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Herbicide Programs for Control of Glyphosate-Resistant Volunteer Corn in Glufosinate-Resistant Soybean

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Glyphosate-resistant (GR) volunteer corn is a significant problem weed in soybean grown in rotation with corn in the midwestern United States and eastern Canada. The objective of this study was to evaluate the efficacy of glufosinate applied in single or sequential applications compared with acetyl-coenzyme A carboxylase (ACCase) inhibitors applied alone or tank mixed with glufosinate for controlling GR volunteer corn in glufosinate-resistant soybean. At 15 d after early-POST (DAEP), ACCase inhibitors applied alone controlled volunteer corn 76 to 93% compared to 71 to 82% control when tank mixed with glufosinate. The expected volunteer corn control achieved by tank mixing ACCase inhibitors and glufosinate was greater than the glufosinate alone, indicating that glufosinate antagonized ACCase inhibitors at 15 DAEP, but not at later rating dates. ACCase inhibitors applied alone or tank mixed with glufosinate followed by late-POST glufosinate application controlled volunteer corn and green foxtail $\geq$ 97% at 30 DAEP. Single early-POST application of glufosinate controlled common waterhemp and volunteer corn 53 to 78%, and green foxtail 72 to 93% at 15 DAEP. Single as well as sequential glufosinate applications controlled green foxtail and volunteer corn greater than or equal to 90%, and common waterhemp greater than 85% at 75 d after late-POST (DALP). Contrast analysis suggested that glufosinate applied sequentially provided greater control of volunteer corn at 15 and 75 DALP compared to a single application. Similar results were reflected in volunteer corn density and biomass at 75 DALP. Volunteer corn interference did not affect soybean yield, partly because of extreme weather conditions (hail and high winds) in both years of this study.

Nomenclature: Clethodim; fenoxaprop-P; fluazifop-P; glufosinate; quizalofop-P; sethoxydim; common waterhemp, *Amaranthus rudis* Sauer; green foxtail, *Setaria viridis* (L.) Beauv.; soybean, *Glycine max* (L.) Merr.; volunteer corn, *Zea mays* L.

Key words: Antagonism, herbicide interaction, resistance management, weed control.

El maíz voluntario resistente a glyphosate (GR) es un problema significativo de malezas en soja producida en rotación con maíz en el centro oeste de los Estados Unidos y en el este de Canadá. El objetivo de este estudio fue evaluar la eficacia de glufosinate aplicado solo o en aplicaciones secuenciales comparado con inhibidores de acetyl-coenzyme A carboxylase (ACCase) aplicados solos o en mezclas en tanque con glufosinate para el control de maíz GR voluntario en soja resistente a glufosinate. A 15 d después de la aplicación POST temprana (DAEP), los inhibidores de ACCase aplicados solos controlaron el maíz voluntario 76 a 93% comparado con 71 a 82% de control con la mezcla en tanque con glufosinate. El control esperado de maíz voluntario con las mezclas en tanque con ACCase y glufosinate fue mayor que el de glufosinate solo, lo que indicó que glufosinate antagonizó a los inhibidores de ACCase a 15 DAEP, pero no en fechas de evaluación posteriores. Los inhibidores de ACCase aplicados solos o en mezclas en tanque con glufosinate seguidos de aplicaciones tardías POST de glufosinate controlaron el maíz voluntario y *Setaria viridis* $\geq$ 97% a 30 DAEP. Aplicaciones POST tempranas de glufosinate solo controlaron *Amaranthus rudis* y maíz voluntario 53 a 78%, y *S. viridis* 72 a 93% a 15 DAEP. Aplicaciones solas y secuenciales de glufosinate controlaron *S. viridis* y maíz voluntario en 90% o más, y *A. rudis* más de 85% a 75 d después de la aplicación POST tardía (DALP). Análisis de contrastes sugirieron que glufosinate aplicado secuencialmente brindó mayor control del maíz voluntario a 15 y 75 DALP al compararse con una única aplicación. Resultados similares fueron observados en la densidad y biomasa del maíz voluntario a 75 DALP. La interferencia del maíz voluntario no afectó el rendimiento de la soja, parcialmente porque se presentaron condiciones extremas del estado del tiempo (granizo y vientos fuertes) en los dos años de este estudio.

GR corn and soybean have been widely adopted crops in the United States since commercialization in 1998 and 1996, respectively (Castle et al. 2006). In the United States, 94% of soybean and 89% of corn planted in 2014 were herbicide resistant,

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primarily GR (USDA 2014). Increased adoption of GR corn has resulted in volunteer corn becoming a problem weed in GR soybean grown in rotation (Davis et al. 2008). Volunteer corn is overwintering F_2 generation of corn hybrids grown in the previous year or a corn hybrid emerging from a failed corn stand in a corn-replant situation (Shauck and Smeda 2012; Steckel et al. 2009). Volunteer corn is a competitive weed that results in significant yield reduction of crops grown in rotation (Beckett and Stoller 1988; Chahal et al. 2015; Clewis et al. 2008; Wilson et al. 2010). Volunteer corn encourages the dispersal and survival of western corn rootworm (*Diabrotica virgifera virgifera* LeConte) and gray leaf spot disease (Cercospora zeae-maydis Tehon & E. Y. Daniels), thus limiting the benefits of a corn–soybean rotation (Krupke et al. 2009; Marquardt et al. 2012; Shaw et al. 1978). If not controlled, volunteer corn may interfere with soybean harvest and reduce seed quality (Deen et al. 2006).

Before the commercialization of GR corn and soybean, volunteer corn was controlled with glyphosate with the use of rope wick applicators in conventional soybean (Andersen et al. 1982; Andersen and Geadelmann 1982). Volunteer corn plants; however, were required to grow taller than soybean canopy before glyphosate treatment, allowing early-season competition that usually results in reduced soybean yield (Andersen et al. 1982). A recent study reported that PRE herbicides registered for weed control in soybean provided unacceptable control of GR volunteer corn (Chahal et al. 2014). Several studies reported that the acetyl-coenzyme A carboxylase (ACCase)–inhibiting herbicides provided effective POST control of volunteer corn in soybean (Beckett and Stoller 1988; Beckett et al. 1992; Chahal et al. 2014; Deen et al. 2006; Young and Hart 1997). However, efficacy of these herbicides can vary depending on growth stage, type of ACCase inhibitors applied, environmental conditions at the time of application, and distribution of volunteer corn (Deen et al. 2006; Wilson et al. 2010). The overreliance on glyphosate for weed control in corn and soybean in the last 17 yr has resulted in the evolution of GR weeds (Beckie and Hall 2014; Owen 2008), and as of 2014, 29 weed species worldwide have evolved resistance to glyphosate, including 14 species in the United States (Heap 2014a). Therefore, alternate herbicide programs are required for controlling GR weeds and limiting continued evolution of resistance (Aulakh and Jhala 2015; Ganie et al. 2015; Jhala et al. 2014; Sarangi et al. 2015).

Glufosinate is a nonselective, contact, POST herbicide that inhibits the synthesis of glutamine synthetase in sensitive plants (Wendler et al. 1990; Wild and Wendler 1991) and results in the accumulation of a toxic level of ammonia within the cell, causing photosynthesis cessation, disruption of chloroplast structure, and vesiculation of stroma (Devine et al. 1993; Hinchee et al. 1993). Before the commercialization of glufosinate-resistant corn and soybean, application of glufosinate was limited to noncrop areas, preplant applications in reduced tillage system, and weed control in orchards and vineyards (Coetzer et al. 2002; Jhala et al. 2013; Singh and Tucker 1987). However, glufosinate-resistant crops have provided growers an opportunity to apply glufosinate POST to control many troublesome weeds, including glyphosate-resistant giant ragweed (*Ambrosia trifida* L.) (Jhala et al. 2014; Kaur et al. 2014).

Glufosinate is a broad-spectrum herbicide that controls many weeds (Anonymous 2014). Steckel et al. (1997) reported at least 80% control of 10-cm-tall common cocklebur (*Xanthium strumarium* L.), giant foxtail (*Setaria faberi* Herrm.), and Pennsylvania smartweed (*Polgonum pensylvanicum* L.) with glufosinate application. Glufosinate is effective for controlling certain weed species that are difficult to control with glyphosate, such as *Ipomoea* spp., hemp sesbania [*Sesbania exaltata* (Raf.) Rydb. ex A.W. Hill] (Askew at al. 1997; Corbett et al. 2004), and *Amaranthus* species resistant to glyphosate (Coetzer et al. 2002; Culpepper et al. 2009; Whitaker et al. 2011a).

Glufosinate is usually more effective on annual broadleaf weeds than on grasses (Corbett et al. 2004; Culpepper et al. 2000; Steckel et al. 1997). For example, Culpepper et al. (2000) reported more than 80% control of common lambsquarters (*Chenopodium album* L.), and prickly sida (*Sida spinosa* L.) with a single application of glufosinate compared to less than 75% control of broadleaf signalgrass [*Urochloa platyphylla* (Nash) R.D. Webster], goosegrass [*Eleusine indica* (L.) Gaertn.], and johnsongrass [*Sorghum halepense* (L.) Pers.]. However, variable control of volunteer corn has been reported. Shauck and Smeda (2012) reported $<$ 80% control of GR corn hybrids when glufosinate was applied to 10- and 40-cm–tall plants compared to 20 cm ($>$ 80% control) in a corn-replant situation. Steckel et al. (2009) also reported variability in glufosinate efficacy depending on the height of volunteer corn plants. In contrast, Terry et al. (2012) reported no difference in control of GR corn hybrids and their progenies with glufosinate.

Glufosinate can be applied sequentially in glufosinate-resistant corn and soybean. According to the label, a single glufosinate application up to 740 g ai ha^{-1} can be made in soybean, with a cumulative 1,340 per growing season (Anonymous 2014). Earnest et al. (1998) reported $\geq$ 90% control of barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.], when glufosinate was applied sequentially in glufosinate-resistant corn. Similarly, Aulakh et al. (2011) reported $\geq$ 97% control of large crabgrass [*Digitaria sanguinalis* (L.) Scop.], Palmer amaranth [*Amaranthus palmeri* S. Wats.], sicklepod [*Senna obtusifolia* (L.) H.S. Irwin & Barneby], and small-flower morningglory [*Jacquemontia tamnifolia* (L.) Griseb.] with glufosinate applied sequentially. Therefore, sequential applications of glufosinate or tank mixing glufosinate with ACCase inhibitors may provide better control of GR volunteer corn in glufosinate-resistant soybean. However, several studies also reported that when tank mixed with ACCase inhibitors, glufosinate antagonized control of some annual and perennial grasses (Burke et al. 2005; Gardner at al. 2006). However, information is not available on efficacy of ACCase inhibitors applied in tank mix with glufosinate for control of volunteer corn.

A recent survey reported that cultivation of glufosinate-resistant soybean is increasing in the midsouthern United States, specifically for control of GR Palmer amaranth (Aulakh et al. 2013; Barnett et al. 2013). It is further likely that the cultivation of glufosinate-resistant soybean in the midwestern United States may increase in the near future to control GR weeds more effectively (Kaur et al. 2014), including volunteer corn (Chahal et al. 2014). There is no information in the scientific literature on the efficacy of glufosinate applied alone at different rates or when tank mixed with ACCase inhibitors for control of GR volunteer corn in glufosinate-resistant soybean. The objectives of this study were (1) to compare the efficacy of glufosinate applied at different rates in single or sequential applications for control of GR volunteer corn, (2) to compare the efficacy of ACCase inhibitors applied alone or tank mixed with glufosinate in an early-POST followed by a late-POST application of glufosinate for control of GR volunteer corn and other weeds, and (3) to evaluate crop injury and yield of glufosinate-resistant soybean in presence of GR volunteer corn.

Materials and Methods

Field experiments were conducted at the South Central Agricultural Laboratory (SCAL), University of Nebraska–Lincoln, near Clay Center, NE in 2013 and 2014. 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. GR hybrid corn (Mycogen 2G 681) was seeded at 35,000 seeds ha^{-1} in rows spaced 76 cm apart on May 23, 2013 and May 6, 2014. This project was initiated in 2012 by hand-planting volunteer corn seeds collected in the fall of 2011; however, emergence was poor ($<$ 4 plants $plot^{-1}$) which was not sufficient to test several herbicide programs included in this study. Therefore, in 2013 and 2014 glyphosate-resistant hybrid corn was planted at a density of 35,000 seeds ha^{-1} to mimic volunteer corn, which resulted in excellent corn emergence both years. Glufosinate-resistant soybean ('Stine 30 LC 28') was seeded perpendicular to the corn rows at a density of 380,000 seeds ha^{-1} in rows spaced 76 cm apart on May 28, 2013 and May 8, 2014. The experiment was arranged in a randomized complete block design with four replications. Plots were 3 m wide and 9 m long, consisting of four soybean rows.

A tank mixture of glyphosate (Roundup PowerMAX, Monsanto Company, 800 North Lindberg Ave., St. Louis, MO) at 1.06 kg ae ha^{-1} plus *S*-metolachlor (Dual II Magnum, Syngenta Crop Protection, Inc., Greensboro, NC 27419) at 1.63 kg ai ha^{-1} was applied to the entire experimental area for the control of emerged weeds and residual control of annual grasses 2 d before seeding corn. Herbicide treatments included glufosinate applied at different rates in single or sequential applications, and ACCase inhibitors (clethodim, fenoxaprop plus fluazifop, fluazifop, quizalofop, or sethoxydim) applied alone or tank mixed with glufosinate applied early-POST and followed by a late-POST application of glufosinate (Table 1). A nontreated

Table 1. Herbicide treatments, application timing, rates, and products used in glufosinate-resistant soybean in a field experiment conducted in Nebraska in 2013 and 2014.

Herbicide common name	Timing[a]	Rate	Trade name	Manufacturer	Adjuvant[b]
Glufosinate	E-POST	450	Liberty 280	Bayer Crop Science, Research Triangle Park, NC 27709	AMS
Glufosinate	E-POST	600	Liberty 280	Bayer Crop Science	AMS
Glufosinate	E-POST	740	Liberty 280	Bayer Crop Science	AMS
Glufosinate fb	E-POST	450	Liberty 280	Bayer Crop Science	AMS
glufosinate	L-POST	600	Liberty 280		AMS
Glufosinate fb	E-POST	600	Liberty 280	Bayer Crop Science	AMS
glufosinate	L-POST	600	Liberty 280		AMS
Glufosinate fb	E-POST	740	Liberty 280	Bayer Crop Science	AMS
glufosinate	L-POST	600	Liberty 280		AMS
Clethodim fb	E-POST	140	Select Max	Valent USA Corporation, Walnut Creek, CA 94596	AMS + NIS
glufosinate	L-POST	600	Liberty 280	Bayer Crop Science	AMS
Clethodim + glufosinate fb	E-POST	140 + 600	Select Max + Liberty 280	Valent USA Corporation + Bayer Crop Science	AMS + NIS
glufosinate	L-POST	600	Liberty 280	Bayer Crop Science	AMS
Quizalofop fb	E-POST	40	Assure II	DuPont Crop Protection, P.O. Box 80705, Wilmington, DE 19880	COC
glufosinate	L-POST	600	Liberty 280	Bayer Crop Science	AMS
Quizalofop + glufosinate fb	E-POST	40 + 600	Assure II + Liberty 280	DuPont Crop Protection + Bayer Crop Science	COC
glufosinate	L-POST	600	Liberty 280	Bayer Crop Science	AMS
Fluazifop fb	E-POST	210	Fusilade DX	Syngenta Crop Protection, Inc., Greensboro, NC 27419	NIS + UAN-28
glufosinate	L-POST	600	Liberty 280	Bayer Crop Science	AMS
Fluazifop + glufosinate fb	E-POST	210 + 600	Fusilade DX + Liberty 280	Syngenta Crop Protection + Bayer Crop Science	NIS
glufosinate	L-POST	600	Liberty 280	Bayer Crop Science	AMS
Fenoxaprop + fluazifop fb	E-POST	130	Fusion	Syngenta Crop Protection	COC + AMS
glufosinate	L-POST	600	Liberty 280	Bayer Crop Science	AMS
Fenoxaprop + fluazifop + glufosinate fb	E-POST	130 + 600	Fusion + Liberty 280	Syngenta Crop Protection + Bayer Crop Science	COC + AMS
glufosinate	L-POST	600	Liberty 280	Bayer Crop Science	AMS
Sethoxydim fb	E-POST	350	Poast Plus	BASF Corporation, 26 Davis Drive, Research Triangle Park, NC 27709	COC + AMS
glufosinate	L-POST	600	Liberty 280	Bayer Crop Science	AMS
Sethoxydim + glufosinate fb	E-POST	350 + 600	Poast Plus + Liberty 280	BASF Corporation + Bayer Crop Science	COC + AMS
glufosinate	L-POST	600	Liberty 280	Bayer Crop Science	AMS

[a] Abbreviations: AMS, ammonium sulfate (DSM Chemicals North America Inc., Augusta, GA); COC, crop oil concentrate (Agridex, Helena Chemical Co., Collierville, TN); E-POST, early POST; L-POST, late POST; fb, followed by; NIS, nonionic surfactant (Induce, Helena Chemical Co., Collierville, TN); UAN-28, urea ammonia nitrate solution 28% (Sylvite Agri-Services, Ontario, Canada).

[b] AMS at 2% wt/v, COC at 1% v/v, UAN-28 at 2.34 L ha^{-1}, and NIS at 0.25% v/v was mixed with herbicides.

control was included for comparison. The application rates of herbicides were selected based on the manufacturer's recommended rates in glufosinate-resistant soybean.

Herbicide treatments were applied with a CO_2-pressurized backpack sprayer consisting of a four-nozzle boom fitted with AIXR 110015 flat-fan nozzles (TeeJet Spraying Systems Co., P.O. Box 7900, Wheaton, IL 60189) calibrated to deliver 140 L ha^{-1} at 276 kPa. GR volunteer corn was 25 to 30 cm tall and soybean was at the V2 to V3 stage at the time of early-POST application of herbicides (June 26, 2013 and June 10, 2014). Glufosinate at 600 g ha^{-1} was applied late-POST in selected treatments (Table 1) on July 12, 2013 and June 26, 2014 when volunteer corn was 32 to 38 cm tall and soybean was at the V5 to V6 stage.

Visual control estimates were recorded for volunteer corn and other existing weeds at 15 d after early POST (DAEP) and 15, 30, 45, and 75 d after late-POST (DALP) herbicide treatments based on 0 to 100% scale, where 0% equals no control and 100% equals plant death. A similar scale was used to assess glufosinate-resistant soybean injury at 7 and 21 d after early- and late-POST herbicide applications, where 0% equals no foliar injury and 100% equals plant death. The density and biomass were assessed from two randomly selected 0.25-m^2 quadrats per plot at 45 DALP herbicide treatment. The aboveground biomass of volunteer corn and other weeds was hand harvested separately and oven dried at 65 C for 3 d, and dry weight was recorded. Soybean was harvested at maturity with a small-plot combine, weight and moisture content were recorded, and yields were adjusted to 13% moisture content.

Statistical Analysis. Data for visual weed control estimates, density, and biomass, and soybean injury and yield were subjected to ANOVA without the PROC GLIMMIX procedure in SAS version 9.3 (SAS Institute Inc., Cary, NC 27513). Year and treatments were considered fixed effects, whereas replication was considered a random effect in the model. Biomass data of common waterhemp were arc-sine square-root transformed before analysis; however, data presented are the means of actual values for comparison based on interpretation from the transformed data. Where the ANOVA indicated treatment effects were significant, means were separated at $P \leq 0.05$ with the use of the Tukey-Kramer pairwise comparison test. Additionally, the PROC GLIMMIX procedure was used to test single-degree-of-freedom contrasts to compare the effect of different herbicide programs. Preplanned contrasts were performed to compare herbicide programs containing single vs. sequential glufosinate applications, and programs containing ACCase inhibitors applied alone vs. ACCase inhibitors tank mixed with glufosinate. Expected values for herbicide interactions were calculated with the use of Colby equation (Colby 1967):

$$E = (X + Y) - (XY/100), \qquad [1]$$

where E is the expected control of GR volunteer corn or green foxtail with application of herbicides A + B in tank mixture, X and Y are observed control of GR volunteer corn or green foxtail with the application of herbicides A and B, respectively, at specific rates. The expected and observed control values for herbicide combination A + B were subjected to t tests to determine whether means were different. The herbicide combination was considered antagonistic if the expected mean was significantly greater than the observed mean. If the expected mean was significantly lower than the observed mean, the herbicide combination was considered synergistic.

Results and Discussion

The interaction of year by treatment was not significant for visual weed control estimates, density, biomass, soybean injury and yield; therefore, data were pooled over years. Glufosinate applied at 450, 600, and 740 g ha^{-1} provided 66, 73, and 75% control of GR volunteer corn, respectively. The ACCase-inhibiting herbicides, applied alone, provided $\geq$ 93% control, except for sethoxydim, which provided 76% control of GR volunteer corn (Table 2). Similarly, Soltani et al. (2006) reported $<$ 80% control of GR volunteer corn with sethoxydim compared to $>$ 85% control with other ACCase inhibitors (clethodim, fenoxaprop-P, fluazifop-P, quizalofop-P) at 28 DAT. Volunteer corn was controlled 71 to 82% when ACCase inhibitors were tank mixed with glufosinate compared to 76 to 96% control when applied alone at 15 DAEP, indicating possible antagonism when tank mixed with glufosinate. The Colby analysis also showed that the expected volunteer corn control achieved by

Table 2. Effect of herbicide treatments on glyphosate-resistant volunteer corn control, density, and biomass in glufosinate-resistant soybean in a field experiment conducted in Nebraska in 2013 and 2014.[a]

Herbicide[b]	Timing	Rate	Control			Density[c]	Biomass[c]
			15 DAEP[b,c]	15 DALP[b,c]	75 DALP[b,c]		
		g ai ha^{-1}	%			No. m^{-2}	g m^{-2}
Nontreated control[d]	–	–	0	0	0	17 a	230 a
Glufosinate	E-POST	450	66 ef	79 c	93 b	3 b	19 b
Glufosinate	E-POST	600	73 de	90 b	96 ab	2 b	13 b
Glufosinate	E-POST	740	75 de	93 b	99 a	0 c	0 c
Glufosinate fb	E-POST	450					
glufosinate	L-POST	600	61 f	98 a	99 a	0 c	0 c
Glufosinate fb	E-POST	600					
glufosinate	L-POST	600	70 ef	98 a	99 a	0 c	0 c
Glufosinate fb	E-POST	740					
glufosinate	L-POST	600	78 de	98 a	99 a	0 c	0 c
Clethodim fb	E-POST	140					
glufosinate	L-POST	600	94 a	99 a	99 a	0 c	0 c
Clethodim + glufosinate fb	E-POST	140 + 600					
glufosinate	L-POST	600	81 bcd	99 a	99 a	0 c	0 c
Quizalofop fb	E-POST	40					
glufosinate	L-POST	600	95 a	98 a	99 a	0 c	0 c
Quizalofop + glufosinate fb	E-POST	40 + 600					
glufosinate	L-POST	600	82 bcd	98 a	99 a	0 c	0 c
Fluazifop fb	E-POST	210					
Glufosinate	L-POST	600	96 a	97 a	99 a	0 c	0 c
Fluazifop + glufosinate fb	E-POST	210 + 600					
Glufosinate	L-POST	600	80 bcd	97 a	99 a	0 c	0 c
Fenoxaprop + fluazifop fb	E-POST	130					
Glufosinate	L-POST	600	93 a	99 a	99 a	0 c	0 c
Fenoxaprop + fluazifop + glufosinate fb	E-POST	130 + 600					
Glufosinate	L-POST	600	81 bcd	98 a	99 a	0 c	0 c
Sethoxydim fb	E-POST	350					
glufosinate	L-POST	600	76 cd	99 a	99 a	0 c	0 c
Sethoxydim + glufosinate fb	E-POST	350 + 600					
glufosinate	L-POST	600	71 def	99 a	99 a	0 c	0 c
P value			<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Contrasts							
Glufosinate single vs. sequential application			–	$P < 0.0001$	$P < 0.0001$	–	–
ACCase alone vs. ACCase tank mixed with glufosinate			$P < 0.001$	$P = 0.7660$	$P = 0.7813$	–	–

[a] Year-by-treatment interaction was not significant; therefore, data from both years were combined.

[b] Abbreviations: E-POST, early POST; L-POST, late POST; DAEP, days after early POST; DALP, days after late POST; fb, followed by.

[c] Means within columns with no common letter(s) are significantly different according to Tukey-Kramer's pairwise comparison test at $P \leq 0.05$.

[d] The percent control (0%) data of nontreated control were not included in analysis.

tank mixing ACCase inhibitors and glufosinate was greater than their respective observed control at 15 DAEP (Table 3), indicating that glufosinate antagonized ACCase inhibitors. This is consistent with previous studies that have reported antagonism of the ACCase-inhibiting herbicides when tank mixed with some broadleaf herbicides (Culpepper et al. 1998, 1999; Holshouser and Coble 1990; Vidrine et al. 1995). For instance, Burke et al. (2005) reported a 50% reduction in goosegrass

Table 3. Observed and expected control of glyphosate-resistant volunteer corn by acetyl-coenzyme A carboxylase (ACCase) inhibitors applied alone or tank mixed with glufosinate in glufosinate-resistant soybean at 15 d after early-POST (DAEP) in a field experiment conducted in 2013 and 2014 in Nebraska.

Herbicide	Rate	Observed	Expected[a]
	g ai ha^{-1}	%	
Glufosinate	600	73	
Clethodim	140	94	
Clethodim + glufosinate	140 + 600	81	98[b]
Quizalofop	40	95	
Quizalofop + glufosinate	40 + 600	82	99[b]
Fluazifop	210	96	
Fluazifop + glufosinate	210 + 600	80	99[b]
Fenoxaprop + fluazifop	130	93	
Fenoxaprop + fluazifop + glufosinate	130 + 600	81	98[b]
Sethoxydim	350	76	
Sethoxydim + glufosinate	350 + 600	71	97[b]
LSD (0.05)		10	

[a] Expected value determined by the Colby equation: $E = (X + Y) - (XY/100)$, where E is expected percent control with herbicide A + B, X and Y is observed percent control with herbicide A and B, respectively.

[b] Significantly different from the observed value ($P \leq 0.05$) as determined by t test, indicating antagonism of tank mixing herbicides A and B.

control when clethodim was tank mixed with glufosinate compared to clethodim applied alone. No difference in GR volunteer corn control was observed with sethoxydim applied alone (76%) or tank mixed with glufosinate (71%).

At 30 DAEP, glufosinate applied at 450, 600, and 740 g ha^{-1} provided 79, 90, and 93% control of GR volunteer corn, respectively. Shauck and Smeda (2012) reported 80 to 85% control of 20-cm–tall GR corn with glufosinate applied at 450 g ha^{-1}. An early-POST followed by a late-POST application of glufosinate improved volunteer corn control ≥ 98% at 15 DALP. A similar level of volunteer corn control (≥ 97%) was observed with ACCase inhibitors applied alone or tank mixed with glufosinate when followed by a late-POST application of glufosinate. Similarly, Beyers et al. (2002) reported improved control of common waterhemp, giant foxtail, pitted morningglory (*Ipomoea lacunosa* L.), ivyleaf morningglory [*Ipomoea hederacea* (L.) Jacq.], and prickly sida, with sequential applications of glufosinate. By 75 DALP, volunteer corn control was > 90% with all herbicide treatments. However, on the basis of contrasts, sequential applications of glufosinate provided greater control of volunteer corn at 15 and 75 DALP compared to a single glufosinate application, and no difference was observed in contrast analysis between ACCase inhibitors applied alone vs. tank mixed with glufosinate at 15 and 75 DALP glufosinate treatment (Table 2).

Similar results were observed in volunteer corn density and biomass. For example, the nontreated control had the highest volunteer corn density (17 plants m^{-2}) and biomass (230 g m^{-2}) followed by a single application of glufosinate at 450 g ha^{-1} (19 g m^{-2}) and 600 g ha^{-1} (13 g m^{-2}), and the remaining treatments resulted in no volunteer corn biomass. No crop injury was observed in any of herbicide treatments at 7 and 21 d after early- and late-POST treatments during either year of the study (data not shown). This was expected because glufosinate-resistant soybean usually has high level of tolerance to glufosinate applications; however, some level of injury has been reported in literature. For example, Beyers et al. (2002) reported 7 to 21% glufosinate-resistant soybean injury at 14 d after glufosinate applied in combination with quizalofop, lactofen, or imazethapyr compared to < 12% injury with glufosinate applied alone. In another study, Culpepper et al. (2000) reported 30 to 34% injury on glufosinate-resistant soybean, in one out of three site years, at 5 d after glufosinate applied alone or in combination with fomesafen.

In addition to volunteer corn, the primary weeds in the experimental area were green foxtail and common waterhemp. Green foxtail emergence was partially due to lack of activation of *S*-metolachlor because of limited available moisture early in the season during both years. At 15 DAEP, green foxtail control was influenced by glufosinate rates. Glufosinate applied at 450, 600, and 740 g ha^{-1} provided 72 to 75, 81 to 84, and 92 to 93% control, respectively (Table 4). Similarly, Bethke et al. (2013) reported greater control (86%) of giant foxtail with glufosinate applied at higher rates compared to the lower rates (73 to 76%). The ACCase inhibitors applied alone or tank mixed with glufosinate controlled green foxtail > 87% at 15 DAEP, indicating no antagonism when tank mixed with glufosinate. The Colby analysis also showed that the expected control of green foxtail by tank mixing ACCase inhibitors and glufosinate was comparable with their respective observed control at 15 DAEP (Table 5). Similarly, Johnson et al.

Table 4. Effect of herbicide treatments on green foxtail control in glufosinate-resistant soybean in a field experiment conducted in Nebraska in 2013 and 2014.[a]

Herbicide[b]	Timing	Rate	Control		
			15 DAEP[b,c]	15 DALP[b,c]	75 DALP[b,c]
		g ai ha^{-1}	%		
Nontreated control[d]	–	–	0	0	0
Glufosinate	E-POST	450	75 d	91 b	99 a
Glufosinate	E-POST	600	84 c	90 b	99 a
Glufosinate	E-POST	740	92 a	94 ab	99 a
Glufosinate fb	E-POST	450	72 d	93 ab	99 a
glufosinate	L-POST	600			
Glufosinate fb	E-POST	600	81 c	94 ab	99 a
glufosinate	L-POST	600			
Glufosinate fb	E-POST	740	93 a	98 ab	99 a
glufosinate	L-POST	600			
Clethodim fb	E-POST	140	91 a	99 a	99 a
glufosinate	L-POST	600			
Clethodim + glufosinate fb	E-POST	140 + 600	92 a	99 a	99 a
glufosinate	L-POST	600			
Quizalofop fb	E-POST	40	93 a	99 a	99 a
glufosinate	L-POST	600			
Quizalofop + glufosinate fb	E-POST	40 + 600	91 a	99 a	99 a
glufosinate	L-POST	600			
Fluazifop fb	E-POST	210	91 a	99 a	99 a
glufosinate	L-POST	600			
Fluazifop + glufosinate fb	E-POST	210 + 600	90 ab	99 a	99 a
glufosinate	L-POST	600			
Fenoxaprop + fluazifop fb	E-POST	130	91 ab	99 a	99 a
glufosinate	L-POST	600			
Fenoxaprop + fluazifop + glufosinate fb	E-POST	130 + 600	92 a	99 a	99 a
glufosinate	L-POST	600			
Sethoxydim fb	E-POST	350	87 bc	99 a	99 a
glufosinate	L-POST	600			
Sethoxydim + glufosinate fb	E-POST	350 + 600	91 ab	99 a	99 a
glufosinate	L-POST	600			
P value			<0.0001	0.0023	0.4604
Contrasts					
Glufosinate single vs. sequential application			–	P = 0.8208	P = 0.8968
ACCase alone vs. ACCase tank mixed with glufosinate			P = 0.5312	P = 1.0000	P = 0.7721

[a] Year-by-treatment interaction was not significant; therefore, data from both years were combined.

[b] Abbreviations: DAEP, days after early POST; DALP, days after late POST; E-POST, early POST; fb, followed by; L-POST, late POST.

[c] Means within columns with no common letter(s) are significantly different according to the Tukey-Kramer pairwise comparison test at $P \leq 0.05$.

[d] The percent control (0%) data of nontreated control were not included in analysis.

(2014) reported > 90% control of johnsongrass with tank-mixed application of clethodim and glufosinate as early-POST followed by a late-POST glufosinate. Abit et al. (2011) reported > 90% control of green foxtail with quizalofop applied alone. Control of green foxtail was ≥ 90% in all herbicide treatments at 15 DALP. On the basis of contrasts, late-POST glufosinate application did not improve green foxtail control compared to a single application of glufosinate at 15 or 75 DALP. At 75 DALP, all herbicide treatments provided 99% control of green foxtail. Similarly, Corbett et al. (2004) reported > 95% control of green and yellow foxtail [*Setaria pumila* (Poir.) Roemer & J.A. Schultes] with single or sequential applications of glufosinate at 291 and 409 g ha^{-1}. The nontreated

Table 5. Observed and expected control of green foxtail by acetyl-coenzyme A carboxylase (ACCase) inhibitors applied alone or tank mixed with glufosinate in glufosinate-resistant soybean at 15 d after early POST (DAEP) in a field experiment conducted in Nebraska in 2013 and 2014.

Herbicide	Rate	Observed	Expected[a]
	g ai ha^{-1}	%	
Glufosinate	600	84	
Clethodim	140	91	
Clethodim + glufosinate	140 + 600	92	99[b]
Quizalofop	40	93	
Quizalofop + glufosinate	40 + 600	91	99[b]
Fluazifop	210	91	
Fluazifop + glufosinate	210 + 600	90	99[b]
Fenoxaprop + fluazifop	130	91	
Fenoxaprop + fluazifop + glufosinate	130 + 600	92	99[b]
Sethoxydim	350	87	
Sethoxydim + glufosinate	350 + 600	91	98[b]
LSD (0.05)		9	

[a] Expected value determined by the Colby's equation: $E = (X + Y) - (XY/100)$, where E is expected percent control with herbicide A + B, X and Y is observed percent control with herbicide A and B, respectively.

[b] Not significantly different from the observed value ($P \leq 0.05$), as determined by t test.

control had the highest green foxtail biomass (29 g m^{-2}), and no biomass was present in any of the herbicide-treated plots (data not shown).

A single application of glufosinate provided variable control of common waterhemp at 15 DAEP; the highest rate (740 g ha^{-1}) provided 76% control compared to less than 65% at the lower rates (Table 6). The ACCase inhibitors applied alone provided no control of common waterhemp, and their tank-mixed application with glufosinate provided 60 to 65% control. At 15 and 75 DALP, 85 to 95% control of common waterhemp was observed with a single application of glufosinate, and the sequential applications (irrespective of glufosinate rate) provided ≥ 93% control. Similarly, Beyers et al. (2002) reported 93% control of common waterhemp with sequential applications of glufosinate compared to a single application (85%). At 75 DALP, all herbicide treatments provided ≥ 86% control of common waterhemp. However, based on the contrasts, sequential applications of glufosinate provided greater control of common waterhemp at 75 DALP compared to a single application. Sarangi et al. (2015) reported > 85% control of GR common waterhemp with a single glufosinate application at 594 g ha^{-1}. The highest biomass (327 g m^{-2}) of common waterhemp was recorded in the nontreated control plots compared to < 70 g m^{-2} in herbicide-treated plots with no difference among them (data not shown).

No difference in soybean yield was observed between herbicide treatments, partly because of the effects of hail- and windstorms on plants later in the season during both years. Results of this study conclude that glufosinate applied in single or sequential applications can effectively control GR volunteer corn in glufosinate-resistant soybean. However, ACCase inhibitors controlled green foxtail and GR volunteer corn more effectively than a single application of glufosinate early in the season (15 DAEP). The control was comparable with both groups of herbicides later in the season. Results suggested that ACCase inhibitors can be applied tank mixed with glufosinate without any injury on glufosinate-resistant soybeans. However, glufosinate reduced GR volunteer corn control when tank mixed with ACCase inhibitors at 15 DAEP and therefore, a late-POST application of glufosinate is needed to maximize volunteer corn control. Glufosinate applied in single or sequential applications provided greater than 85% control of GR volunteer corn along with other weeds; however, herbicide programs based on a single herbicide or herbicides with the same mode of action favor selection pressure and, if used repeatedly, result in the evolution of herbicide-resistant weeds (Beckie and Tardif 2012). In fact, two weed species have evolved resistance to glufosinate worldwide (Heap 2014b), including Italian ryegrass (*Lolium perenne* L. ssp. *multiflorum*), currently the only known glufosinate-resistant species in the United States (Avila-Garcia et al. 2012). Therefore, glufosinate should be carefully incorporated into herbicide programs along with herbicides with other modes of action in glufosinate-resistant soybean (Aulakh and Jhala 2015; Johnson et al. 2014; Kaur et al. 2014).

The objective of this study was to control GR volunteer corn in glufosinate-resistant soybean, and because PRE herbicides registered in soybean are not effective for controlling volunteer corn (Chahal et al. 2014), herbicide programs in this study were based on glufosinate and/or ACCase inhibitors, which are not the best programs for managing other weeds (such as common waterhemp). Several

Table 6. Effect of herbicide treatments on common waterhemp control, density, biomass, and soybean yield in glufosinate-resistant soybean in a field experiment conducted in Nebraska in 2013 and 2014.[a]

Herbicide[b]	Timing	Rate[b]	Control			Density[c]	Biomass[c,d]	Soybean yield[c]
			15 DAEP[b,c]	15 DALP[b,c]	75 DALP[b,c]			
		g ai ha^{-1}	%			plants m^{-2}	g m^{-2}	kg ha^{-1}
Nontreated control[e]	–	–	–	–	–	6 a	327 a	236 b
Glufosinate	E-POST	450	53 d	85 cde	86 b	3 b	67 b	1,960 a
Glufosinate	E-POST	600	61 bcd	93 a-d	89 ab	2 b	65 b	1,815 a
Glufosinate	E-POST	740	76 a	94 abc	91 ab	1 b	30 b	1,991 a
Glufosinate fb	E-POST	450						
glufosinate	L-POST	600	56 cd	98 a	93 ab	1 b	27 b	1,767 a
Glufosinate fb	E-POST	600						
glufosinate	L-POST	600	63 bcd	97 a	95 a	1 b	19 b	1,859 a
Glufosinate fb	E-POST	740						
glufosinate	L-POST	600	77 a	99 a	96 a	1 b	15 b	1,842 a
Clethodim fb	E-POST	140						
glufosinate	L-POST	600	0 e	86 b-e	93 ab	2 b	28 b	1,833 a
Clethodim + glufosinate fb	E-POST	140 + 600						
glufosinate	L-POST	600	62 bcd	95 ab	94 ab	1 b	26 b	1,998 a
Quizalofop fb	E-POST	40						
glufosinate	L-POST	600	0 e	81 de	93 ab	2 b	34 b	1,672 a
Quizalofop + glufosinate fb	E-POST	40 + 600						
glufosinate	L-POST	600	64 bc	99 a	98 a	1 b	17 b	1,842 a
Fluazifop fb	E-POST	210						
glufosinate	L-POST	600	0 e	79 e	93 ab	1 b	24 b	1,614 a
Fluazifop + glufosinate fb	E-POST	210 + 600						
glufosinate	L-POST	600	66 bc	99 a	96 a	2 b	18 b	1,936 a
Fenoxaprop + fluazifop fb	E-POST	130						
glufosinate	L-POST	600	0 e	82 cde	91 a	2 b	31 b	1,701 a
Fenoxaprop + fluazifop + glufosinate fb	E-POST	130 + 600						
glufosinate	L-POST	600	65 bc	96 ab	96 a	1 b	19 b	1,969 a
Sethoxydim fb	E-POST	350						
glufosinate	L-POST	600	0 e	83 cde	90 ab	2 b	37 b	1,795 a
Sethoxydim + glufosinate fb	E-POST	350 + 600						
glufosinate	L-POST	600	63 ccd	95 ab	95 a	1 b	10 b	1,988 a
P-value			< 0.0001	< 0.0001	0.0031	< 0.0001	< 0.0001	< 0.0001
Contrasts								
Glufosinate single vs. sequential application			–	$P < 0.0001$	$P < 0.0001$	–	–	–
ACCase alone vs. ACCase tank mixed with glufosinate			$P < 0.0001$	$P < 0.0001$	$P = 0.6737$	–	–	–

[a] Year-by-treatment interaction was not significant; therefore, data from both years were combined.

[b] Abbreviations: DAEP, days after early POST; DALP, days after late POST; E-POST, early POST; fb, followed by; L-POST, late POST.

[c] Means within columns with no common letter(s) are significantly different according to the Tukey-Kramer pairwise comparison test at $P \leq 0.05$.

[d] Biomass data were arc-sine square-root transformed before analysis; however, data presented are the means of actual values for comparison based on interpretation from the transformed data.

[e] The percent control (0%) data of nontreated control were not included in analysis.

studies reported that the use of residual herbicides and herbicides with different modes of action is an important component of weed management programs (Aulakh et al. 2012; Whitaker et al. 2011b). Therefore, an integrated weed management approach is necessary for controlling existing herbicide-resistant weeds and to limit the evolution of new herbicide-resistant weeds (Norsworthy et al.

2012). The results of this study indicate that a high level of GR volunteer corn control can be achieved through glufosinate in single or sequential applications; however, continuous use of glufosinate alone may result in the evolution of glufosinate-resistant weeds (Avila-Garcia et al. 2012; Jalaludin et al. 2010). Additionally, we believe that use of glyphosate-resistant hybrid corn vs. true volunteer corn would have slightly impacted the results because several factors, including the active growth of the plant, determine the plant's response to an herbicide application. Therefore, the use of hybrid corn seeds over volunteer corn (F2 corn seed) in this study might have resulted in slight overestimation of volunteer corn control because using F2 corn may have reduced vigor (Jugenheimer 1976) and ultimately may have slightly reduced response to herbicides compared to hybrid corn.

The results of this study are limited for controlling GR volunteer corn in glufosinate-resistant soybean because glufosinate will not be an effective option for control of GR volunteer corn in all situations. For example, glyphosate plus glufosinate-resistant corn hybrid is available in the marketplace; thus glufosinate will not be an effective option for controlling volunteer corn if hybrid corn planted the previous year is stacked resistant. Additionally, multiple herbicide-resistant crops, including corn resistant to 2,4-D, glyphosate, aryloxyphenoxy propionate, and glufosinate may be commercialized in the near future (Craigmyle et al. 2013), leaving cyclohexanedione herbicides as the only option for volunteer corn control (Sikkema and Soltani 2014).

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