control estimates at soybean harvest suggest 82% control with PRE fb POST herbicide programs compared with 45% control with POST-only programs. In a study conducted in Nebraska, Sarangi (2016) reported 84% control of GR common waterhemp at soybean harvest in a PRE fb POST program, but only 42% control with a POST-only program. We found that PRE fb POST programs using chlorimuron plus thifensulfuron plus flumioxazin, *S*-metolachlor plus fomesafen or

Table 4. Effect of PRE followed by POST herbicide programs on glyphosate-resistant common waterhemp control in glufosinate-resistant soybean at 14 d after PRE herbicide application, 14 d after early-POST herbicide application, 14 d after late-POST herbicide application, and at soybean harvest, in field experiments conducted near Fremont, Nebraska in 2013 and 2014.[a,b]

Herbicide program	Application timing	Rate	Common waterhemp control[c,d]			
			14 DAPRE	14 DAEPOST	14 DALPOST	At harvest
		g ae or ai ha^{-1}	%			
Flumioxazin fb glufosinate	PRE fb late POST	107 594	88 c	83 d	88 c	59 e
Flumioxazin + cloransulam fb glufosinate	PRE fb late POST	107 + 35.3 594	99 a	96 bc	97 ab	87 cd
Chlorimuron + thifensulfuron + flumioxazin fb glufosinate	PRE fb late POST	153 594	99 a	98 ab	99 a	96 ab
Alachlor fb glufosinate	PRE fb late POST	3,360 594	96 b	93 c	96 b	86 cd
S-metolachlor fb glufosinate	PRE fb late POST	1,420 594	76 d	71 e	80 d	54 e
S-metolachlor + imazethapyr fb glufosinate	PRE fb late POST	1,420 + 70 594	78 d	74 e	81 d	61 e
S-metolachlor + fomesafen fb glufosinate	PRE fb late POST	1,480 594	99 a	99 a	99 a	98 a
S-metolachlor + metribuzin fb glufosinate	PRE fb late POST	2,050 594	99 a	98 ab	99 a	95 ab
Sulfentrazone + metribuzin fb glufosinate	PRE fb late POST	570 594	98 ab	96 bc	96 b	91 bc
Saflufenacil fb glufosinate	PRE fb late POST	25 594	90 c	87 d	92 c	83 d
Saflufenacil + dimethenamid fb glufosinate	PRE fb late POST	25 + 950 594	99 a	99 a	99 a	97 a
P-value			<0.0001	<0.0001	<0.0001	<0.0001

[a] Year-by-treatment interaction for glyphosate-resistant common waterhemp control was not significant; therefore, data were combined across the two years.

[b] Abbreviations: DAEPOST, d after early-POST herbicide application; DALPOST, d after late-POST herbicide application; DAPRE, d after PRE herbicide application; fb, followed by.

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

[d] Means presented within each column with no common letter(s) are significantly different according to Fisher's protected LSD test at $P \leq 0.05$.

metribuzin, and saflufenacil plus dimethenamid fb glufosinate applied POST provided ≥95% control at soybean harvest. In a 2-yr study in Arkansas, Bell et al. (2015) observed 86% to 95% Palmer amaranth control at harvest in GFR soybean with *S*-metolachlor plus metribuzin applied PRE fb glufosinate applied POST, but only 50% to 85% control with a POST-only program. The results of this study are consistent with several previous studies in suggesting that PRE fb POST programs are better for control of *Amaranthus* than POST-only programs (Aulakh and Jhala 2015; Bell et al. 2015; 2016; Butts et al. 2016; Hager et al. 2002b; Jhala et al. 2015; Johnson et al. 2012; Meyer et al. 2015; Norsworthy et al. 2012; Sarangi 2016).

Common Waterhemp Density and Biomass. Common waterhemp density and biomass were both affected by the herbicide programs evaluated (Tables 6 and 7). At 14 DAPRE, plots that received PRE herbicides had common waterhemp densities as low as 0 to 34 plants m^{-2}. Similarly, Sarangi (2016) reported common waterhemp density of <35 plants m^{-2} at 21 d after PRE herbicide application compared with 323 to 391 plants m^{-2} with a POST-only program. Aulakh and Jhala (2015) also reported 0 to 6 common waterhemp plants m^{-2} with several PRE programs, compared with 11 to 12 plants m^{-2} in a POST-only program 15 d after POST herbicides were applied.

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Table 5. Effect of POST-only herbicide programs on glyphosate-resistant common waterhemp control in glufosinate-resistant soybean at 14 d after early-POST herbicide application, 14 d after late-POST herbicide application, and at soybean harvest, in field experiments conducted near Fremont, Nebraska in 2013 and 2014.[a,b]

			Common waterhemp control[c,d]		
Herbicide program	Application timing	Rate	14 DAEPOST	14 DALPOST	At harvest[c,d]
		g ae or ai ha^{-1}	——	%	——
Glufosinate + fomesafen + imazethapyr + acetochlor	Early POST	594 + 263 + 70 + 1,680	81 a	58 c	19 c
Glufosinate fb glufosinate	Early POST fb late POST	594 594	71 c	76 b	41 b
Glufosinate + acetochlor fb glufosinate	Early POST fb late POST	594 + 1,680 594	77 ab	81 ab	53 a
Glufosinate + acetochlor + imazethapyr fb glufosinate	Early POST fb late POST	594 + 1,680 + 70 594	77 ab	81 ab	54 a
Glufosinate + fomesafen fb glufosinate	Early POST fb late POST	594 + 263 594	75 bc	82 a	41 b
Glufosinate + fomesafen + acetochlor fb glufosinate	Early POST fb late POST	594 + 263 + 1,680 594	79 ab	83 a	55 a
Glufosinate + fomesafen + imazethapyr + acetochlor fb glufosinate	Early POST fb late POST	594 + 263 + 70 + 1,680 594	82 a	85 a	58 a
P-value			0.002	<0.0001	<0.0001

[a] Year-by-treatment interaction for glyphosate-resistant common waterhemp control was not significant; therefore, data were combined across two years.

[b] Abbreviations: DAEPOST, d after early-POST herbicide application; DALPOST, d after late-POST herbicide application; fb, followed by.

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

[d] Means presented within each column with no common letter(s) are significantly different according to Fisher's protected LSD test at $P \leq 0.05$.

Common waterhemp densities at 28 DALPOST ranged from 88 to 124 plants m^{-2} with the POST-only program (Table 7), and ranged from 1 to 78 plants m^{-2} with PRE fb POST program (Table 6). Monthly precipitation ranging from 28 to 318 mm in June and July of 2013 and 2014 (Table 1) may have triggered the emergence of common waterhemp; Hartzler et al. (1999) reported that common waterhemp emergence can be enhanced if sufficient moisture is present in the soil. Among PRE fb POST programs, flumioxazin plus cloransulam, chlorimuron plus thifensulfuron plus flumioxazin, alachlor, *S*-metolachlor plus fomesafen or metribuzin, sulfentrazone plus metribuzin, and saflufenacil alone or with dimethenamid applied PRE fb glufosinate applied POST, was associated with the lowest density of common waterhemp (≤16 plants m^{-2}), and in most cases provided ≥90% reduction in common waterhemp biomass at 28 DALPOST (Table 6). Legleiter et al. (2009) reported common waterhemp density as low as 2 plants m^{-2} at 42 DAPOST with a PRE fb POST program, compared with 66 to 76 plants m^{-2} with a POST-only program. Averaged across treatments at 28 DALPOST, a POST-only program resulted in a common waterhemp density of 99 plants m^{-2} and a 53% reduction in waterhemp biomass, while a PRE fb POST program resulted in 23 plants m^{-2} and an 86% reduction in common waterhemp biomass. In an integrated management approach to resistant common waterhemp in Missouri, Schultz et al. (2015) reported >98% density reduction using a PRE fb POST herbicide programs across all row spacings, whereas the two-pass POST program provided 87%, 80%, and 50% density reduction in 19-, 38-, and 76-cm soybean row spacings, respectively.

Soybean Yield. The lowest soybean yield was obtained from the non-treated control (826 kg ha^{-1}),

Table 6. Effect of PRE followed by POST herbicide programs on glyphosate-resistant common waterhemp density and biomass reduction, and glufosinate-resistant soybean yield, in field experiments conducted near Fremont, Nebraska in 2013 and 2014.[a,b]

Herbicide program	Application timing	Rate	Common waterhemp density[c] 14 DAPRE	28 DALPOST	Biomass reduction[c,d]	Soybean yield[c]
		g ae or ai ha^{-1}	Plants m^{-2}		%	kg ha^{-1}
Flumioxazin fb	PRE fb	107	20 b	64 b	71 cd	1,477 e
glufosinate	late POST	594				
Flumioxazin + cloransulam fb	PRE fb	107 + 35.3	1 c	7 cd	92 ab	1,805 bcd
glufosinate	late POST	594				
Chlorimuron + thifensulfuron + flumioxazin fb	PRE fb	153	0 c	1 d	97 ab	2,109 a
glufosinate	late POST	594				
Alachlor fb	PRE fb	3,360	1 c	13 cd	90 ab	1,733 cde
glufosinate	late POST	594				
S-metolachlor fb	PRE fb	1,420	34 a	78 a	63 d	1,480 e
glufosinate	late POST	594				
S-metolachlor + imazethapyr fb	PRE fb	1,420 + 70	31 a	66 ab	70 cd	1,522 de
glufosinate	late POST	594				
S-metolachlor + fomesafen fb	PRE fb	1,480	0 c	2 d	97 ab	2,065 ab
glufosinate	late POST	594				
S-metolachlor + metribuzin fb	PRE fb	2,050	1 c	2 d	94 ab	1,984 abc
glufosinate	late POST	594				
Sulfentrazone + metribuzin fb	PRE fb	570	1 c	4 cd	92 ab	1,810 bcd
glufosinate	late POST	594				
Saflufenacil fb	PRE fb	25	2 c	16 c	86 bc	1,633 de
glufosinate	late POST	594				
Saflufenacil + dimethenamid fb	PRE fb	25 + 950	0 c	1 d	99 a	2,210 a
glufosinate	late POST	594				
P-value			<0.0001	<0.0001	0.002	<0.0001

[a] Year-by-treatment interactions for glyphosate-resistant common waterhemp density and biomass reduction and soybean yield were not significant; therefore, data were combined across the two years.

[b] Abbreviations: DALPOST, d after late-POST herbicide application; DAPRE, d after PRE herbicide application; fb, followed by.

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

[d] Percent biomass reduction data were arcsine square root transformed before analysis; however, back-transformed original mean values are presented with the interpretation from the transformed data.

and was comparable with a one-pass POST program (975 kg ha^{-1}) (Table 7). It was clear that a one-pass POST program of glufosinate plus fomesafen plus imazethapyr plus acetochlor was insufficient to provide effective control due to the continuous emergence pattern of common waterhemp (Table 7). Averaged across treatments, two-pass POST programs provided 1,190 kg ha^{-1} soybean yield compared with 1,803 kg ha^{-1} with a PRE fb POST program (Table 3). Chlorimuron plus thifensulfuron plus flumioxazin, *S*-metolachlor plus fomesafen or metribuzin, or saflufenacil plus dimethenamid, applied PRE fb glufosinate applied POST provided 1,984 to 2,210 kg ha^{-1} soybean yield, the highest yields of all the treatments tested (Table 6). Bell et al. (2015) also reported that the use of PRE herbicides improved soybean yield and economic returns compared with POST-only programs for control of Palmer amaranth in GFR soybean. Johnson et al. (2012) further reported that a PRE fb POST program reduced the chance of crop yield loss due to weed interference because of the program's ability to control early- as well as late-emerging weeds. No significant soybean injury was observed in any herbicide program (data not shown), indicating that all programs evaluated in this study were safe for GFR soybean if applied as per the label directions.

Table 7. Effect of POST-only herbicide programs on glyphosate-resistant common waterhemp density and biomass reduction and glufosinate-resistant soybean yield in field experiments conducted near Fremont, NE in 2013 and 2014.[a,b]

Herbicide program	Application timing	Rate	Density[c] 28 DALPOST	Biomass reduction[c,d]	Soybean yield[c]
		g ae or ai ha^{-1}	Plants m^{-2}	%	kg ha^{-1}
Non-treated control	—	—	186 a	–	826 c
Glufosinate + fomesafen + imazethapyr + acetochlor	Early POST	594 + 263 + 70 + 1,680	124 b	25 b	975 bc
Glufosinate fb glufosinate	Early POST fb late POST	594 594	107 bc	49 ab	1,136 ab
Glufosinate + acetochlor fb glufosinate	Early POST fb late POST	594 + 1,680 594	99 c	62 a	1,173 ab
Glufosinate + acetochlor + imazethapyr fb glufosinate	Early POST fb late POST	594 + 1,680 + 70 594	87 c	61 a	1,267 a
Glufosinate + fomesafen fb glufosinate	Early POST fb late POST	594 + 263 594	95 c	50 ab	1,185 a
Glufosinate + fomesafen + acetochlor fb glufosinate	Early POST fb late POST	594 + 263 + 1,680 594	88 c	65 a	1,322 a
Glufosinate + fomesafen + imazethapyr + acetochlor fb glufosinate	Early POST fb late POST	594 + 263 + 70 + 1,680 594	95 c	65 a	1,275 a
P-value			<0.0001	0.04	<0.0001

[a] Year-by-treatment interactions for glyphosate-resistant common waterhemp density and biomass reduction and soybean yield were not significant; therefore, data were combined across the two years.

[b] Abbreviations: DALPOST, d after late-POST herbicide application; DAPRE, d after PRE herbicide application; fb, followed by.

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

[d] Percent biomass reduction data were arcsine square root transformed before analysis; however, back-transformed original mean values are presented with the interpretation from the transformed data.

Practical Implications. The evolution of common waterhemp biotypes resistant to glyphosate and ALS-inhibitors, and their widespread occurrence in the Midwest, has resulted in a decrease in the number of effective POST herbicide options in GR soybean. Averaged across treatments, glufosinate-based one- or two-pass herbicide programs provided ≤50% control of GR common waterhemp at soybean harvest, while the PRE fb POST programs evaluated in this study provided 82% control (Table 3). Glufosinate should not be applied after the bloom stage in GFR soybean (Anonymous 2016), and the results of this study revealed that residual herbicides with multiple modes of action applied at soybean planting are a foundation of GR common waterhemp control. The results also suggest that a follow-up application of glufosinate can provide season-long control in GFR soybean. Additionally, using PRE herbicide combinations with multiple modes of action at soybean planting can effectively control *Amaranthus,* reducing the number of weeds exposed to POST herbicides and thus reducing the effects of selection pressure while improving the efficacy of POST herbicide(s) applied later in the season. Although not evaluated in this study, Aulakh and Jhala (2015) reported that a residual herbicide such as acetochlor or pyroxasulfone can be tank-mixed with a POST glufosinate application for residual control of common waterhemp later in the season.

Herbicide programs in GFR soybean should not rely solely on glufosinate, because repeated applications of glufosinate in the same field may result in the evolution of glufosinate-resistant weeds. For instance, glufosinate-resistant Italian ryegrass (*Lolium perenne* L. ssp. *multiflorum*) in California (Avia-Garcia et al. 2012) and goosegrass [Eleusine indica (L.) Gaertn.] in Malaysia (Jalaludin et al. 2010) have been reported. Herbicide programs in GFR soybean have shown effective control of GR giant ragweed (Kaur et al. 2014), common waterhemp (Schultz et al. 2015), Palmer amaranth (Butts et al. 2016; Bell et al. 2015; 2016), johnsongrass [*Sorghum halepense* (L.) Pers.] (Johnson et al. 2014), and volunteer corn (Chahal and Jhala 2015). The results of this research indicate that there are herbicide programs capable of providing effective control of GR common waterhemp in GFR soybean that can be incorporated into existing cropping systems. Furthermore, multiple-herbicide-resistant soybean cultivars have been developed and tested, and will be available in the marketplace in the near future (Craigmyle et al. 2013a, 2013b; Spaunhorst et al. 2014). These crops can provide an additional tool for controlling the increasing numbers of GR weeds, including common waterhemp (Chahal et al. 2015; Meyer et al. 2015); however, more research is needed on herbicide programs that provide multiple effective modes of action with the judicious use of herbicide-resistant crop technology and other methods for integrated broad-spectrum weed control in order to achieve optimum crop yields in corn and soybean rotations.

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