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Economics of Management of Photosystem II- and HPPD-inhibitor-Resistant Palmer amaranth in Corn

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ABSTRACT

A Palmer amaranth biotype resistant to photosystem (PS) II- and 4-hydroxyphenylpyruvate dioxygenase (HPPD)-inhibitor in continuous seed corn production fields in southcentral Nebraska is a management challenge for corn growers. Field studies were conducted on a grower's field in 2014 through 2016 near Shickley in Fillmore County, Nebraska to determine the efficacy of herbicide programs for control of resistant Palmer amaranth, net economic return, and yield of glyphosate- and glufosinate-resistant corn. Based on contrast analysis, pyroxasulfone + fluthiacet-ethyl + atrazine applied pre-emergence (PRE) had the highest (95%) Palmer amaranth control compared with saflufenacil + dimethenamid-P, mesotrione + *S*-metolachlor + atrazine (91 to 92%), and acetochlor + clopyralid + flumetsulam (87%) at 21 d after PRE in 2014 to 2015. Glufosinate or glyphosate alone, or tank-mixed with dicamba applied post-emergence (POST)-only or aforementioned PRE herbicides followed by POST programs had 89 to 99% control at 28 and 72 d after POST in 2014 to 2015. Corn yields and net returns were higher where PRE followed by POST and POST-only herbicide programs were used compared with PRE-only programs in glufosinate- and glyphosate-resistant corn in 2014 and 2016. In 2015, corn yields and net returns were similar where PRE-only, POST-only, and PRE followed by POST herbicide programs were used in glufosinate- and glyphosate-resistant corn. Results of this study suggest that effective PRE followed by POST herbicide programs are available for controlling PS II- and HPPD-inhibitor-resistant Palmer amaranth in corn and growers need to adopt an integrated weed management approach to reduce the chances of evolution of herbicide-resistant weeds.

Core Ideas

- Glufosinate + dicamba had similar Palmer amaranth control as glufosinate.
- Glyphosate + dicamba had similar control as glyphosate.
- Pre-emergence followed by post-emergence and post-emergence-only programs had similar control.

Palmer amaranth (*Amaranthus palmeri* S. Wats.) is the most problematic and difficult to control weed among crops in the United States (Chahal et al., 2015, 2017; Kohrt and Sprague, 2017). Palmer amaranth biotypes resistant to microtubule-, acetolactate synthase (ALS)-, photosystem (PS) II-, 5-enol-pyruvylshikimate-3-phosphate synthase (EPSPS)-, hydroxyphenylpyruvate dioxygenase (HPPD)-, and protoporphyrinogen oxidase (PPO)-inhibitor herbicides have been reported in the United States (Heap, 2017a). Photosystem II- and HPPD-inhibitors are commonly used herbicides for weed control in sweet corn (*Zea mays* L.), seed corn, popcorn, and field corn due to their pre-emergence (PRE) and post-emergence (POST) activity, broad-spectrum of weed control, and crop safety (Bollman et al., 2008; Fleming et al., 1988; Swanton et al., 2007). The evolution of PS II- and HPPD-inhibitor-resistant Palmer amaranth in Nebraska has become a management challenge for corn growers because it reduces the number of herbicide options for Palmer amaranth control (Jhala et al., 2014).

Growers require alternate herbicide programs focusing on the use of herbicides with different sites of action applied PRE and POST, herbicide rotation, rotation of herbicide-resistant (HR) crop traits, and rotation with conventional cultivars for the management of HR Palmer amaranth (Norsworthy et al., 2012; Oliveira et al., 2017). The majority of corn acreage in Nebraska is planted to glyphosate [N-(phosphonomethyl)glcine]-resistant corn hybrids, utilizing either single or sequential glyphosate applications for POST weed control (Chahal et al., 2017; Jhala et al., 2014). Glyphosate is a systemic herbicide and has a broad-spectrum of weed control (Anonymous, 2017a). Glyphosate could be considered as an effective herbicide option for the management of PS II- and HPPD-inhibitor-resistant Palmer amaranth in glyphosate-resistant corn; however, the continuous use of glyphosate for weed control in glyphosate-resistant corn-soybean [*Glycine max* (L.) Merr.] cropping systems over the last two decades has resulted in the evolution of glyphosate-resistant weeds (Heap, 2017a). In Nebraska, glyphosate-resistant weeds, including common ragweed (*Ambrosia artemisiifolia* L.), common waterhemp (*Amaranthus rudis* Sauer), horseweed [*Conyza canadensis* (L.) Cronq.], giant ragweed (*Ambrosia trifida* L.), kochia [*Kochia scoparia* (L.) Schrad.], and Palmer amaranth have been reported (Chahal et al., 2017; Ganie and Jhala, 2017; Heap, 2017a; Sarangi et al., 2015). Therefore, glyphosate cannot

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Abbreviations: HPPD, 4-hydroxyphenylpyruvate dioxygenase; PRE, pre-emergence; POST, post-emergence; PS, photosystem.

be considered as a single weed management option, and the rotation of glyphosate-resistant corn with corn bearing other HR traits, such as glufosinate {2-amino-4-[hydroxy(methyl) phosphonoyl]butanoic acid} resistance, is essential to create a more diverse array of herbicide options.

Glufosinate is a nonselective, contact, POST herbicide that controls many grass and broadleaf weed species (Anonymous, 2017b). The commercialization of glufosinate-resistant corn and soybean traits has provided growers an opportunity to apply glufosinate POST to control glyphosate-resistant weeds, including Palmer amaranth (Chahal et al., 2017; Jhala et al., 2014). Since their commercialization, the adoption of glufosinate-resistant crops has been limited compared to the adoption of glyphosate-resistant crop technology in the United States (Aulakh and Jhala, 2015; Reddy and Nandula, 2012). However, recent surveys have reported that cultivation of glufosinate-resistant crops is increasing in the mid-southern United States, specifically for the control of glyphosate-resistant Palmer amaranth (Aulakh et al., 2013; Barnett et al., 2013). It is further likely that the planting of glufosinate-resistant corn will expand in the near future in the northcentral United States. Additionally, glyphosate- plus glufosinate-resistant corn is also available in the market, thus providing growers an opportunity to apply glyphosate and/or glufosinate for POST weed control (Chahal and Jhala, 2015).

In view of increasing number of HR weeds, it has become important to proactively implement herbicide resistance management programs for reducing the evolution of new HR weeds (Barnett et al., 2013; Chahal and Jhala, 2015; Shaw et al., 2011). The cost of programs that include multiple site of action residual PRE as well as POST herbicides is usually higher than that of commonly used weed management programs that involve the use of a single site of action POST herbicide such as glyphosate. Therefore, most growers do not adopt HR weed management recommendations until they notice the presence of HR weeds in their fields (Edwards et al., 2014; Norsworthy et al., 2012; Peterson, 1999). In addition, some growers avoid PRE herbicide application and depend only on POST herbicides to reduce production costs, a decision driven by low corn and/or soybean prices over the last few years. However, avoiding PRE herbicide applications allows early-season crop-weed competition, which could result in a yield penalty (Hall et al., 1992; Schuster and Smeda, 2007). In addition to herbicide program costs, other factors including increased crop safety and the convenience and flexibility of single site of action herbicide applications in HR crops are responsible for the reduced adoption of integrated weed management programs among growers (Bonny, 2007; Hurley and Frisvold, 2016). Therefore, it has become crucial to evaluate the economic benefits of implementing HR weed management programs to encourage their adoption among growers.

Information is not available regarding the control of PS II- and HPPD-inhibitor-resistant Palmer amaranth using different herbicide programs and their net economic return in glufosinate- and glyphosate-resistant corn. The objectives of this study were to determine the effect of PRE-only, POST-only, and PRE followed by POST herbicide programs on PS II- and HPPD-inhibitor-resistant Palmer amaranth control, corn yield, and net economic return in glufosinate- and glyphosate-resistant corn. We hypothesized that PRE followed by POST herbicide programs with multiple sites of action will provide effective control of PS II- and HPPD-inhibitor-resistantPalmer amaranth and prevent corn yield reductions compared to PRE-only or POST-only programs.

MATERIALS AND METHODS

Site Description and Experimental Design

Field experiments were conducted in 2014, 2015, and 2016 in a grower's field with confirmed PS II- and HPPD-inhibitor-resistant Palmer amaranth near Shickley in Fillmore County, Nebraska (40.46° N, 97.80° E). The level of atrazine resistance was 9- to 14-fold, while the level of resistance for mesotrione, tembotrione, and topramezone was 4-, 4- to 6-, and 14- to 23-fold, respectively, applied POST (Jhala et al., 2014). Soil at the experimental site was a Crete silt loam (fine, smectitic, mesic Pachic Udertic Argiustolls) with a pH of 6.5, 26% sand, 57% silt, 17% clay, and 3.5% organic matter. Corn hybrids resistant to glyphosate (Mycogen 2D351) and glufosinate (Stine 9808E-10L) were seeded in two separate studies at 87,500 seeds ha^{-1} in rows spaced 76 cm apart on 9 May 2014; 30 May 2015; and 1 June 2016. The treatments within the studies were arranged in a randomized complete block design with four replications, using field slope as the blocking factor. The experimental site was under a center-pivot irrigation system and plots were 3 m wide and 9 m long, consisting of four corn rows, and two middle rows were treated with the herbicide treatments leaving untreated running checks on the sides of the treated plots. Monthly mean air temperature and total precipitation at the research site during the 2014, 2015, and 2016 growing seasons and 30-yr average are provided in Table 1. During 2014 and 2015, 13 to 28 cm of rainfall was received within 2 d after PRE while 7 cm rainfall was received at 14 d after PRE at the experimental site in 2016.

Herbicide Application

Herbicide programs included PRE-only, POST-only, and PRE followed by POST herbicides with a total of 17 program combinations including the nontreated control in glufosinate- and glyphosate-resistant corn. The herbicide application timings and rates were based on the label recommendations for corn (Table 2). Herbicide programs were applied with a CO_2–pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} at 276 kPa, consisting of a four-nozzle boom fitted with TT 110015 nozzles (TeeJet Spraying Systems Co., Wheaton, IL) for application of glufosinate (Liberty 280, Bayer Crop Science, Research Triangle Park, NC) and AIXR 110015 flat-fan nozzles for the remainder of the herbicide programs. Pre-emergence herbicides were applied within 3 d after corn planting and POST herbicides were applied when Palmer amaranth was 12 to 15 cm tall.

Data Collection

Palmer amaranth control was visually estimated at 21 d after PRE and 28 and 72 d after POST, and at corn harvest based on a 0 to 100% scale, with 0% corresponding to no control and 100% corresponding to plant death. A similar scale was used to assess corn injury at 7, 14, and 21 d after PRE and POST herbicide applications, with 0% corresponding to no injury and 100% corresponding to plant death. Palmer amaranth density was assessed from two randomly selected 0.25 m^2 quadrats per plot at 21 d after PRE herbicide application. Aboveground biomass

Table 1. Monthly mean air temperature and total precipitation during the 2014, 2015, and 2016 growing seasons and 30-yr average at Shickley, NE. Mean air temperature and total precipitation data were obtained from National Weather Service and Cooperative Observer Network (2017).

Month	Mean temperature				Total precipitation			
	2014	2015	2016	30-yr average	2014	2015	2016	30-yr average
	°C				mm			
March	5	7	9	5	2	12	14	48
April	11	12	12	11	94	42	99	68
May	18	17	16	17	57	108	200	124
June	23	23	25	22	154	264	7	117
July	23	24	25	25	56	124	55	86
August	23	22	23	24	154	69	147	88
September	19	22	20	19	76	104	52	86
October	14	14	15	12	47	22	64	59
Annual	11	12	13	11	664	908	726	763

Table 2. Herbicide products and rates used for control of Photosystem (PS) II- and 4-hydroxyphenylpyruvate dioxygenase (HPPD)-inhibitor-resistant Palmer amaranth in glufosinate-and glyphosate-resistant corn in field experiments conducted in 2014, 2015, and 2016 at Shickley, NE.

Herbicide	Trade name	Rate of ai or ae applied†	Manufacturer
		g ha^{-1}	
Glufosinate	Liberty 280	595	Bayer Crop Science, Research Triangle Park, NC
Glyphosate	Roundup PowerMax	870	Monsanto Company, St. Louis, MO
Dicamba	DiFlexx	280	Bayer Crop Science
Mesotrione + *S*-metolachlor + Atrazine	Lumax EZ	2780	Syngenta Crop Protection, Inc., Greensboro, NC
Acetochlor + Clopyralid + Flumetsulam	Surestart II	1190	Dow AgroSciences LLC, Indianapolis, IN
Saflufenacil + Dimethenamid-P	Verdict	780	BASF Corporation, Research Triangle Park, NC
Pyroxasulfone + Fluthiacet-ethyl + Atrazine	Anthem ATZ	1580	FMC Corporation, Philadelphia, PA

† ai, active ingredient; ae, acid equivalent.

of Palmer amaranth was harvested from the same quadrat areas as used for density data collection at 28 d after POST, oven-dried at 65 C for 3 d, and weighed. Palmer amaranth density and biomass data were converted into percent density or biomass reduction compared with the nontreated control (Ganie et al., 2017; Sarangi et al., 2017):

$$\text{Biomass / Density reduction}(\%) = \frac{(C-B)}{C} \times 100 \quad [1]$$

where C is the biomass or density of the nontreated control plot and B is the biomass or density collected from the experimental plot. At maturity, corn was harvested from the middle two rows of each plot with a plot combine, and the weight and moisture content were recorded. Corn yields were adjusted to 15.5% moisture content (Ganie et al., 2017).

Economic analysis was performed to evaluate the net return associated with each herbicide program using corn yield from each replication and herbicide program cost using the following formula (Bradley et al., 2000; Edwards et al., 2014; Johnson et al., 2000):

$$\text{Net return} = \text{Gross revenue} - \text{Herbicide program cost} \quad [2]$$

Gross revenue was calculated by multiplying the corn yield from each replication for each program by an average grain price received in Nebraska at harvest time during the experimental years ($0.14 kg^{-1}; USDA-NASS, 2016). Herbicide program cost included an average herbicide cost ha^{-1} obtained from agricultural chemical dealers in Nebraska and a custom application cost of $18.11 ha^{-1} application^{-1}.

Statistical Analysis

Data of Palmer amaranth control estimates, density and aboveground biomass reduction, corn injury and yield, and net return from glufosinate- and glyphosate-resistant corn studies were subjected to ANOVA separately using the PROC GLIMMIX procedure in SAS version 9.3 (SAS Institute Inc., Cary, NC). Herbicide programs and experimental years were considered fixed effects, whereas replications were considered a random effect in the model. Data were combined over years when there was no year × program interaction. Year × program interaction was significant for Palmer amaranth control and density reduction in glufosinate- and glyphosate-resistant corn, with no difference between 2014 and 2015; therefore, control and density reduction data for these years were combined, but are presented separately for 2016. Similarly, year × program interaction for corn yield and net return was significant, with no difference between 2014 and 2016; therefore, corn yield and net return data for these years were combined, but are presented separately for 2015 in the glufosinate- and glyphosate-resistant corn studies. Year × program interaction for Palmer amaranth biomass reduction was not significant; therefore, data were combined over 3 yr for both studies.

The nontreated control was not included in the data analysis for control estimates, percent density, and biomass reduction. Before analysis, data were tested for normality and homogeneity of variance using Shapiro-Wilks goodness-of-fit and Levene's test in SAS. The normality and homogeneity of variance assumptions were met; therefore, no data transformation was required. Where the ANOVA indicated program effects were significant, means were separated at $P \leq 0.05$ with the Tukey-Kramer pairwise comparison test to reduce type I error for series of comparisons. Pearson correlation coefficients (r) were calculated to determine the relationship between corn yield and percent biomass reduction in glufosinate- and glyphosate-resistant corn for all experimental years. Pre-planned single degree-of-freedom contrast analysis was accomplished to determine the relative efficacy of PRE herbicides by combining Palmer amaranth control and density reduction data at 21 d after PRE from glufosinate- and glyphosate-resistant corn studies.

RESULTS AND DISCUSSION

Palmer Amaranth Control, Density Reduction, and Biomass Reduction

Acetochlor [2-chloro-N-ethoxymethyl-N-(2-ethyl-6-methylphenyl)acetamide] + clopyralid (3,6-dichloro-2-pyridinecarboxylic acid) + flumetsulam {N-(2,6-difluorophenyl)-5-methyl-1,2,4-triazolo[1,5-a]pyrimidine-2-sulfonamide}, mesotrione [2-(4-mesyl-2-nitrobenzoyl)-3-hydroxycylohex-2-enone] + *S*-metolachlor [2-chloro-N-(2-ethyl-6-methylphenyl)-N-(2-methoxy-1-methylethyl)acetamide] + atrazine [6-chloro-N-ethyl-N'-(1-methylethyl)-1,3,5-triazine-2,4-diamine], pyroxasulfone {3-({[5-(difluormethoxy)-1-methyl-3-(trifluormethyl)-1H-pyrazol-4-yl]methyl}sulfonyl)-5,5-dimethyl-4,5-dihydro-1,2-oxazol} + fluthiacet-ethyl {[[2-chloro-4-fluoro-5-[(tetrahydro-3-oxo-1H,3H-[1,3,4]thiadiazolo[3,4-a]pyridazin-1-ylidene)amino]phenyl]thio]acetic acid} + atrazine, or saflufenacil {2-chloro-5-[3,6-dihydro-3-methyl-2,6-dioxo-4-(trifluoromethyl)-1(2H)-pyrimidinyl[-4-fluoro-N-[[methyl(1-methylethyl)amino]sulfonyl]benzamide} + dimethenamid-P [2-chloro-N-(2,4-dimethyl-3-thienyl)-N-(2-methoxy-1-methylethyl)acetamide] applied PRE had 88 to 97% Palmer amaranth control in glufosinate-resistant corn and 80 to 97% control in glyphosate-resistant corn at 21 d after PRE in 2014 to 2015 (Tables 3 and 4). However, in 2016, PRE herbicides provided only 60 to 75% control in glufosinate-resistant and 59 to 79% control in glyphosate-resistant corn, which could be due to very high density of Palmer amaranth ranging from 400 to 450 plants m^{-2} compared to 250 to 300 plants m^{-2} in 2014 to 2015 (Tables 3 and 4). This high density might have been caused by the accumulation of Palmer amaranth seeds at the research site over the previous 2 yr, specifically from nontreated control plots and running checks. In addition, very low rainfall amounts of 7 mm were received after corn planting in June 2016 compared with 154 to 264 mm in 2014 and 2015 (Table 1), which could also explain the lower level of control due to reduced herbicide activation in the soil. Palmer amaranth control was reduced to 42 to 55% at 44 d after PRE (14 d after POST) with PRE herbicides applied alone in 2014 to 2015, except pyroxasulfone + fluthiacet-ethyl + atrazine which had 72 to 80% control in glufosinate- and glyphosate-resistant corn (Tables 3 and 4). Based on the contrast analysis, pyroxasulfone + fluthiacet-ethyl + atrazine applied PRE had the highest Palmer amaranth control of 95% compared to 91 to 92% control with saflufenacil + dimethenamid-P and mesotrione + *S*-metolachlor + atrazine, and 87% control with acetochlor + clopyralid + flumetsulam at 21 d after PRE in glufosinate- and glyphosate-resistant corn in 2014 to 2015 (Table 5). In 2016, saflufenacil + dimethenamid-P had the highest control of 74% compared to 61 to 65% control with mesotrione + *S*-metolachlor + atrazine, pyroxasulfone + fluthiacet-ethyl + atrazine, or acetochlor + clopyralid + flumetsulam (Table 5). Previous studies have reported similar levels of Palmer amaranth or common waterhemp control with the PRE herbicides applied in this study. For instance, Janak and Grichar (2016) reported >95% Palmer amaranth control with saflufenacil + dimethenamid-P, or mesotrione + *S*-metolachlor + atrazine at 95 d after PRE. Similarly, Oliveira et al. (2017) reported ≥90% control of HPPD inhibitor-resistant tall waterhemp [*Amaranthus tuberculatus* (Moq.) Sauer] with acetochlor + clopyralid + flumetsulam, mesotrione + *S*-metolachlor + atrazine, or pyroxasulfone + fluthiacet-ethyl + atrazine at 30 d after PRE in Nebraska. In another study in Nebraska, Aulakh and Jhala (2015) reported 96% common waterhemp control with saflufenacil + dimethenamid-P at 15 d after PRE.

Similarly, all PRE herbicides had similar Palmer amaranth density reduction of 66 to 78% at 21 d after PRE in 2014 to 2015 in glufosinate- and glyphosate-resistant corn based on the contrast analysis (Table 5). However, in 2016, saflufenacil + dimethenamid-P had the highest density reduction of 70% compared to 60% reduction with mesotrione + *S*-metolachlor + atrazine, pyroxasulfone + fluthiacet-ethyl + atrazine, and 49% with acetochlor + clopyralid + flumetsulam (Table 5). In contrast, Oliveira et al. (2017) reported ≥88% density reduction of HPPD inhibitor-resistant tall waterhemp with acetochlor + clopyralid + flumetsulam, or pyroxasulfone + fluthiacet-ethyl + atrazine at 30 d after PRE. Aulakh and Jhala (2015) also reported 96% common waterhemp density reduction with saflufenacil + dimethenamid-P at 15 d after PRE in a 2-yr study in Nebraska.

Glufosinate or glufosinate + dicamba (3,6-dichloro-2-methoxybenzoic acid) applied POST-only or in PRE followed by POST programs had similar control of 89 to 98% in 2014 to 2015 and 72 to 99% in 2016 at 28 and 72 d after POST in glufosinate-resistant corn (Table 3). Similarly, glufosinate or glufosinate + dicamba applied POST-only or in PRE followed by POST programs had similar biomass reduction of 77 to 91% at 28 d after POST (Table 3). Braswell et al. (2016) also reported similar Palmer amaranth control of 98 to 100% with glufosinate applied POST or PRE herbicides followed by glufosinate. However, Cahoon et al. (2015a) reported 90% Palmer amaranth control with glufosinate + dicamba compared to 81 to 85% control with glufosinate at 14 d after POST. Among PRE-only programs, pyroxasulfone + fluthiacet-ethyl + atrazine, or saflufenacil + dimethenamid-P had 25 to 45% biomass reduction compared to 13% reduction with acetochlor + clopyralid + flumetsulam, and 9% with mesotrione + *S*-metolachlor + atrazine (Table 3).

Glyphosate or glyphosate + dicamba applied POST-only or in PRE followed by POST programs had similar control of 89 to 99% in 2014 to 2015 and 79 to 94% in 2016 at 28 d after POST in glyphosate-resistant corn (Table 4). Similarly, at 72 d after POST, POST-only and PRE followed by POST programs had similar control of 94 to 99% in 2014 to 2015 and 75 to 98% in 2016. In this study, even single POST application of glufosinate or glyphosate resulted in similar control as PRE followed by POST programs. This might be because PS II- and HPPD-inhibitor-resistant Palmer amaranth was sensitive to glyphosate

Table 3. Effect of herbicide programs on photosystem (PS II)- and 4-hydroxyphenylpyruvate dioxygenase (HPPD)-inhibitor-resistant Palmer amaranth control, density reduction, and biomass reduction in glufosinate-resistant corn in field experiments conducted at Shickley, NE in 2014, 2015, and 2016.

			Control¶						Density reduction¶		Biomass reduction¶
	Rate of ai or ae		21 d after PRE		28 d after POST		72 d after POST		21 d after PRE		
Herbicide program†	applied‡	Timing†§	2014–2015	2016	2014–2015	2016	2014–2015	2016	2014–2015	2016	28 d after POST
	g ha^{-1}		%								
Glufosinate	595	POST	0 b	0 b	89 ab	79 a	96 a	72 ab	–	–	77 a
Glufosinate + Dicamba	595 + 280	POST	0 b	0 b	91 ab	81 a	95 ab	89 a	–	–	88 a
Mesotrione + *S*-metolachlor + Atrazine	2780	PRE	91 a	71 a	55 de	18 bc	51 c	39 c	59 ab	60 ab	9 c
Mesotrione + *S*-metolachlor + Atrazine fb Glufosinate	2780 595	PRE fb POST	96 a	66 a	95 a	84 a	98 a	80 a	75 ab	77 a	85 a
Mesotrione + *S*-metolachlor + Atrazine fb Glufosinate + Dicamba	2780 595 + 280	PRE fb POST	92 a	64 a	96 a	93 a	98 a	97 a	54 b	54 ab	91 a
Acetochlor + Clopyralid + Flumetsulam	1190	PRE	91 a	66 a	43 e	6 c	42 c	19 c	83 ab	55 ab	13 c
Acetochlor + Clopyralid + Flumetsulam fb Glufosinate	1190 595	PRE fb POST	97 a	60 a	91 ab	85 a	96 a	91 a	81 ab	54 ab	86 a
Acetochlor + Clopyralid + Flumetsulam fb Glufosinate + Dicamba	1190 595 + 280	PRE fb POST	88 a	61 a	92 ab	97 a	96 a	96 a	65 ab	39 b	87 a
Saflufenacil + Dimethenamid-P	780	PRE	96 a	74 a	67 cd	45 b	67 b	49 bc	73 ab	83 a	25 bc
Saflufenacil + Dimethenamid-P fb Glufosinate	780 595	PRE fb POST	93 a	75 a	94 a	97 a	98 a	96 a	85 a	80 a	89 a
Saflufenacil + Dimethenamid-P fb Glufosinate + Dicamba	780 595 + 280	PRE fb POST	97 a	74 a	95 a	99 a	96 a	98 a	80 ab	76 a	90 a
Pyroxasulfone + Fluthiacet-ethyl + Atrazine	1580	PRE	93 a	63 a	77 bc	28 bc	74 b	40 c	78 ab	63 ab	45 b
Pyroxasulfone + Fluthiacet-ethyl + Atrazine fb Glufosinate	1580 595	PRE fb POST	94 a	63 a	98 a	81 a	98 a	78 ab	78 ab	68 ab	89 a
Pyroxasulfone + Fluthiacet-ethyl + Atrazine fb Glufosinate + Dicamba	1580 595 + 280	PRE fb POST	97 a	65 a	97 a	90 a	98 a	95 a	86 a	57 ab	91 a

† All POST herbicide programs were mixed with AMS, ammonium sulfate (DSM Chemicals North America Inc., Augusta, GA) at 2.5% (w/v) and NIS, nonionic surfactant (Induce, Helena Chemical Co., Collierville, TN) at 0.25% (v/v). No AMS or NIS were added to PRE herbicides. Pre-emergence applications were made within 3 d after planting and POST herbicides were applied when Palmer amaranth was 12 to 15 cm tall.

‡ ai, active ingredient; ae, acid equivalent.

§ POST, post-emergence; PRE, pre-emergence; fb, followed by.

¶ Means within columns with no common letter(s) are significantly different according to Tukey-Kramer's pairwise comparison test $P \leq 0.05$. Year × program interaction was significant for Palmer amaranth control and density reduction, with no difference between 2014 and 2015; therefore, data were combined for these years and presented separately for 2016. Year × program interaction was not significant for biomass reduction; therefore, data were combined over three experimental years.

Table 4. Effect of herbicide programs on photosystem (PS II)- and 4-hydroxyphenylpyruvate dioxygenase (HPPD)-inhibitor-resistant Palmer amaranth control, density reduction, and biomass reduction in glyphosate-resistant corn in field experiments conducted at Shickley, NE in 2014, 2015, and 2016.†

Herbicide program†	Rate of ai or ae applied‡	Timing†§	Control¶ 21 d after PRE 2014–2015	Control¶ 21 d after PRE 2016	Control¶ 28 d after POST 2014–2015	Control¶ 28 d after POST 2016	Control¶ 72 d after POST 2014–2015	Control¶ 72 d after POST 2016	Density reduction¶ 21 d after PRE 2014–2015	Density reduction¶ 21 d after PRE 2016	Biomass reduction¶ 28 d after POST
	g ha^{-1}		%								
Glyphosate	870	POST	0 d	0 d	96 a	79 ab	99 a	80 a	–	–	76 b
Glyphosate + Dicamba	870 + 280	POST	0 d	0 d	97 a	80 ab	99 a	93 a	–	–	97 a
Mesotrione + *S*-metolachlor + Atrazine	2780	PRE	87 a	66 ab	49 d	30 c	55 bc	41 b	69 a	57 ab	36 c
Mesotrione + *S*-metolachlor + Atrazine fb Glyphosate	2780 870	PRE fb POST	90 a	63 b	89 ab	84 ab	98 a	83 a	76 a	62 ab	76 a
Mesotrione + *S*-metolachlor + Atrazine fb Glyphosate + Dicamba	2780 870 + 280	PRE fb POST	93 a	59 b	94 a	92 ab	99 a	95 a	63 a	48 b	86 ab
Acetochlor + Clopyralid + Flumetsulam	1190	PRE	85 a	60 b	47 d	10 d	40 c	21 b	74 a	54 ab	45 c
Acetochlor + Clopyralid + Flumetsulam fb Glyphosate	1190 870	PRE fb POST	80 a	59 b	93 a	79 ab	94 a	75 a	79 a	47 b	73 b
Acetochlor + Clopyralid + Flumetsulam fb Glyphosate + Dicamba	1190 870 + 280	PRE fb POST	81 a	60 b	94 a	94 a	97 a	99 a	71 a	63 ab	94 a
Saflufenacil + Dimethenamid-P	780	PRE	90 a	74 ab	59 cd	35 c	44 c	25 b	68 a	78 a	42 c
Saflufenacil + Dimethenamid-P fb Glyphosate	780 870	PRE fb POST	92 a	79 a	97 a	83 ab	99 a	85 a	75 a	63 ab	94 a
Saflufenacil + Dimethenamid-P fb Glyphosate + Dicamba	780 870 + 280	PRE fb POST	85 a	64 ab	98 a	93 a	99 a	98 a	78 a	58 ab	98 a
Pyroxasulfone + Fluthiacet-ethyl + Atrazine	1580	PRE	96 a	61 b	73 bc	6 d	67 b	17 b	72 a	43 b	49 c
Pyroxasulfone + Fluthiacet-ethyl + Atrazine fb Glyphosate	1580 870	PRE fb POST	97 a	64 ab	99 a	81 ab	98 a	83 a	74 a	61 ab	90 a
Pyroxasulfone + Fluthiacet-ethyl + Atrazine fb Glyphosate + Dicamba	1580 870 + 280	PRE fb POST	95 a	65 ab	98 a	86 ab	99 a	96 a	80 a	63 ab	97 a

† All POST herbicide programs were mixed with AMS, ammonium sulfate (DSM Chemicals North America Inc., Augusta, GA) at 2.5% (w/v) and NIS, nonionic surfactant (Induce, Helena Chemical Co., Collierville, TN) at 0.25% (v/v). No AMS or NIS were added to PRE herbicides. Pre-emergence applications were made within 3 d after planting and POST herbicides were applied when Palmer amaranth was 12 to 15 cm tall.

‡ ai, active ingredient; ae, acid equivalent.

§ POST, post-emergence; PRE, pre-emergence; fb, followed by.

¶ Means within columns with no common letter(s) are significantly different according to Tukey-Kramer's pairwise comparison test $P \leq 0.05$. Year × program interaction was significant for Palmer amaranth control and density reduction, with no difference between 2014 and 2015; therefore, data were combined for these years and presented separately for 2016. Year × program interaction was not significant for biomass reduction; therefore, data were combined over three experimental years.

Table 5. Contrast means for photosystem (PS) II- and 4-hydroxyphenylpyruvate dioxygenase (HPPD)-inhibitor-resistant Palmer amaranth control and density reduction at 21 d after pre-emergence application in glufosinate- and glyphosate-resistant corn in field experiments conducted at Shickley, NE in 2014, 2015, and 2016.†

Herbicide program	Control‡		Density reduction‡	
	2014–2015	2016	2014–2015	2016
	%			
Mesotrione + *S*-metolachlor + Atrazine vs. Acetochlor + Clopyralid + Flumetsulam	91 vs. 87*	65 vs. 61*	66 vs. 76	60 vs. 49*
Mesotrione + *S*-metolachlor + Atrazine vs. Saflufenacil + Dimethenamid-P	91 vs. 92	65 vs. 74*	66 vs. 76	60 vs. 70*
Mesotrione + *S*-metolachlor + Atrazine vs. Pyroxasulfone + Fluthiacet-ethyl + Atrazine	91 vs. 95*	65 vs. 63	66 vs. 78	60 vs. 60

* Significant at $p < 0.05$.

† Single degree-of-freedom contrast analysis.

‡ Palmer amaranth control and density reduction data were combined from glufosinate- and glyphosate-resistant corn experiments and analyzed for single degree-of-freedom contrast. Year × program interaction was significant for Palmer amaranth control and density reduction, with no difference between 2014 and 2015; therefore, data were combined for these years and presented separately for 2016.

Table 6. Effect of herbicide programs on corn yield, and cost of herbicide programs and net return received from glufosinate-resistant corn yield in field experiments conducted at Shickley, NE in 2014, 2015, and 2016. †

Herbicide program†	Rate ai or ae applied‡	Timing†§	Corn yield¶		Program cost#	Net return¶††	
			2014 + 2016	2015		2014 +2016	2015
	g ha^{-1}		kg ha^{-1}		$ ha^{-1}		
Glufosinate	595	POST	10,660 ab	16,177 a	61.46	1423 abc	2192 a
Glufosinate + Dicamba	595 + 280	POST	11,392 a	16,518 a	98.67	1489 ab	2197 a
Mesotrione + *S*-metolachlor + Atrazine	2780	PRE	8192 abc	17,812 a	120	1021 bc	2361 a
Mesotrione + *S*-metolachlor + Atrazine fb Glufosinate	2780 595	PRE fb POST	11,421 a	17,305 a	181.47	1398 abc	2229 a
Mesotrione + *S*-metolachlor + Atrazine fb Glufosinate + Dicamba	2780 595 + 280	PRE fb POST	11,253 ab	16,486 a	218.68	1349 abc	2077 a
Acetochlor + Clopyralid + Flumetsulam	1190	PRE	4972 c	15,900 a	52.49	640 d	2162 a
Acetochlor + Clopyralid + Flumetsulam fb Glufosinate	1190 595	PRE fb POST	11,797 a	17,370 a	113.95	1529 a	2305 a
Acetochlor + Clopyralid + Flumetsulam fb Glufosinate + Dicamba	1190 595 + 280	PRE fb POST	11,200 ab	17,926 a	151.16	1409 abc	2345 a
Saflufenacil + Dimethenamid-P	780	PRE	7625 bc	17,064 a	84.7	978 c	2292 a
Saflufenacil + Dimethenamid-P fb Glufosinate	780 595	PRE fb POST	11,609 a	17,782 a	146.16	1471 abc	2330 a
Saflufenacil + Dimethenamid-P fb Glufosinate + Dicamba	780 595 + 280	PRE fb POST	11,045 ab	15,814 a	183.37	1355 abc	2019 a
Pyroxasulfone + Fluthiacet-ethyl + Atrazine	1580	PRE	7678 bc	17,607 a	87.3	982 c	2365 a
Pyroxasulfone + Fluthiacet-ethyl + Atrazine fb Glufosinate	1580 595	PRE fb POST	11,714 a	17,348 a	148.76	1483 abc	2267 a
Pyroxasulfone + Fluthiacet-ethyl + Atrazine fb Glufosinate + Dicamba	1580 595 + 280	PRE fb POST	11,373 a	17,158 a	185.97	1389 abc	2204 a

† All POST herbicide programs were mixed with AMS, ammonium sulfate (DSM Chemicals North America Inc., Augusta, GA) at 2.5% (w/v) and NIS, nonionic surfactant (Induce, Helena Chemical Co., Collierville, TN) at 0.25% (v/v). No AMS or NIS were added to PRE herbicides. Pre-emergence applications were made within 3 d after planting and POST herbicides were applied when Palmer amaranth was 12 to 15 cm tall.

‡ ai, active ingredient; ae, acid equivalent.

§ POST, post-emergence; PRE, pre-emergence; fb, followed by.

¶ Year × program interaction was significant for corn yield and net return with no difference between 2014 and 2016; therefore, data were combined for these years and presented separately for 2015. Means within columns with no common letter(s) are significantly different according to Tukey-Kramer's pairwise comparison test $P \leq 0.05$.

Program cost includes the average cost of herbicide, AMS, and NIS, and the cost of application ($18.11 ha^{-1} application^{-1}) from two independent sources in Nebraska.

†† Net return was calculated as gross income from glufosinate-resistant corn yield minus herbicide program cost.

or glufosinate since they had not been used over the past 8 yr while the field was kept under continuous seed corn production. Similarly, previous studies have reported similar Palmer amaranth control of 90 to 99% with glyphosate or glyphosate + dicamba at 14 d after POST (Cahoon et al., 2015a, 2015b; Jhala et al., 2014). However, Crow et al. (2016) reported greater (89%) control of >20-cm tall Palmer amaranth with glyphosate + dicamba compared to glyphosate (69%) at 28 d after POST. Underwood et al. (2017) reported greater redroot pigweed (*Amaranthus retroflexus* L.) control of 99% with glyphosate + dicamba compared to 94% control with glyphosate at 14 d after POST. In contrast to percent control, glyphosate + dicamba applied alone POST provided greater Palmer amaranth biomass reduction of 97% compared to 76% reduction with glyphosate at 28 d after POST (Table 4). However, Underwood et al. (2017) reported similar redroot pigweed biomass reduction of 90 to 94% with glyphosate applied alone or tank-mixed with dicamba. Pre-emergence herbicides followed by glyphosate + dicamba or glyphosate had similar biomass reduction of 76 to 98%, except acetochlor + clopyralid + flumetsulam applied

Table 7. Effect of herbicide programs on corn yield, and cost of herbicide programs and net return received from glyphosate-resistant corn yield in field experiments conducted at Shickley, NE in 2014, 2015, and 2016.

Herbicide program†	Rate of ai or ae applied‡	Timing†§	Corn yield¶ 2014 + 2016	Corn yield¶ 2015	Program cost#	Net return¶†† 2014 + 2016	Net return¶†† 2015
	g ha^{-1}		kg ha^{-1}		$ ha^{-1}		
Glyphosate	870	POST	10,243 ab	17,755 a	29.2	1397 a	2444 a
Glyphosate + Dicamba	870 + 280	POST	10,972 ab	17,412 a	66.41	1461 a	2359 a
Mesotrione + *S*-metolachlor + Atrazine	2780	PRE	7645 b	16,969 a	120	944 a	2243 a
Mesotrione + *S*-metolachlor + Atrazine fb Glyphosate	2780 870	PRE fb POST	11,542 ab	21,810 a	149.21	1458 a	2888 a
Mesotrione + *S*-metolachlor + Atrazine fb Glyphosate + Dicamba	2780 870 + 280	PRE fb POST	11,652 ab	18,122 a	186.42	1436 a	2338 a
Acetochlor + Clopyralid + Flumetsulam	1190	PRE	8049 ab	16,386 a	52.49	1068 a	2230 a
Acetochlor + Clopyralid + Flumetsulam fb Glyphosate	1190 870	PRE fb POST	10,962 ab	18,260 a	81.69	1445 a	2461 a
Acetochlor + Clopyralid + Flumetsulam fb Glyphosate + Dicamba	1190 870 + 280	PRE fb POST	12,170 ab	17,354 a	119	1576 a	2298 a
Saflufenacil + Dimethenamid-P	780	PRE	10,350 ab	16,864 a	84.7	1356 a	2264 a
Saflufenacil + Dimethenamid-P fb Glyphosate	780 870	PRE fb POST	11,491 ab	19,077 a	113.9	1486 a	2543 a
Saflufenacil + Dimethenamid-P fb Glyphosate + Dicamba	780 870 + 280	PRE fb POST	12,545 a	17,265 a	151.11	1596 a	2254 a
Pyroxasulfone + Fluthiacet-ethyl + Atrazine	1580	PRE	5984 c	17,305 a	87.3	746 b	2323 a
Pyroxasulfone + Fluthiacet-ethyl + Atrazine fb Glyphosate	1580 870	PRE fb POST	11,234 ab	17,531 a	116.5	1448 a	2325 a
Pyroxasulfone + Fluthiacet-ethyl + Atrazine fb Glyphosate + Dicamba	1580 870 + 280	PRE fb POST	12,463 a	16,423 a	153.7	1582 a	2134 a

† All POST herbicide programs were mixed with AMS, ammonium sulfate (DSM Chemicals North America Inc., Augusta, GA) at 2.5% (w/v) and NIS, nonionic surfactant (Induce, Helena Chemical Co., Collierville, TN) at 0.25% (v/v). No AMS or NIS were added to PRE herbicides. PRE applications were made within 3 d after planting and POST herbicides were applied when Palmer amaranth was 12 to 15 cm tall.

‡ ai, active ingredient; ae, acid equivalent.

§ POST, post-emergence; PRE, pre-emergence; fb, followed by.

¶ Year × program interaction was significant for corn yield and net return, with no difference between 2014 and 2016; therefore, data were combined for these years and presented separately for 2015. Means within columns with no common letter(s) are significantly different according to Tukey-Kramer's pairwise comparison test $P \leq 0.05$.

Program cost includes an average cost of herbicide, AMS, and NIS, and cost of application ($18.11 ha^{-1} application^{-1}) from two independent sources in Nebraska.

†† Net return were calculated as gross income from glufosinate-resistant corn yield minus herbicide program cost.

PRE followed by glyphosate + dicamba POST had greater biomass reduction of 94% compared to 73% reduction when followed by glyphosate (Table 4).

Corn Injury and Yield

No corn injury was observed at 7, 14, and 21 d after PRE and POST herbicide applications in glufosinate- and glyphosate-resistant corn during the 3-yr study (data not shown). Similarly, previous studies have reported minimal to no corn injury with PRE applications of saflufenacil + dimethenamid-P (750–780 g ha^{-1}), or mesotrione + *S*-metolachlor + atrazine applied at 1880 or 2960 g ha^{-1} (Janak and Grichar, 2016; Ganie et al., 2017). Post-emergence-only or PRE followed by POST programs resulted in similar corn yield in glufosinate-resistant (10,660–11,797 kg ha^{-1}) and glyphosate-resistant corn (10,243–12,545 kg ha^{-1}) in 2014 and 2016 which was higher than PRE-only programs (4972–8192 kg ha^{-1}) (Tables 6 and 7). In 2015, comparatively higher corn yield was obtained in glufosinate-resistant (15,814–17,926 kg ha^{-1}) and glyphosate-resistant corn (16,386–21,810 kg ha^{-1}), with no difference between PRE-only, POST-only, and PRE followed by POST herbicide programs (Tables 6 and 7), even though Palmer amaranth control was lower in PRE-only programs (Tables 3 and 4). Corn yield was positively correlated with Palmer amaranth control ($r = 0.68$ to 0.78, $P < 0.0001$) at 28 and 72 d after POST in glufosinate- and glyphosate-resistant corn in 2014 and 2016; however, in 2015, corn yield was poorly correlated with Palmer amaranth control ($r = 0.13$ to 0.33, $P = 0.01$). Although, previous studies have reported significant corn yield losses due to Palmer amaranth interference during the critical period of corn growth (Liphadzi and Dille, 2006; Massinga et al., 2001, 2003), various factors including environmental conditions such as soil water availability and heat unit accumulation, weed species, and weed density play an important role defining the critical period of weed interference (Hall et al., 1992; Steckel and Sprague, 2004). For instance, some studies have reported lower corn yield loss, with no difference among herbicide programs, due to weed interference in years receiving more rainfall or irrigation (Crow et al., 2016; Young et al., 1984; Wiggins et al., 2016). In 2015, higher rainfall was received at the experimental site during the critical period of corn growth from the V2 to V8 stages or the 8- to 76-cm corn canopy height during June and July compared to 2014 and 2016 (Table 1). The total rainfall received during the 2015 growing season was also higher (908 mm) compared to 2014 (664 mm), 2016 (726 mm), and the 30-yr average (763 mm) at the experimental site which could explain the poor correlation of corn yield and Palmer amaranth control and no difference in corn yield among herbicide programs in 2015.

Economic Analysis

The cost of PRE-only, POST-only, and PRE followed by POST herbicide programs ranged from \$52.49 to \$120, \$61.46 to \$66.41, and \$113.95 to \$218.68 ha^{-1}, respectively, in glufosinate-resistant corn (Table 6). In 2014 and 2016, PRE followed by POST or POST-only programs had higher net return of \$1,349 to \$1,489 ha^{-1} from corn yield compared to \$640 to \$1,021 from PRE-only programs. However, in 2015, all herbicide programs had similar and higher net return of \$2,019 to \$2,365 compared to 2014 and 2016 because of higher corn yields in 2015. In glyphosate-resistant corn, the cost of PRE-only, POST-only, and PRE followed by POST herbicide programs ranged from \$52.49 to \$120, \$29.20 to \$66.41, and \$81.69 to \$186.42, respectively (Table 7). In 2014 and 2016, PRE followed by POST, POST-only or PRE-only programs, except pyroxasulfone + fluthiacet-ethyl + atrazine applied PRE-only had the lowest net return of \$746, provided similar net return of \$944 to \$1,596 ha^{-1} from corn yield. All herbicide programs had similar and higher net return of \$2,134 to \$2,888 in 2015 compared to 2014 and 2016 (Table 7).

Corn yields and economic returns were similar where PRE followed by glufosinate or glyphosate and PRE followed by glufosinate or glyphosate tank-mixed with dicamba were used (Tables 6 and 7). However, because six weed species, including Palmer amaranth, have evolved resistance to glyphosate in Nebraska (Heap, 2017a), glyphosate is not a good choice and other herbicides with different site of action should be considered. Three weed species have evolved resistance to glufosinate worldwide (Heap, 2017b), including Italian ryegrass (*Lolium perenne* L. ssp. multiflorum), the only known glufosinate-resistant weed in the United States (Avila-Garcia et al., 2012). Therefore, glufosinate should be applied in combination with different site of action herbicides in glufosinate-resistant corn as applied in this study.

Practical Implications

The evolution of PS II- and HPPD-inhibitor-resistant Palmer amaranth in Nebraska has reduced the number of herbicide options in field corn, popcorn, and seed corn production fields. Additionally, glyphosate-resistant common waterhemp and Palmer amaranth are widespread and hard-to-control in glyphosate-resistant corn-soybean cropping systems in eastern Nebraska. This is the first study investigating herbicide programs and their net returns for control of PS II- and HPPD-inhibitor-resistant Palmer amaranth in glufosinate and glyphosate-resistant corn. Growers should consider rotating different HR cultivars such as glufosinate- and glyphosate-resistant corn and utilize the effective PRE followed by POST herbicide programs investigated in this study for controlling PS II- and HPPD-inhibitor-resistant Palmer amaranth and to reduce the chances of evolution of HR weeds. Growers also need to adopt an integrated weed management approach that includes the use of different site of action PRE followed by POST herbicides, crop rotation, narrow row spacing, the rotation of different HR cultivars with conventional crop cultivars, tillage, and POST-harvest weed seed control to mitigate the evolution and spread of multiple HR Palmer amaranth (Crow et al., 2015; Price et al., 2012; Wiggins et al., 2016).

REFERENCES

Anonymous. 2017a. Roundup POWERMAX herbicide specimen label. http://www.cdms.net/ldat/ld8CC010.pdf (accessed 5 May 2017).

Anonymous. 2017b. Liberty 280 SL herbicide specimen label. http://www.cdms.net/ldat/ldUA5013.pdf (accessed 5 May 2017).

Aulakh, J.S., and A.J. Jhala. 2015. Comparison of glufosinate-based herbicide programs for broad-spectrum weed control in glufosinate-resistant soybean. Weed Technol. 29:419–430. doi:10.1614/WT-D-15-00014.1

Aulakh, J.S., A.J. Price, S.F. Enloe, G. Wehtje, and M.G. Patterson. 2013. Integrated Palmer amaranth management in glufosinate resistant cotton: II. Primary, secondary and conservation tillage. Agron. 3:28–42. doi:10.3390/agronomy3010028

Avila-Garcia, W.V., E. Sanchez-Olguin, A.G. Hulting, and C. Mallory-Smith. 2012. Target-site mutation associated with glufosinate resistance in Italian ryegrass (*Lolium perenne* L. ssp. multiflorum). Pest Manag. Sci. 68:1248–1254.

Barnett, K.A., A.S. Culpepper, A.C. York, and L.E. Steckel. 2013. Palmer amaranth (*Amaranthus palmeri*) control by glufosinate plus fluometuron applied postemergence to WideStriket cotton. Weed Technol. 27:291–297. doi:10.1614/WT-D-12-00158.1

Bollman, J.D., C.M. Boerboom, R.L. Becker, and V.A. Fritz. 2008. Efficacy and tolerance to HPPD-inhibiting herbicides in sweet corn. Weed Technol. 22:666–674. doi:10.1614/WT-08-036.1

Bonny, S. 2007. Genetically modified glyphosate-tolerant soybean in the USA: Adoption factors, impacts and prospects: A review. Agron. Sustain. Dev. 28:21–32. doi:10.1051/agro:2007044

Bradley, P.R., W.G. Johnson, S.E. Hart, M.L. Buesinger, and R.E. Massey. 2000. Economics of weed management in glufosinate-resistant corn (*Zea mays* L.). Weed Technol. 14:495–501.

Braswell, L.R., C.W. Cahoon, A.C. York, D.L. Jordan, and R.W. Seagroves. 2016. Fluridone and encapsulated acetochlor reduce protoporphyrinogen oxidase inhibitor use in a glufosinate-based Palmer amaranth management program for cotton. Weed Technol. 30:838–847. doi:10.1614/WT-D-16-00025.1

Cahoon, C.W., A.C. York, D.L. Jordan, W.J. Everman, R.W. Seagroves, A.S. Culpepper, and P.M. Eure. 2015a. Palmer Amaranth (*Amaranthus palmeri*) management in dicamba-resistant cotton. Weed Technol. 29:758–770. doi:10.1614/WT-D-15-00041.1

Cahoon, C.W., A.C. York, D.L. Jordan, R.W. Seagroves, W.J. Everman, and K.M. Jennings. 2015b. Sequential and co-application of glyphosate and glufosinate in cotton. J. of Cotton Sci. 19:337–350.

Chahal, P.S., and A.J. Jhala. 2015. Herbicide programs for control of glyphosate-resistant volunteer corn in glufosinate-resistant soybean. Weed Technol. 29:431–443. doi:10.1614/WT-D-15-00001.1

Chahal, P.S., J.S. Aulakh, M. Jugulum, and A.J. Jhala. 2015. Herbicide-resistant Palmer amaranth (*Amaranthus palmeri* S. Wats.) in the United States—Mechanisms of resistance, impact, and management. In: A. Price, editor, Herbicides, agronomic crops, and weed biology. InTech, Rijeka. p. 1–29. doi:10.5772/61512

Chahal, P.S., V.K. Varanasi, M. Jugulam, and A.J. Jhala. 2017. Glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) in Nebraska: Confirmation, EPSPS gene amplification, and response to POST corn and soybean herbicides. Weed Technol. 31:80–93. doi:10.1614/WT-D-16-00109.1

Crow, W.D., L.E. Steckel, R.M. Hayes, and T.C. Mueller. 2015. Evaluation of post-harvest herbicide applications for seed prevention of glyphosate-resistant palmer amaranth (*Amaranthus palmeri*). Weed Technol. 29:405–411. doi:10.1614/WT-D-14-00146.1

Crow, W.D., L.E. Steckel, T.C. Mueller, and R.M. Hayes. 2016. Management of large, glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) in corn. Weed Technol. 30:611–616. doi:10.1614/WT-D-15-00164.1

Edwards, C.B., D.L. Jordan, M.D.K. Owen, P.M. Dixon, B.G. Young, R.G. Wilson, S.C. Weller, and D.R. Shaw. 2014. Benchmark study on glyphosate-resistant crop systems in the United States. Economics of herbicide resistance management practices in a 5 year field-scale study. Pest Manag. Sci. 70:1924–1929.

Fleming, A.A., P.A. Banks, and J.G. Legg. 1988. Differential response of maize inbreds to bentazon and other herbicides. Can. J. Plant Sci. 68:501–507. doi:10.4141/cjps88-060

Ganie, Z.A., and A.J. Jhala. 2017. Glyphosate-resistant common ragweed (*Ambrosia artemisiifolia*) in Nebraska: Confirmation and response to postemergence corn and soybean herbicides. Weed Technol. 31:225–237. doi:10.1017/wet.2016.26

Ganie, Z.A., J.L. Lindquist, M. Jugulam, G. Kruger, D. Marx, and A.J. Jhala. 2017. An integrated approach for management of glyphosate-resistant *Ambrosia trifida* with tillage and herbicides in glyphosate-resistant corn. Weed Res. 57:112–122. doi:10.1111/wre.12244

Hall, M., C.J. Swanton, and G.W. Anderson. 1992. The critical period of weed control in corn (*Zea mays*). Weed Sci. 40:441–447.

Heap, I. 2017a. Herbicide resistant Palmer amaranth globally. http://www.weedscience.org/Summary/Species.aspx (accessed 3 Aug. 2017).

Heap, I. 2017b. Weeds resistant to glutamine synthase inhibitors. http://www.weedscience.org/Summary/MOA.aspx (accessed 1 July 2017).

Hurley, T.M., and G. Frisvold. 2016. Economic barriers to herbicide-resistance management. Weed Sci. sp1:585–594. doi:10.1614/WS-D-15-00046.1

Janak, T.W., and W.J. Grichar. 2016. Weed control in corn (*Zea mays* L.) as influenced by preemergence herbicides. Int. J. of Agron. 2016. doi:10.1155/2016/2607671

Jhala, A.J., L.D. Sandell, N. Rana, G.R. Kruger, and S.Z. Knezevic. 2014. Confirmation and control of triazine and 4-hydroxyphenylpyruvate dioxygenase-inhibiting herbicide-resistant Palmer amaranth (*Amaranthus palmeri*) in Nebraska. Weed Technol. 28:28–38. doi:10.1614/WT-D-13-00090.1

Johnson, W.G., P.R. Bradley, S.E. Hart, M.L. Buesinger, and R.E. Massey. 2000. Efficacy and economics of weed management in glyphosate-resistant corn (*Zea mays*). Weed Technol. 14:57–65. doi:10.1614/0890-037X(2000)014[0057:EAEOWM]2.0.CO;2

Kohrt, J.R., and C.L. Sprague. 2017. Herbicide management strategies in field corn for a three-way herbicide-resistant Palmer amaranth (*Amaranthus palmeri*) population. Weed Technol. 31:364–372. doi:10.1017/wet.2017.18

Liphadzi, K.B., and J.A. Dille. 2006. Annual weed competitiveness as affected by preemergence herbicide in corn. Weed Sci. 54:156–165. doi:10.1614/WS-05-156R1.1

Massinga, R.A., R.S. Currie, M.J. Horak, and J. Boyer, Jr. 2001. Interference of Palmer amaranth in corn. Weed Sci. 49:202–208. doi:10.1614/0043-1745(2001)049[0202:IOPAIC]2.0.CO;2

Massinga, R.A., R.S. Currie, and T.P. Troien. 2003. Water use and light interception under Palmer amaranth (*Amaranthus palmeri*) and corn competition. Weed Sci. 51:523–531. doi:10.1614/0043-1745(2003)051[0523:WUALIU]2.0.CO;2

Norsworthy, J.K., S.M. Ward, D.R. Shaw, R.S. Llewellyn, R.L. Nichols, T.M. Webster, K.W. Bradley, G. Frisvold, S.B. Powles, N.R. Burgos, W.W. Witt, and M. Barrett. 2012. Reducing the risks of herbicide resistance: Best management practices and recommendations. Weed Sci. 60:31–62. doi:10.1614/WS-D-11-00155.1

Oliveira, M.C., A.J. Jhala, T. Gaines, S. Irmak, K. Amundsen, J.E. Scott, and S.Z. Knezevic. 2017. Confirmation and control of HPPD-inhibiting herbicide–resistant waterhemp (*Amaranthus tuberculatus*) in Nebraska. Weed Technol. 31:67–79. doi:10.1017/wet.2016.4

Peterson, D.E. 1999. The impact of herbicide-resistant weeds on Kansas agriculture. Weed Technol. 13:632–635. doi:10.1017/S0890037X00046315

Price, A.J., K.S. Balkcom, L.M. Duzy, and J.A. Kelton. 2012. Herbicide and cover crop residue integration for *Amaranthus* control in conservation agriculture cotton and implications for resistance management. Weed Technol. 26:490–498. doi:10.1614/WT-D-11-00127.1

Reddy, K.N., and V.K. Nandula. 2012. Herbicide resistant crops: History, development and current technologies. Indian J. Agron. 57:1–7.

Sarangi, D., L.D. Sandell, G.R. Kruger, S.Z. Knezevic, S. Irmak, and A.J. Jhala. 2017. Comparison of herbicide programs for season-long control of glyphosate-resistant common waterhemp (*Amaranthus rudis*) in soybean. Weed Technol. 31:53–66. doi:10.1017/wet.2016.1

Sarangi, D., L.D. Sandell, S.Z. Knezevic, J.S. Aulakh, J.L. Lindquist, S. Irmak, and A.J. Jhala. 2015. Confirmation and control of glyphosate-resistant common waterhemp (*Amaranthus rudis*) in Nebraska. Weed Technol. 29:82–92. doi:10.1614/WT-D-14-00090.1

Schuster, C.L., and R.J. Smeda. 2007. Management of *Amaranthus rudis* S. In: glyphosate-resistant corn (*Zea mays* L.) and soybean (*Glycine max* L. Merr.). Crop Prot. 26:1436–1443. doi:10.1016/j.cropro.2006.12.005

Shaw, D.R., M.D.K. Owen, S.C. Weller, B.G. Young, R.G. Wilson, and D. Jordan. 2011. Benchmark study on glyphosate-resistant cropping systems in the United States. Part 1. Introduction to 2006–2008. Pest Manag. Sci. 67:741–746.

Steckel, L.E., and C.L. Sprague. 2004. Common waterhemp (*Amaranthus rudis*) interference in corn. Weed Sci. 52:359–364. doi:10.1614/WS-03-066R1

Swanton, C.J., R.H. Gulden, and K. Chandler. 2007. A rationale for atrazine stewardship in corn. Weed Sci. 55:75–81. doi:10.1614/WS-06-104.1

Underwood, M.G., N. Soltani, D.C. Hooker, D.E. Robinson, J.P. Vink, C.J. Swanton, and P.H. Sikkema. 2017. Benefit of tank-mixing dicamba with glyphosate applied post-emergence for weed control in dicamba plus glyphosate resistant soybean. Can J. of Plant Sci. doi:10.1139/CJPS-2016-0292

USDA-NASS. 2016. Quick stats. USDA National Agricultural Statistics Service, Washington, DC. https://quickstats.nass.usda.gov/ (accessed 15 Aug. 2017).

Wiggins, M.S., R.M. Hayes, and L.E. Steckel. 2016. Evaluating cover crops and herbicides for glyphosate-resistant palmer amaranth (*Amaranthus palmeri*) control in cotton. Weed Technol. 30:415–422. doi:10.1614/WT-D-15-00113.1

Young, F.L., D.L. Wyse, and R.J. Jones. 1984. Quackgrass (*Agropyron repens*) interference in corn (*Zea mays*). Weed Sci. 32:226–234.