*Weed Technology* 2015 29:419–430

# Comparison of Glufosinate-Based Herbicide Programs for Broad-Spectrum Weed Control in Glufosinate-Resistant Soybean

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Because of the increasing number of glyphosate-resistant weeds, alternate herbicide-resistant crops and herbicides with different modes of action are required to protect crop yield. Glufosinate is a broad-spectrum POST herbicide for weed control in glufosinate-resistant crops, including soybean. The objective of this study was to compare herbicide programs with glufosinate applied singly at late-POST (LPOST) or sequentially at early POST (EPOST) followed by (fb) LPOST applications and PRE herbicides fb EPOST/LPOST glufosinate alone or tank-mixed with acetochlor, pyroxasulfone, or *S*-metolachlor in glufosinate-resistant soybean. A field experiment was conducted at the South Central Agriculture Laboratory in Clay Center, NE, in 2012 and 2013. Glufosinate applied in a single LPOST or sequential EPOST fb LPOST application controlled common lambsquarters, common waterhemp, eastern black nightshade, green foxtail, large crabgrass, and velvetleaf $\leq$ 82% and resulted in a weed density of 6 to 10 plants $m^{-2}$ by the end of the season. Flumioxazin-, saflufenacil-, or sulfentrazone-based premixes provided 84 to 99% control of broadleaf and grass weeds tested in this study at 15 d after PRE application and a subsequent LPOST application of glufosinate alone controlled broadleaf and grass weeds 69 to 93% at harvest, depending on the herbicide program and weed species being investigated. The PRE application of sulfentrazone plus metribuzin fb EPOST glufosinate tank-mixed with acetochlor, pyroxasulfone, or *S*-metolachlor controlled the tested broadleaf and grass weeds $\geq$ 90%, reduced density to $\leq$ 2 plants $m^{-2}$, and reduced weed biomass to $\leq$ 10 g $m^{-2}$ and produced soybean yields of $\geq$ 4,450 and 3,040 kg $ha^{-1}$ in 2012 and 2013, respectively. Soybean injury was 0 to 20% from PRE or POST herbicides, or both and was inconsistent, but transient, during the 2-yr study, and it did not affect soybean yield. Sulfentrazone plus metribuzin applied PRE fb glufosinate EPOST tank-mixed with acetochlor, pyroxasulfone, or *S*-metolachlor provided the highest level of weed control throughout the growing season and increased soybean yield compared with a single LPOST or a sequential EPOST fb LPOST glufosinate application. Additionally, these herbicide programs provide four distinct mechanisms of action that constitute an effective weed-resistance management strategy in glufosinate-resistant soybean.

**Nomenclature**: Acetochlor; flumioxazin; glufosinate; metribuzin; pyroxasulfone; saflufenacil; *S*-metolachlor; sulfentrazone; common lambsquarters, *Chenopodium album* L.; common waterhemp, *Amaranthus rudis* Sauer.; eastern black nightshade, *Solanum ptychanthum* Dunal; green foxtail, *Setaria viridis* (L.) Beauv.; large crabgrass, *Digitaria sanguinalis* (L.) Scop.; velvetleaf, *Abutilon theophrasti* Medik.; soybean, *Glycine max* (L.) Merr.

**Key words**: Broadleaf weeds, grass weeds, herbicide-resistance, resistance management, weed biomass.

Debido al creciente número de malezas resistentes a glyphosate, es necesario alternar cultivos resistente a herbicidas con diferentes modos de acción para proteger los rendimientos de los cultivos. Glufosinate es un herbicida POST de amplio espectro para el control de malezas en cultivos resistentes a glufosinate, incluyendo soja. El objetivo de este estudio fue comparar programas de herbicidas con glufosinate aplicado solo en POST-tarde (LPOST), o secuencialmente en POST-temprano (EPOST) seguido de (fb) aplicaciones LPOST, y herbicidas PRE fb glufosinate solo en EPOST/LPOST, o mezclas en tanque con acetochlor, pyroxasulfone, o *S*-metolachlor, en soja resistente a glufosinate. Se realizó un experimento de campo en el Laboratorio de Agricultura del Centro Sur, en Clay Center, Nebraska, en 2012 y 2013. Glufosinate aplicado solo LPOST o en secuencia EPOST fb LPOST controló *Chenopodium album*, *Amaranthus rudis*, *Solanum ptychanthum*, *Setaria viridis*, *Digitaria sanguinalis*, y *Abutilon theophrasti* $\leq$ 82% y resultaron en una densidad de malezas de 6 a 10 plantas $m^{-2}$ al final de la temporada. Premezclas basadas en flumioxazin, saflufenacil, o sulfentrazone

DOI: 10.1614/WT-D-15-00014.1

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brindaron 84 a 99% de control de malezas de hoja ancha y gramíneas evaluadas en este estudio a 15 d después de la aplicación; PRE fb glufosinate solo (EPOST/LPOST) controlaron malezas de hoja ancha y gramíneas 69 a 93% al momento de la cosecha, dependiendo del programa de herbicidas y las especies de malezas investigadas. La aplicación PRE de sulfentrazone más metribuzin fb EPOST con glufosinate mezclado en tanque con acetochlor, pyroxasulfone, o *S*-metolachlor controló las especies de malezas de hoja ancha y gramíneas evaluadas $\geq$ 90%, redujo la densidad $\leq$ 2 plantas $m^{-2}$, redujo la biomasa de malezas $\leq$ 10 g $m^{-2}$, y produjo rendimientos de soja $\geq$ 4,450 y 3,040 kg $ha^{-1}$, en 2012 y 2013, respectivamente. El daño en la soja fue 0 a 20% en los tratamientos PRE, POST, o ambos, y fue inconsistente pero fue transitorio, durante los 2 años del estudio, y no afectó el rendimiento de la soja. Sulfentrazone más metribuzin aplicados PRE fb glufosinate EPOST mezclado en tanque con acetochlor, pyroxasulfone, o *S*-metolachlor brindó el mayor nivel de control de malezas a lo largo de la temporada de crecimiento e incrementó el rendimiento de la soja al compararse con una aplicación de glufosinate LPOST o aplicaciones secuenciales EPOST fb EPOST. Adicionalmente, estos programas de herbicidas permitieron el uso de cuatro mecanismos de acción distintos lo que constituye una estrategia efectiva para el manejo de resistencia en soja resistente a glufosinate.

Glyphosate-resistant crop production systems were highly successful in achieving higher levels of weed control, facilitating the adoption of conservation tillage systems, and reducing the use of herbicides with groundwater advisories (Culpepper et al. 2000; Fernandez-Cornejo and Caswell 2006; Price et al. 2011; Young 2006). However, overreliance on glyphosate for weed control for several years has resulted in the evolution of glyphosate-resistant weeds (Culpepper et al. 2006; Owen and Zelaya 2005; VanGessel 2001). As of 2015, 31 weed species worldwide have evolved resistance to glyphosate, including 14 species in the United States (Heap 2015). In Nebraska, glyphosate-resistance has been confirmed in common ragweed (*Ambrosia artemisiifolia* L.), common waterhemp, horseweed [*Conyza canadensis* (L.) Cronq.], giant ragweed (*Ambrosia trifida* L.), kochia [*Kochia scoparia* (L.) Schrad.], and Palmer amaranth (*Amaranthus palmeri* S. Wats.) (Jhala 2015).

Control of glyphosate-resistant weeds is a challenge, particularly for soybean growers, because effective POST herbicides are limited (Riley and Bradley 2014). In addition, several glyphosate-resistant weeds, including common waterhemp, are also resistant to acetolactate synthase (ALS)–inhibiting herbicides (Heap 2015; Sarangi et al. 2015). Therefore, alternate herbicide-resistant crops or diversified herbicide programs are required to manage multiple herbicide-resistant weeds. Recently, weed management has shifted toward glufosinate (Liberty Link, Bayer CropScience, Alfred-Nobel-Str. 50, D-40789, Monheim am Rhein, Germany)-based systems in the midsouthern United States, especially in areas with glyphosate-resistant Palmer amaranth infestations (Riar et al. 2013). Glufosinate-resistant soybean was developed by incorporating the *PAT* gene of *Streptomyces viridochromogenes* (Droge et al. 1992), which encodes for phosphinothricin *N*-acetyltransferase (EC 2.3.1.183), an enzyme that renders glufosinate nonphytotoxic (Devine et al. 1993). Glufosinate-resistant soybean was first released for large-scale commercial cultivation in 2009, although limited cultivation had already begun in 1999 (Wiesbrook et al. 2001).

Glufosinate is a nonselective, contact, broad-spectrum, POST herbicide (Haas and Muller 1987). It inhibits the glutamine synthetase enzyme (EC 6.3.12) and thereby causes rapid accumulation of ammonia and glyoxylate within the plant, eventually leading to cell membrane disruption and necrosis (Devine et al. 1993; Hinchee et al. 1993). Glufosinate efficacy has been variable for control of grass weeds, and it has no soil-residual activity (Ritter and Menbere 2001; Steckel et al. 1997; Thomas et al. 2007). Poor control of giant foxtail (*Setaria faberi* Herrm.) with early POST application of glufosinate in glufosinate-resistant soybean has been reported (Ritter and Menbere 2001). Furthermore, glufosinate efficacy is dependent on the growth stage of the weed. For example, Steckel et al. (1997) reported 45% less control of giant foxtail, common lambsquarters, common cocklebur (*Xanthium strumarium* L.), and Pennsylvania smartweed (*Polygonum pensylvanicum* L.) when glufosinate was applied at 420 g $ha^{-1}$ to 15-cm-tall, compared with 10-cm-tall, plants. Weed-stage specificity, limited grass activity, and lack of soil residual activity of glufosinate necessitate sequential applications or tank-mixing with residual herbicides such as acetochlor or *S*-metolachlor to enhance the degree and duration of weed control in glufosinate-resistant corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), and soybean (Aulakh

2013; Aulakh et al. 2012, 2013; Beyers et al. 2002; Lanie et al. 1994). Preplant or PRE residual herbicides with multiple modes of action can reduce the number of POST glufosinate applications (Bruce and Kells 1990; Bruff and Shaw 1992a,b; Riley et al. 2014). For example, Lanie et al. (1994) reported 98% control of pitted morningglory (*Ipomoea lacunosa* L.) with a tank-mixture of glufosinate and imazaquin, which was 36% greater than when glufosinate was applied alone in glufosinate-resistant soybean.

Several ALS-inhibiting, soil-applied herbicides, such as chlorimuron, cloransulam, flumetsulam, imazaquin, and imazethapyr have been widely used in soybean, particularly before the commercialization of glyphosate-resistant soybean (Dayan et al. 1996; Dirks et al. 2000; Duff et al. 2008; Ellis and Griffin 2002; Whitaker et al. 2010). However, because of their repeated usage, 151 weed species have been confirmed resistant to ALS-inhibitors by 2014 (Heap 2015). Therefore, residual herbicides, such as acetochlor, flumioxazin, fomesafen, metribuzin, pendimethalin, or sulfentrazone applied PRE, as well as POST herbicides, such as acifluorfen, fomesafen, or lactofen, are being used for managing ALS and glyphosate-resistant weeds in soybean (Riley and Bradley 2014; Sarangi et al. 2015). Additionally, several herbicides, including acetochlor, cloransulam, dimethenamid-*P*, and *S*-metolachlor have been registered for POST application in soybean. When applied POST, residual herbicides are usually tank-mixed with foliar-active herbicides, such as glyphosate, in glyphosate-resistant crops or with glufosinate in glufosinate-resistant crops (Aulakh et al. 2012, 2013, Taylor-Lovell et al. 2002; Thomas et al. 2007; Whitaker et al. 2010). Additionally, pyroxasulfone (an herbicide that inhibits very long chain fatty acid synthesis) is registered for weed control in several crops, including soybean. It can be applied PRE or POST from the first- to third-trifoliate leaf stage in soybean (Anonymous 2015). Although the PRE herbicides provide early season weed control and allow for flexibility in timing of POST applications, tank-mixing residual herbicides with POST herbicides may extend the residual weed control later into the season (Knezevic et al. 2009). To minimize selection pressure and improve grass-weed control, glufosinate can be applied in conjunction with residual herbicides applied PRE or POST in glufosinate-resistant soybean weed-management systems.

The objectives of this study were to (1) compare broadleaf and grass weed control across different glufosinate-based herbicide programs with and without residual herbicides, and (2) evaluate their effect on soybean injury and yield. We hypothesized that broadleaf and grassy weeds would be more effectively controlled with (1) sequential glufosinate applications than single application, (2) a residual PRE herbicide followed by (fb) glufosinate applied alone or tank-mixed with a residual herbicide compared with a sequential glufosinate program, and (3) a residual PRE herbicide fb glufosinate tank-mixed with a residual herbicide compared with a residual PRE fb glufosinate program.

## Materials and Methods

The field experiment was conducted at South Central Agricultural Laboratory, University of Nebraska-Lincoln, Clay Center, NE (40.58°N, 98.14°W) in 2012 and 2013. Soil was a Crete silt loam (fine, montmorillonitic, mesic, Pachic Argiustolls) with a pH of 6.5, 17% sand, 58% silt, 25% clay, and 2.5% organic matter. The previous crop was glyphosate-resistant corn, planted under conventional tillage with EPOST and LPOST applications of glyphosate applied at 950 g ha$^{-1}$. The experiment was arranged in a randomized complete-block design with four replications. The site was tilled before soybean was planted, and fertilizers were applied per local recommendations. Glufosinate-resistant soybean ('Stine S100211') was planted at 370,000 seeds ha$^{-1}$ on May 7, 2012, and May 15, 2013. Seeds were planted 3 cm deep, with 76-cm spacing between rows. The plot size was 3 m wide by 9 m long, comprising four soybean rows. The indigenous weed species present at the test site included common lambsquarters, common waterhemp, eastern black nightshade, green foxtail, large crabgrass, and velvetleaf. Twelve glufosinate-based herbicide programs, with and without residual herbicides, were compared for weed control and crop tolerance in glufosinate-resistant soybean (Table 1). A nontreated control was included for comparison. The herbicide application rates were selected based on the labeled rates in soybean.

Herbicides were applied with a $CO_2$-pressurized backpack sprayer calibrated to deliver 140 L ha$^{-1}$ at

Table 1. Herbicide treatments, application timing, rates, and the products used in glufosinate-resistant soybean in field experiments conducted at Clay Center, NE, in 2012 and 2013.[a]

| Herbicide treatment[b] | Herbicide trade name | Timing[a] | Rate | Manufacturer[c] |
|---|---|---|---|---|
| | | | g ha$^{-1}$ | |
| Glufosinate | Liberty 280 | LPOST | 1,333 | Bayer CropScience |
| Glufosinate fb | Liberty 280 fb | EPOST | 740 | Bayer CropScience |
| Glufosinate | Liberty 280 | LPOST | 593 | Bayer CropScience |
| Glufosinate fb | Liberty 280 fb | EPOST | 880 | Bayer CropScience |
| Glufosinate | Liberty 280 | LPOST | 880 | Bayer CropScience |
| Flumioxazin fb | Valor SX fb | PRE | 107 | Valent U.S.A. |
| Glufosinate | Liberty 280 | LPOST | 593 | Bayer Crop Science |
| Sulfentrazone + cloransulam fb | Sonic fb | PRE | 220 | Dow AgroSciences |
| Glufosinate | Liberty 280 | LPOST | 593 | Bayer CropScience |
| Sulfentrazone + imazethapyr fb | Authority Assist fb | PRE | 350 | FMC |
| Glufosinate | Liberty 280 | LPOST | 593 | Bayer CropScience |
| Saflufenacil + dimethenamid-*P* fb | Verdict fb | PRE | 244 | BASF |
| Glufosinate | Liberty 280 | LPOST | 593 | Bayer CropScience |
| Sulfentrazone + metribuzin fb | Authority MTZ fb | PRE | 630 | FMC |
| Glufosinate | Liberty 280 | LPOST | 593 | Bayer CropScience/Syngenta |
| Sulfentrazone + metribuzin fb | Authority MTZ fb | PRE | 630 | FMC |
| Glufosinate + pyroxasulfone | Liberty 280 +Zidua | EPOST | 593 + 149 | Bayer CropScience/BASF |
| Sulfentrazone + metribuzin fb | Authority MTZ fb | PRE | 630 | FMC |
| Glufosinate + *S*-metolachlor | Liberty 280 +Dual ll Magnum | EPOST | 593 + 1,390 | Bayer CropScience/Syngenta |
| Sulfentrazone + metribuzin fb | Authority MTZ fb | PRE | 630 | FMC |
| Glufosinate + acetochlor | Liberty 280 + Warrant | EPOST | 593 + 1,680 | Bayer CropScience/Monsanto |
| Flumioxazin + chlorimuron fb | Valor XLT fb | PRE | 141 | Valent U.S.A. |
| Glufosinate + acetochlor | Liberty 280 + Warrant | EPOST | 593 + 1,680 | Bayer CropScience/Monsanto |

[a] Abbreviations: LPOST, late-POST; fb, followed by; EPOST, early POST.

[b] AMS, ammonium sulfate (DSM Chemicals North America, Augusta, GA 20901) was added at 2% w/v to all EPOST and LPOST herbicide treatments.

[c] Bayer CropScience, Research Triangle Park, NC 27709; Valent U.S.A. Corporation, Walnut Creek, CA 94596; Dow AgroSciences, Indianapolis, IN 46268; FMC Corporation, Philadelphia, PA 19103; BASF Corporation, Research Triangle Park, NC 27709; Syngenta Crop Protection, Greensboro, NC 27419; Monsanto Company, St. Louis, MO 63167.

276 kPa and equipped with a four-nozzle boom fitted with AIXR 110015 flat-fan nozzles (TeeJet, Spraying Systems Co., P.O. Box 7900, Wheaton, IL 60189). Herbicide treatments were applied as PRE (May 8, 2012, and May 17, 2013), EPOST (May 28, 2012, and June 6, 2013) to V2 soybean, and LPOST (June 21, 2012, and July 2, 2013) to V6 soybean. Glufosinate was applied in sequential EPOST and LPOST applications, which is a standard growers' practice in glufosinate-resistant soybean. When the PRE herbicides were followed by LPOST glufosinate-alone, the objective was to evaluate residual activity of PRE herbicide and control of late season weeds. When PRE herbicides were followed by EPOST glufosinate tank-mixed with residual herbicides (acetochlor, pyroxasulfone, or *S*-metolachlor), the objective was to evaluate overlapping residual programs and to avoid weed escapes. The experimental site was under a central pivot-irrigation system; the crop was irrigated within a week of residual herbicide application and as required to prevent drought stress during the growing season.

Visual weed-control data were collected on a scale of 0 to 100% (0% equaling no control and 100% equaling complete control) at 15 d after PRE (DAPRE) and early-POST treatments, 15 and 30 d after late-POST herbicide treatment, and within a week before soybean harvest. Herbicide injury symptoms on soybean were recorded on a scale of 0 to 100% (0% equaling no injury and 100% equaling plant death) at the same time as weed control. Weed densities were assessed from two randomly placed 0.25-m$^2$ quadrats per plot at 15 DAPRE and 30 d after late-POST herbicide treatments, and within a week before soybean harvest. Weeds were clipped at the stem base within 2 cm from the soil surface, dried in an oven for 72 h at 65 C, and the biomass was recorded. Soybean was harvested using a plot combine, and yields were adjusted to 13% moisture content.

**Statistical Analysis.** Data were subjected to ANOVA using the PROC GLIMMIX in SAS version 9.3 (SAS Institute Inc, 100 SAS Campus Dr., Cary, NC 27513). Herbicide treatments and experimental year were the fixed effects, whereas replication was considered a random effect in the model. To satisfy ANOVA assumptions, visual weed-control estimates, weed density, and biomass data were arcsine square-root transformed before analysis. However, back-transformed data are presented with mean separation based on transformed data. If the year-by-treatment interaction was not significant, data were combined. Where the ANOVA test indicated treatment effects were significant, means were separated at $P \leq 0.05$ using Fisher's protected LSD test.

## Results and Discussion

Year-by-treatment interaction was not significant for all response variables, with the exception of soybean injury and yield. Therefore, data were pooled over years, but soybean injury and seed yield data are presented separately by year. Early spring was comparatively drier in 2013 than in 2012, which may have resulted in differences in soybean injury rates. Year-by-treatment interaction for soybean yield was significant ($P < 0.0001$) because of hail damage in 2013 that significantly reduced yield.

The most common broadleaf weeds infesting the experimental site in both years were common lambsquarters, common waterhemp, eastern black nightshade, and velvetleaf. Glufosinate (1,333 g $ha^{-1}$) applied in a single LPOST application controlled common lambsquarters, common waterhemp, and velvetleaf $\leq$ 65% at harvest compared with a maximum of 85% control from EPOST fb LPOST sequential applications of glufosinate at low (740 fb 593 g $ha^{-1}$) or high (880 fb 880 g $ha^{-1}$) rates (Table 2). However, a single LPOST glufosinate application was not different from sequential EPOST fb LPOST glufosinate applications at lower rates. Wiesbrook et al. (2001) observed 5 to 50% greater control of common cocklebur, common lambsquarters, giant ragweed, and velvetleaf with sequential EPOST fb LPOST glufosinate applications compared with a single EPOST application. Flumioxazin, saflufenacil plus dimethenamid-*P*, or sulfentrazone plus cloransulam/imazethapyr/metribuzin applied PRE controlled broadleaf weeds > 90% at 15 DAPRE. Krausz and Young (2003) reported $\geq$ 95% control of several broadleaf weeds, including common waterhemp, with sulfentrazone plus cloransulam applied PRE. The PRE application of flumioxazin, saflufenacil plus dimethenamid-*P*, or sulfentrazone plus metribuzin fb EPOST/LPOST glufosinate controlled broadleaf weeds 69 to 87% at harvest. When sulfentrazone plus metribuzin applied PRE was fb EPOST glufosinate tank-mixed with acetochlor, pyroxasulfone, or *S*-metolachlor, broadleaf weeds were controlled $\geq$ 90%. Residual activity of acetochlor and pyroxasulfone has been shown to provide $\geq$ 75% control of common waterhemp (Hausman et al. 2013). Taylor-Lovell et al. (2002) reported $\geq$ 90% control of common lambsquarters and velvetleaf with flumioxazin applied PRE fb POST glyphosate/imazamox/imazethapyr compared with the same herbicides applied POST without flumioxazin in glyphosate-resistant soybean. Gonzini et al. (1999) reported 95% weed control with PRE fb POST and POST tank-mixed herbicide programs compared with glyphosate-only program in glyphosate-resistant soybean.

Large crabgrass and green foxtail were the most common grass weeds in both years. Glufosinate applied in a single LPOST application controlled both grass weeds $\leq$ 67%, compared with sequential EPOST fb LPOST glufosinate applications (82 to 87%) at harvest (Table 3). Previous researchers reported consistently greater control (> 90%) of green foxtail (Chahal and Jhala 2015) and giant foxtail (Wiesbrook et al. 2001) with sequential EPOST fb LPOST glufosinate applications, compared with a single EPOST glufosinate application. Flumioxazin-, saflufenacil-, or sulfentrazone-based premixes controlled grass weeds $\geq$ 84% at 15 DAPRE. Chahal et al. (2014) reported > 70% control of volunteer corn with sulfentrazone plus imazethapyr/metribuzin applied PRE at 21 d after treatment (DAT). With the PRE application of sulfentrazone plus metribuzin fb EPOST application of glufosinate tank-mixed with acetochlor, pyroxasulfone, or *S*-metolachlor, control of large crabgrass and green foxtail was $\geq$ 94% at harvest, indicating season-long grass-weed control with these

Table 2. Effect of herbicide treatments on broadleaf weed control at 15 d after PRE and at harvest in glufosinate-resistant soybean in field experiments conducted at Clay Center, NE, in 2012 and 2013.[a]

| | | | Weed control[b,c] | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Common lambsquarters | | Common waterhemp | | Eastern black nightshade | | Velvetleaf | |
| Herbicide treatment[a] | Timing | Rate | 15 DAPRE | At harvest | 15 DAPRE | At harvest | 15 DAPRE | At harvest | 15 DAPRE | At harvest |
| | | g ha$^{-1}$ | % | | | | | | | |
| Glufosinate | LPOST | 1,333 | 0 b | 64 d | 0 b | 65 f | 0 b | 76 d | 0 b | 60 e |
| Glufosinate fb | EPOST | 740 | 0 b | 74 cd | 0 b | 73 ef | 0 b | 80 cd | 0 b | 73 cde |
| Glufosinate | LPOST | 593 | | | | | | | | |
| Glufosinate fb | EPOST | 880 | 0 b | 81 bc | 0 b | 81 de | 0 b | 82 bcd | 0 b | 80 cd |
| Glufosinate | LPOST | 880 | | | | | | | | |
| Flumioxazin fb | PRE | 107 | 97 a | 77 bcd | 98 a | 87 bcd | 98 a | 80 cd | 98 a | 85 bc |
| Glufosinate | LPOST | 593 | | | | | | | | |
| Sulfentrazone + cloransulam fb | PRE | 220 | 99 a | 87 ab | 95 a | 93 ab | 97 a | 90 ab | 92 a | 91 ab |
| Glufosinate | LPOST | 593 | | | | | | | | |
| Sulfentrazone + imazethapyr fb | PRE | 350 | 99 a | 78 bc | 94 a | 78 def | 98 a | 82 bcd | 99 a | 78 cd |
| Glufosinate | LPOST | 593 | | | | | | | | |
| Saflufenacil + dimethenamid-*P* fb | PRE | 244 | 98 a | 81 bc | 96 a | 84 cd | 99 a | 82 bcd | 98 a | 80 cd |
| Glufosinate | LPOST | 593 | | | | | | | | |
| Sulfentrazone + metribuzin fb | PRE | 630 | 97 a | 69 cd | 92 a | 69 ef | 99 a | 78 d | 97 a | 70 de |
| Glufosinate | LPOST | 593 | | | | | | | | |
| Sulfentrazone + metribuzin fb | PRE | 630 | 98 a | 93 a | 94 a | 99 a | 97 a | 90 ab | 98 a | 96 a |
| Glufosinate + pyroxasulfone | EPOST | 593 + 149 | | | | | | | | |
| Sulfentrazone + metribuzin fb | PRE | 630 | 98 a | 90 a | 94 a | 92 bc | 97 a | 90 ab | 96 a | 92 ab |
| Glufosinate + *S*-metolachlor | EPOST | 593 + 1,390 | | | | | | | | |
| Sulfentrazone + metribuzin fb | PRE | 630 | 98 a | 92 a | 93 a | 99 a | 98 a | 95 a | 96 a | 96 a |
| Glufosinate + acetochlor | EPOST | 593 + 1,680 | | | | | | | | |
| Flumioxazin + chlorimuron fb | PRE | 141 | 98 a | 91 a | 94 a | 99 a | 98 a | 90 ab | 99 a | 98 a |
| Glufosinate + acetochlor | EPOST | 593 + 1,680 | | | | | | | | |

[a] Abbreviations: DAPRE, days after PRE; LPOST, late-POST; fb, followed by; EPOST, early POST.

[b] Weed control data were arcsine square-root transformed before analysis; however, data presented are the back-transformed means for comparison based on analysis of the transformed data.

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

Table 3. Effect of herbicide treatments on grass weed control and density at 15 d after PRE and at harvest in glufosinate-resistant soybean in field experiments conducted at Clay Center, NE, in 2012 and 2013.[a]

| | | | Weed control[b,c] | | | | Weed density[b,c] | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Green foxtail | | Large crabgrass | | Green foxtail | | Large crabgrass | |
| Herbicide treatment | Timing | Rate | 15 DAPRE | At harvest | 15 DAPRE | At harvest | 15 DAPRE | At harvest | 15 DAPRE | At harvest |
| | | g ha$^{-1}$ | % | | | | plants m$^{-2}$ | | | |
| Nontreated control[d] | | — | — | — | — | — | 10 a | 15 a | 10 a | 19 a |
| Glufosinate | LPOST | 1,333 | 0 b | 61 e | 0 b | 67 e | 10 a | 10 b | 10 a | 11 b |
| Glufosinate fb | EPOST | 740 | 0 b | 87 cd | 0 b | 87 cd | 10 a | 6 bc | 10 a | 6 bc |
| Glufosinate | LPOST | 593 | | | | | | | | |
| Glufosinate fb | EPOST | 880 | 0 b | 82 cd | 0 b | 83 cd | 10 a | 5 bc | 10 a | 4 bc |
| Glufosinate | LPOST | 880 | | | | | | | | |
| Flumioxazin fb | PRE | 107 | 91 a | 78 d | 95 a | 79 d | 1 b | 8 ab | 0 b | 6 bc |
| Glufosinate | LPOST | 593 | | | | | | | | |
| Sulfentrazone + cloransulam fb | PRE | 220 | 94 a | 89 bc | 92 a | 89 bc | 2 b | 5 bc | 1 b | 4 bc |
| Glufosinate | LPOST | 593 | | | | | | | | |
| Sulfentrazone + imazethapyr fb | PRE | 350 | 95 a | 83 cd | 97 a | 88 cd | 0 b | 8 ab | 0 b | 4 bc |
| Glufosinate | LPOST | 593 | | | | | | | | |
| Saflufenacil + dimethenamid-*P* fb | PRE | 244 | 95 a | 86 cd | 89 a | 90 bc | 2 b | 6 bc | 1 b | 3 c |
| Glufosinate | LPOST | 593 | | | | | | | | |
| Sulfentrazone + metribuzin fb | PRE | 630 | 93 a | 81 cd | 95 a | 85 cd | 0 b | 7 ab | 0 b | 6 bc |
| Glufosinate | LPOST | 593 | | | | | | | | |
| Sulfentrazone + metribuzin fb | PRE | 630 | 96 a | 98 ab | 98 a | 98 a | 0 b | 0 c | 0 b | 0 c |
| Glufosinate + pyroxasulfone | EPOST | 593 + 149 | | | | | | | | |
| Sulfentrazone + metribuzin fb | PRE | 630 | 97 a | 99 ab | 95 a | 99 a | 2 b | 0 c | 1 b | 0 c |
| Glufosinate + *S*-metolachlor | EPOST | 593 + 1,390 | | | | | | | | |
| Sulfentrazone + metribuzin fb | PRE | 630 | 96 a | 99 ab | 84 a | 97 a | 0 b | 0 c | 2 b | 2 c |
| Glufosinate + acetochlor | EPOST | 593 + 1,680 | | | | | | | | |
| Flumioxazin + chlorimuron fb | PRE | 141 | 95 a | 94 ab | 98 a | 95 ab | 2 b | 2 c | 0 b | 2 c |
| Glufosinate + acetochlor | EPOST | 593 + 1,680 | | | | | | | | |

[a] Abbreviations: DAPRE, days after PRE; LPOST, late-POST; fb, followed by; EPOST, early POST.

[b] Weed density and control data were arcsine square-root transformed before analysis; however, data presented are the back-transformed means for comparison based on analysis of the transformed data.

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

[d] Nontreated control with zero values were not included in visual control-data analysis.

herbicide programs. Previous studies have reported > 85% control of green foxtail and large crabgrass with pyroxasulfone applied PRE (Geier et al. 2009; Knezevic et al. 2009).

Glufosinate applied in single LPOST or sequential EPOST fb LPOST application reduced broadleaf and grass-weed density to 6 to 12 and 4 to 11 plants $m^{-2}$, respectively (Tables 3 and 4). Herbicides applied PRE reduced broadleaf and grass-weed density to as low as $\leq$ 2 plants $m^{-2}$ at 15 DAPRE. Although comparable with the residual herbicides applied PRE fb EPOST/LPOST glufosinate treatments, tank-mixing residual herbicides with EPOST glufosinate resulted in $\leq$ 4 and $\leq$ 2 plants $m^{-2}$, broadleaf and grass weeds, respectively, at harvest. Similar results were reflected in weed biomass. Herbicide programs containing a PRE fb EPOST/LPOST glufosinate alone or tank-mixed with a residual herbicide usually resulted in the lowest weed biomass ($\leq$ 340 g $m^{-2}$) compared with a single LPOST or a sequential EPOST fb LPOST glufosinate application (> 360 g $m^{-2}$), indicating the importance of including residual herbicides in PRE or POST herbicide programs.

During both years, soybean injury was < 20% in response to any PRE treatment at 15 DAT (data not shown). Maximum injury (20%) occurred with flumioxazin or flumioxazin plus chlorimuron applied PRE (15%) (data not shown). Mahoney et al. (2014) reported similar levels of soybean response with flumioxazin. Year-by-treatment interaction was significant ($P < 0.0001$) for POST herbicide injury evaluated at 15 DAT. In 2012, soybean injury was 15 to 20% when glufosinate was tank-mixed with acetochlor, pyroxasulfone, or *S*-metolachlor (Table 5). Culpepper et al. (2000) reported up to 34% injury with glufosinate in glufosinate-resistant soybean. In 2013, soybean injury ranged from 10 to 20% across POST herbicide programs; however, injury during both years was transient and did not affect soybean yield (Table 5). Similarly, Beyers et al. (2002) observed no yield penalty from injury with glufosinate applied alone or tank-mixed with other herbicides.

Year-by-treatment interaction for soybean yield was significant ($P < 0.0001$) because of hail damage in 2013, which significantly reduced yield. In 2012, soybean yield (3,530 kg $ha^{-1}$) with a single LPOST glufosinate treatment was comparable to the nontreated control, indicating failure of this treatment to provide season-long weed control and to prevent soybean yield reductions. Culpepper et al. (2000) reported that sequential applications of glufosinate or a PRE fb POST glufosinate program was more effective than a single glufosinate application in glufosinate-resistant soybean. In 2012, herbicide programs containing a PRE fb EPOST/LPOST glufosinate alone or in tank mixes produced soybean yields in the range of 4,230 to 4,590 kg $ha^{-1}$. However, in 2013, a PRE fb EPOST glufosinate tank-mixed with residual herbicides produced a greater yield, compared with other treatments (Table 5). Results indicate the importance of a PRE residual herbicide to avoid early season weed competition. In fact, a PRE fb EPOST glufosinate tank-mixed with a residual herbicide provided season-long control of late-emerging weeds, such as common waterhemp, and thereby preserved soybean yield potential. Previous studies have shown that either PRE fb POST or sequential POST foliar programs are more likely to produce greater yields than a single POST program in glyphosate- or glufosinate-resistant soybean (Heatherly et al. 2002; Hoffner et al. 2012; Payne and Oliver 2000; Stewart et al. 2011).

Results indicate that glufosinate applied in a single LPOST application may not control the weed species tested in this study effectively enough to ensure optimum soybean yield. Sequential EPOST fb LPOST applications of glufosinate were more effective, but this practice may impose selection pressure, leading to the evolution of glufosinate-resistant weeds. In fact, resistance to glufosinate has been confirmed in goosegrass [*Eleusine indica* (L.) Gaertn.] in Malaysia (Jalaludin et al. 2010) and in Italian ryegrass [*Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot] in Oregon (Avila-Garcia et al. 2012). Therefore, a herbicide program with sequential applications of glufosinate-only should be avoided. Herbicides applied PRE were highly effective in reducing early season broadleaf and grass-weed densities and allowed for flexibility in the application timing of the POST herbicides (Grichar 2006). Several studies reported that weed management programs consisting of a residual PRE herbicide fb a POST herbicide have the potential to reduce weed densities, improve weed control, and, in some instances, preserve yield potential (Aulakh et al. 2011, 2012; Barnes and Oliver 2004; Ellis and

Table 4. Effect of herbicide treatments on broadleaf weed density at 15 d after PRE and at harvest in glufosinate-resistant soybean in field experiments conducted at Clay Center, NE, in 2012 and 2013.[a]

| | | | Weed density[b,c] | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Common lambsquarters | | Common waterhemp | | Eastern black nightshade | | Velvetleaf | |
| Herbicide treatment | Timing | Rate | 15 DAPRE | At harvest | 15 DAPRE | At harvest | 15 DAPRE | At harvest | 15 DAPRE | At harvest |
| | | g ha$^{-1}$ | plants m$^{-2}$ | | | | | | | |
| Nontreated control | | — | 10 a | 20 a | 11 a | 19 a | 10 a | 19 a | 10 a | 19 a |
| Glufosinate | LPOST | 1,333 | 11 a | 10 b | 12 a | 8 b | 7 a | 8 b | 7 a | 11 b |
| Glufosinate fb | EPOST | 740 | 10 a | 6 cde | 11 a | 6 bc | 9 a | 6 bc | 8 a | 8 bc |
| Glufosinate | LPOST | 593 | | | | | | | | |
| Glufosinate fb | EPOST | 880 | 9 a | 9 bc | 12 a | 7 b | 9 a | 6 bc | 9 a | 8 bc |
| Glufosinate | LPOST | 880 | | | | | | | | |
| Flumioxazin fb | PRE | 107 | 0 b | 10 b | 0 b | 5 bcd | 0 b | 6 bc | 0 b | 6 bc |
| Glufosinate | LPOST | 593 | | | | | | | | |
| Sulfentrazone + cloransulam fb | PRE | 220 | 0 b | 6 cde | 2 b | 2 cde | 0 b | 2 cd | 0 b | 4 bc |
| Glufosinate | LPOST | 593 | | | | | | | | |
| Sulfentrazone + imazethapyr fb | PRE | 350 | 0 b | 7 cde | 1 b | 6 bc | 0 b | 4 bcd | 0 b | 6 bc |
| Glufosinate | LPOST | 593 | | | | | | | | |
| Saflufenacil + dimethenamid-*P* fb | PRE | 244 | 0 b | 7 cde | 2 b | 5 bcd | 0 b | 6 bc | 0 b | 6 bc |
| Glufosinate | LPOST | 593 | | | | | | | | |
| Sulfentrazone + metribuzin fb | PRE | 630 | 0 b | 9 bc | 6 b | 8 b | 0 b | 8 b | 0 b | 8 bc |
| Glufosinate | LPOST | 593 | | | | | | | | |
| Sulfentrazone + metribuzin fb | PRE | 630 | 0 b | 2 f | 0 b | 0 e | 0 b | 2 cd | 0 b | 1 c |
| Glufosinate + pyroxasulfone | EPOST | 593 + 149 | | | | | | | | |
| Sulfentrazone + metribuzin fb | PRE | 630 | 0 b | 3 def | 2 b | 2 cde | 0 b | 2 cd | 0 b | 2 bc |
| Glufosinate + *S*-metolachlor | EPOST | 593 + 1,390 | | | | | | | | |
| Sulfentrazone + metribuzin fb | PRE | 630 | 0 b | 2 f | 2 b | 0 e | 0 b | 1 d | 0 b | 1 c |
| Glufosinate + acetochlor | EPOST | 593 + 1,680 | | | | | | | | |
| Flumioxazin + chlorimuron fb | PRE | 141 | 0 b | 4 def | 0 b | 0 e | 0 b | 2 cd | 0 b | 0 c |
| Glufosinate + acetochlor | EPOST | 593 + 1,680 | | | | | | | | |

[a] Abbreviations: DAPRE, days after PRE; LPOST, late-POST; fb, followed by; EPOST, early POST.

[b] Weed density data were arcsine square-root transformed before analysis; however, data presented are the back-transformed means for comparison based on analysis of the transformed data.

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

Table 5. Effect of herbicide treatments on weed biomass, soybean injury, and yield in glufosinate-resistant soybean in field experiments conducted at Clay Center, NE, in 2012 and 2013.[a]

| Herbicide treatment | Timing | Rate | Weed biomass[b–d] 30 DLPOST | Soybean injury 15 DLPOST[b–d] 2012 | Soybean injury 15 DLPOST[b–d] 2013 | Soybean yield[b–d] 2012 | Soybean yield[b–d] 2013 |
|---|---|---|---|---|---|---|---|
| | — | g ha$^{-1}$ | g m$^{-2}$ | % | | kg ha$^{-1}$ | |
| Nontreated control | | — | 1,040 a | 0 a | 0 a | 3,270 d | 1,700 d |
| Glufosinate | LPOST | 1,333 | 580 b | 0 a | 0 a | 3,530 d | 1,900 cd |
| Glufosinate fb | EPOST | 740 | 360 bc | 0 a | 15 bc | 3,990 c | 2,250 bc |
| Glufosinate | LPOST | 593 | | | | | |
| Glufosinate fb | EPOST | 880 | 470 bc | 1 a | 10 b | 4,040 c | 2,430 b |
| Glufosinate | LPOST | 880 | | | | | |
| Flumioxazin fb | PRE | 107 | 190 cd | 3 a | 20 c | 4,170 bc | 2,100 bcd |
| Glufosinate | LPOST | 593 | | | | | |
| Sulfentrazone + cloransulam fb | PRE | 220 | 70 d | 20 b | 0 a | 4,340 abc | 2,370 bc |
| Glufosinate | LPOST | 593 | | | | | |
| Sulfentrazone + imazethapyr fb | PRE | 350 | 220 cd | 4 a | 20 c | 4,230 abc | 2,390 b |
| Glufosinate | LPOST | 593 | | | | | |
| Saflufenacil + dimethenamid-*P* fb | PRE | 244 | 130 cd | 3 a | 20 c | 4,250 abc | 2,360 bc |
| Glufosinate | LPOST | 593 | | | | | |
| Sulfentrazone + metribuzin fb | PRE | 630 | 340 bc | 0 a | 20 c | 4,170 bc | 2,330 bc |
| Glufosinate | LPOST | 593 | | | | | |
| Sulfentrazone + metribuzin fb | PRE | 630 | 2 d | 15 a | 12 b | 4,450 ab | 3,140 a |
| Glufosinate + pyroxasulfone | EPOST | 593 + 149 | | | | | |
| Sulfentrazone + metribuzin fb | PRE | 630 | 10 d | 20 b | 20 c | 4,470 ab | 3,040 a |
| Glufosinate + *S*-metolachlor | EPOST | 593 + 1,390 | | | | | |
| Sulfentrazone + metribuzin fb | PRE | 630 | 5 d | 15 b | 0 a | 4,580 a | 3,030 a |
| Glufosinate + acetochlor | EPOST | 593 + 1,680 | | | | | |
| Flumioxazin + chlorimuron fb | PRE | 141 | 2 d | 15 a | 3 a | 4,590 a | 3,000 a |
| Glufosinate + acetochlor | EPOST | 593 + 1,680 | | | | | |

[a] Abbreviations: DLPOST, days after late-POST; LPOST, late-POST; fb, followed by; EPOST, early POST.

[b] Weed biomass and soybean injury data were arcsine square-root transformed before analysis; however, data presented are the back-transformed means for comparison based on analysis of the transformed data.

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

[d] Year-by-treatment interaction for weed biomass was not significant; therefore, data from both years were pooled; a significant difference was observed for soybean injury and yield between two years. Therefore, data are presented separately for 2012 and 2013.

Griffin 2002; Gardner et al. 2006; Norsworthy et al. 2012; Soltani et al. 2014).

Historically, weed control research in glufosinate-resistant soybean has tested a few residual herbicides applied PRE or POST tank-mixed with glufosinate (Beyers et al. 2002; Culpepper et al. 2000; Norris et al. 2002). Additionally, many new prepackaged herbicide mixtures, such as sulfentrazone plus metribuzin, have recently been registered in soybean and limited literature exists on their efficacy on the weed species tested in this study. Results from this study showed that flumioxazin plus chlorimuron or sulfentrazone plus metribuzin applied PRE fb glufosinate EPOST tank-mixed with acetochlor, pyroxasulfone, or *S*-metolachlor may provide ≥ 88% control of tested weed species throughout the growing season and thereby preserve soybean yield. Inclusion of residual herbicides also offer other benefits, such as additional modes of action, which will reduce the selection pressure of a single herbicide (Diggle et al. 2003; Johnson et al. 2012), and reduction of the weed seed bank in the soil (Legleiter et al. 2009). Most important, current weed-resistance issues exclusively demand the adoption of integrated weed-management practices, including diversified herbicide programs.

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*Received January 28, 2015, and approved April 2, 2015.*