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Research Article

Palmer Amaranth (*Amaranthus palmeri*) and Velvetleaf (*Abutilon theophrasti*) Control in No-Tillage Conventional (Non–genetically engineered) Soybean Using Overlapping Residual Herbicide Programs

Debalin Sarangi[1] and Amit J. Jhala[2]

[1]Postdoctoral Research Associate, Department of Agronomy and Horticulture, University of Nebraska–Lincoln, Lincoln, NE, USA and [2]Associate Professor, Department of Agronomy and Horticulture, University of Nebraska–Lincoln, Lincoln, NE, USA

Abstract

Due to depressed corn and soybean prices over the last few years in the United States, growers in Nebraska are showing interest in no-tillage (hereafter referred to as no-till) conventional (non–genetically engineered [non-GE]) soybean production. Due to the increasing number of herbicide-resistant weeds in the United States, weed control in no-till non-GE soybean using POST herbicides is a challenge. The objectives of this study were to compare PRE-only, PRE followed by (fb) POST, and PRE fb POST with residual (POST-WR) herbicide programs for Palmer amaranth and velvetleaf control and soybean injury and yield, as well as to estimate the gross profit margins and benefit–cost ratio of herbicide programs. A field experiment was conducted in 2016 and 2017 at Clay Center, NE. The PRE herbicides tested in this study resulted in ≥95% Palmer amaranth and velvetleaf control at 28 d after PRE (DAPRE). Averaged across the programs, the PRE-only program controlled Palmer amaranth 66%, whereas 86% and 97% control was obtained with the PRE fb POST and PRE fb POST-WR programs, respectively, at 28 d after POST (DAPOST). At 28 DAPOST, the PRE fb POST herbicide programs controlled velvetleaf 94%, whereas the PRE-only program resulted in 85% control. Mixing soil-residual herbicides with foliar-active POST programs did not improve velvetleaf control. Averaged across herbicide programs, PRE fb POST programs increased soybean yield by 10% and 41% in 2016 and 2017, respectively, over the PRE-only programs. Moreover, PRE fb POST-WR programs produced 7% and 40% higher soybean yield in 2016 and 2017, respectively, compared with the PRE fb POST programs. The gross profit margin (US\$1,184.3 ha^{-1}) was highest under flumioxazin/pyroxasulfone (PRE) fb fluthiacet-methyl plus *S*-metolachlor/fomesafen (POST-WR) treatment; however, the benefit–cost ratio was highest (6.1) with the PRE-only program of flumioxazin/chlorimuron-ethyl.

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Nomenclature:
Chlorimuron-ethyl; flumioxazin; fluthiacet-methyl; fomesafen; pyroxasulfone; *S*-metolachlor; Palmer amaranth, *Amaranthus palmeri* S. Watson; velvetleaf, *Abutilon theophrasti* Medik; corn, *Zea mays* L.; soybean, *Glycine max* (L.) Merr

Key words:
Benefit–cost ratio; best management practices; economics; multiple sites of action; PRE followed by POST

Author for correspondence:
Amit J. Jhala, Department of Agronomy and Horticulture, University of Nebraska–Lincoln, Lincoln, NE 68583. (Email: Amit.Jhala@unl.edu)

Introduction

Infestation of weeds in agronomic production systems has long been recognized as a major threat to global food security (Blackman and Templeman 1938; Weber and Staniforth 1957). When selecting weed management programs, growers consider several factors, such as the type of herbicide-resistant crop cultivar, weed control spectrum, selectivity, cost, environment, and fit with conservation agriculture (Buhler 1999; Swanton and Weise 1991). Conservation agriculture comprises a set of three major components: minimal mechanical soil disturbance, permanent soil organic covers using crop residues or cover crops, and crop rotation (FAO 2017). Conservation agriculture can contribute to sustainable crop production. Development and commercialization of herbicide-resistant crops, primarily glyphosate-resistant (GR) crops, ensured a simplified, flexible, and cost-effective weed management program and promoted conservation agriculture by reducing the deep tillage and maintaining the crop residues on the soil surface (Carpenter and Gianessi 1999; Dill et al. 2008; Triplett and Dick 2008). However, due to the overuse of glyphosate, several recent reports have expressed concerns regarding contamination of glyphosate and its primary metabolite, aminomethylphosphonic acid, in soil, surface water, groundwater, and farm produce in the United States and Europe (Battaglin et al. 2014; Bøhn et al. 2014; Kolpin et al. 2006; Silva et al. 2018).

Multiple applications of glyphosate in a growing season in GR crops imposed intense selection pressure on weeds that resulted in the evolution of GR biotypes. Currently, 42 weed species have been reported as GR globally, among which 17 were reported in the United States

(Heap 2018b) and 6 were reported in Nebraska (Jhala 2018). The widespread occurrence of GR weeds in the United States compelled growers to consider applying soil-residual herbicides either as PRE or in mixture with foliar-active POST herbicides (Norsworthy et al. 2012; Sarangi et al. 2017; Whitaker et al. 2010).

Since 2010, demand for non–genetically engineered (non-GE) food products has increased in the United States, with an average growth of 70% each year (Bain and Selfa 2017). The market for non-GE food in the United States reached US$200 billion in 2014 (Cartwright 2016). China is the world's largest producer and importer of conventional (non-GE) soybean (Muhammad 2015; Wang and Houston 2016), and a majority of the soybean (59% of total exported soybean, including both herbicide-resistant and non-GE) produced in the United States is exported to China, with an export value of US$12.4 billion in 2017 (USDA-APHIS 2018; USDA-FAS 2017). Due to the increasing anti-GE movement and mandatory label requirements in certain regions of the food industry, the market for non-GE soybean in China, Europe, and Japan is likely to expand in the near future (Babcock and Beghin 1999; Cartwright 2016; Davison 2010).

The cost of soybean seed has been increasing over the years, with GE soybean seed cost being higher than that of non-GE soybean for having a technology fee. For example, in 2010 the cost of GE soybean seed was 47% higher than the cost of non-GE soybean seed (Benbrook 2012). When the level of weed control and the herbicide cost are comparable between two systems, Reddy and Whiting (2000) described that the selection of a crop cultivar mostly depends on the yield potential and cost of the seed, including the technology fee. With the depressed corn and soybean prices in recent years in the United States, growers have shown interest in non-GE soybean production for its low seed cost and better after-harvest incentives (Hart and Zhang 2016; Jones 2008). Additionally, the epidemic of GR weeds is rapidly lowering the value of GR corn and soybean cultivars in the Midwest. Benbrook (2016) noted that due to an increase in generic glyphosate manufacturing in the United States, glyphosate prices had been going down since 2000; in addition, the report mentioned that the application of glyphosate per unit of land was increasing, which in turn increases the selection pressure and overall production cost. In a survey of soybean growers in South Carolina, Norsworthy (2003) reported that weed management cost in non-GE and GR soybean was similar; however, the additional cost of the technology fee increased the input cost in GR soybean system compared with non-GE soybean. Variety trials assessing the yield potential of GR and non-GE soybean in eight states in the midwestern United States showed that non-GE soybean produced 3% more yield than GR soybean in 1998 to 1999 (Carpenter 2001). In a 2-yr field research study conducted in Stoneville, MS, Reddy and Whiting (2000) reported that GR and non-GE soybean showed similar yield potential.

Weed control, which is a challenge for the non-GE soybean producers, particularly in no-till or reduced-tillage production systems, has led to limited non-GE soybean acreage in the United States (Reddy 2003; Reddy and Whiting 2000; USDA 2015). In 2017, only 6% of soybean area in the United States was planted with non-GE soybean cultivars (USDA-NASS 2017). Palmer amaranth is the most problematic weed in conservation agriculture in the United States (Chahal et al. 2015; Price et al. 2011). A survey conducted by Sarangi and Jhala (2018) ranked Palmer amaranth and velvetleaf among the six most problematic weeds in Nebraska. Palmer amaranth biotypes resistant to acetolactate synthase (ALS), hydroxyphenylpyruvate dioxygenase (HPPD), photosystem II (PSII) inhibitors, and glyphosate have been confirmed in Nebraska (Chahal et al. 2017; Jhala et al. 2014).

Season-long interference of Palmer amaranth at a density of 3.33 and 10 plants m^{-1} of row reduced soybean yield by 64% and 68%, respectively (Klingaman and Oliver 1994). Similarly, Bensch et al. (2003) reported that Palmer amaranth interference at a density of 8 plants m^{-1} of soybean row resulted in 79% yield loss in Kansas. Soybean yield losses due to velvetleaf infestation are inconsistent: for example, Staniforth and Weber (1956) reported no significant soybean yield loss due to 10 to 20 velvetleaf plants m^{-2}, whereas Eaton et al. (1976) found up to 66% yield loss with the season-long interference of velvetleaf at a density of 130 to 240 plants m^{-2}.

During the last two decades, research has generated sufficient information about weed management in GR soybean; however, information on weed management in no-till non-GE soybean is limited. The objectives of this study were to (1) compare PRE-only, PRE followed by (fb) POST, and PRE fb POST with residual (POST-WR) programs for control of Palmer amaranth and velvetleaf in no-till non-GE soybean; and (2) evaluate the soybean injury, yield, gross profit margin, and benefit–cost ratio in response to different herbicide programs.

Materials and Methods

Study Site

Field experiments were conducted during the summer in 2016 and 2017 at the South Central Agricultural Laboratory of the University of Nebraska–Lincoln located near Clay Center, NE (40.57°N, 98.14°W). The experimental site was infested primarily with Palmer amaranth and velvetleaf. Distribution of common lambsquarters (*Chenopodium album* L.), waterhemp [*Amaranthus tuberculatus* (Moq.) J. D. Sauer], large crabgrass [*Digitaria sanguinalis* (L.) Scop.], and foxtails (*Setaria* spp.) was not uniform at this study site; therefore, data from these weed species were not included. No herbicide-resistant weeds apart from ALS inhibitor–resistant Palmer amaranth and waterhemp had been reported at the site. A natural seedbank of Palmer amaranth and velvetleaf was used for this study. The soil at the experiment site was a Crete silt loam (fine, montmorillonite, mesic Pachic Argiustoll) with 17% sand, 58% silt, 25% clay, 3% organic matter, and a pH of 6.5.

Treatments and Plots

The research site was under a continuous no-till corn–soybean rotation for the last 7 yr. Crop residue from the previous cropping season was retained, as the no-till system was practiced in this study. The experimental site was fertilized with 202 kg ha^{-1} of nitrogen in the form of anhydrous ammonia applied in the early spring with additional 11-52-0 fertilizer at 112 kg ha^{-1} at planting. A blanket application (preplant treatment) of paraquat (Gramoxone® SL, Syngenta Crop Protection, Greensboro, NC 24719; at 0.84 kg ai ha^{-1}) plus a nonionic surfactant (Induce®, Helena Chemical, Collierville, TN 38017; at 0.25% v/v) was made in the spring (2 wk before soybean planting) using a tractor-mounted sprayer calibrated to deliver 140 L ha^{-1}. A non-GE soybean cultivar ('U11-622148 BR-16') was planted in no-till conditions on May 12 in 2016 and April 25 in 2017 at

322,000 seeds ha^{-1} to a depth of 3 cm. The experimental site was under a center-pivot irrigation system. The experiment was arranged in a randomized complete block design with four replications. Three weed management programs (PRE-only, PRE fb POST, and PRE fb POST-WR) comprised 15 herbicide treatments, with a nontreated control (Table 1). The plots were 3-m wide by 9-m long, where 4 soybean rows were spaced 76.2 cm apart.

The PRE applications were made within 2 d of soybean planting, and POST treatments were applied on June 20 in 2016 and June 9 in 2017, when the average plant height was 8 to 12 cm for Palmer amaranth, 12 cm for velvetleaf, and soybean was at the V3 to V4 stage. Herbicides were applied using a handheld CO_2-pressurized backpack sprayer equipped with AIXR 110015 flat-fan nozzles (TeeJet® Technologies, Spraying Systems, P.O. Box 7900, Wheaton, IL 60187) calibrated to deliver 140 L ha^{-1} at 276 kPa at a constant speed of 4.8 km h^{-1}.

Data Collection

Palmer amaranth and velvetleaf control was visually assessed at 14 and 28 d after PRE (DAPRE), 14 and 28 d after POST (DAPOST), and at soybean harvest on a scale of 0% to 100%, with 0% representing no control and 100% representing complete control. Weed density was recorded at 14 and 28 DAPRE and 14 and 28 DAPOST by counting Palmer amaranth and velvetleaf in two 0.25-m^2 quadrats placed randomly between the two center soybean rows in each plot and was converted into number of plants per square meter. Palmer amaranth plants surviving herbicide treatments were cut at the soil surface at 56 DAPOST from two randomly selected 0.25-m^2 quadrats, and the samples were put into paper bags and placed in an oven at 65 C for 5 d. Aboveground biomass for velvetleaf was not collected in this study. Palmer amaranth aboveground biomass data were converted into percent biomass reduction compared with the nontreated control using the equation:

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

where C is the aboveground biomass of the nontreated control plot and B is the biomass of an individual treated plot.

Soybean injury was assessed visually at 14 DAPRE, 7 DAPOST, and 21 DAPOST on a scale of 0% to 100% (0% representing no injury and 100% representing complete death) based on leaf chlorosis and necrosis, malformation of leaves, purpling of the veins, and plant stunting. Soybean plant stand was counted at 28 DAPRE from a randomly selected 1-m length of each of the center two rows per plot. Soybean was harvested from the center two rows in each plot using a plot combine (Gleaner K2, AGCO, 4205 River Green Parkway, Duluth, GA 30096), and the grain yield was adjusted to 13% moisture content.

Table 1. Herbicide programs, application timing, and rates used for control of Palmer amaranth and velvetleaf in no-till non-GE soybean in Nebraska.

Herbicide program and rate		Trade name		
PRE	POST[a]	PRE	POST[a]	Manufacturer
Chlorimuron-ethyl/flumioxazin/metribuzin (344 g ai ha^{-1})	——	Trivence®	——	E. I. du Pont de Nemours and Company, Wilmington, DE 19805
	Fluthiacet-methyl/fomesafen (190 g ai ha^{-1})		Marvel™	FMC Corporation, Philadelphia, PA 19103
	Fluthiacet-methyl/fomesafen + acetochlor (190 + 1,930 g ai ha^{-1})		Marvel ™ + Warrant®	FMC Corporation + Monsanto Company, St Louis, MO 63167
Saflufenacil/imazethapyr + dimethenamid-P (95 + 525 g ai ha^{-1})	——	Optill® PRO	——	BASF Corporation, Research Triangle Park, NC 27709
	Lactofen (210 g ai ha^{-1})		Cobra®	Valent U.S.A. Corporation, Walnut Creek, CA 94596
	Lactofen + pyroxasulfone (210 + 124 g ai ha^{-1})		Cobra® + Zidua®	Valent U.S.A. Corp. + BASF Corporation
Flumioxazin/chlorimuron-ethyl (85 g ai ha^{-1})	——	Valor® XLT	——	Valent U.S.A. Corporation
	Acifluorfen (210 g ai ha^{-1})		Ultra Blazer®	United Phosphorus, Inc., King of Prussia, PA 19406
	Acifluorfen + dimethenamid-P (210 + 655 g ai ha^{-1})		Ultra Blazer® + Outlook®	United Phosphorus, Inc. + BASF Corporation
Flumioxazin/pyroxasulfone (200 g ai ha^{-1})	——	Fierce®	——	Valent U.S.A. Corporation
	Fluthiacet-methyl (5 g ai ha^{-1})		Cadet®	FMC Corp.
	Fluthiacet-methyl + *S*-metolachlor/fomesafen (5 + 1,320 g ai ha^{-1})		Cadet® + Prefix®	FMC Corp. + Syngenta Crop Protection, LLC, Greensboro, NC 27419
Sulfentrazone/metribuzin (504 g ai ha^{-1})	——	Authority® MTZ	——	FMC Corporation
	Cloransulam-methyl (18 g ai ha^{-1})		FirstRate®	Dow AgroSciences LLC, Indianapolis, IN 46268
	Cloransulam-methyl + pyroxasulfone/fluthiacet-methyl (18 + 65 g ai ha^{-1})		FirstRate® + Anthem® Maxx	Dow AgroSciences + FMC Corporation

[a] Crop oil concentrate (Agri-Dex, Helena Chemical Company, Collierville, TN 38017; at 1% v/v) and ammonium sulfate (N-Pak AMS Liquid, Winfield Solutions, LLC, St Paul, MN 55164; at 2.5% v/v) were mixed with the POST herbicide treatments.

An economic analysis was performed to assess the profitability of the herbicide programs. Gross profit margin was calculated using the equation:

$$\text{Gross profit margin}(\text{US\$}) = (R - W) \qquad [2]$$

where R is the gross revenue calculated by multiplying soybean yield by the average grain price received at harvest in 2017 (US \$0.38 kg^{-1}; USDA-AMS 2017) and W is the weed management cost, including the cost of herbicides, adjuvants, and custom applications (US\$18.11 ha^{-1} application^{-1}; Barnes et al. 2017). Herbicide prices were obtained from three independent commercial sources (Cargill, Country Partners Cooperative, Crop Production Services) in Nebraska, and were averaged and used to calculate the herbicide cost per hectare.

The benefit–cost ratio indicates the value of the money spent on a herbicide program. It summarizes the rate of return (US\$) per unit capital (US\$) invested for weed management. Benefit–cost ratio was calculated using the equation:

$$\text{Benefit} - \text{cost ratio for a program}(\text{US\$} / \text{US\$}) = (R_T - R_C) / W \qquad [3]$$

where R_T is the gross revenue of a herbicide program, R_C is the gross revenue for the nontreated control, and W is the weed management cost.

Statistical Analysis

Palmer amaranth and velvetleaf control, their density, aboveground biomass reduction, and soybean injury and yield data were subjected to ANOVA using PROC GLIMMIX in SAS (SAS Institute, Cary, NC). Before ANOVA, all data were tested for the normality and homogeneity of error variances using the Shapiro-Wilk test and Bartlett's test, respectively. Visual estimates of weed control and biomass reduction data were arc-sine square-root transformed before analysis; however, back-transformed data are presented with the means separated using Fisher's protected LSD test, where $\alpha = 0.05$. In the model, treatments and years were considered fixed effects, whereas blocks were considered random effects. To determine the relative efficacy of the herbicide programs (PRE-only vs. PRE fb POST; and PRE fb POST vs. PRE fb POST-WR) for Palmer amaranth and velvetleaf control, density, and aboveground biomass reduction, along with soybean injury and yield, a priori orthogonal contrasts (single degree of freedom contrasts) were performed.

Results and Discussion

Year-by-treatment interactions for weed control, density, and aboveground biomass reduction were nonsignificant ($P \geq 0.05$); therefore, data from 2016 and 2017 were combined. Rainfall within 30 DAPRE applications and throughout the season was sufficient for the activity of the soil-applied residual herbicides (Table 2).

Palmer Amaranth Control, Density, and Biomass Reduction

The PRE herbicides tested in this study controlled Palmer amaranth 97% to 100% at 14 and 28 DAPRE and reduced weed density to ≤1 plant m^{-2} compared with 32 plants m^{-2} in nontreated control at 14 DAPRE (Table 3). Similarly, field studies conducted in Kansas showed that chlorimuron-ethyl/flumioxazin/metribuzin, saflufenacil/imazethapyr plus dimethenamid-P, flumioxazin/pyroxasulfone, and sulfentrazone/metribuzin controlled Palmer amaranth ≥97% at 14 DAPRE in soybean (Hay 2017). A study conducted in soybean fields in five midwestern and southern states including Nebraska showed that flumioxazin/pyroxasulfone controlled Palmer amaranth ≥95% at all sites at 28 DAPRE (Meyer et al. 2015). Additionally, Sarangi et al. (2017) reported that saflufenacil/imazethapyr plus dimethenamid-P, flumioxazin/chlorimuron-ethyl, and flumioxazin/pyroxasulfone resulted in 92% to 97% control of GR waterhemp, a species closely related to Palmer amaranth, in GR soybean in Nebraska. Ward et al. (2013) emphasized that PRE-applied residual herbicides are the cornerstone for early-season Palmer amaranth control in soybean.

Table 2. Average air temperature and total precipitation during the 2016 and 2017 growing seasons and the 30-yr average at South Central Agricultural Laboratory of the University of Nebraska–Lincoln, Clay Center, Nebraska.[a]

	Average temperature			Total precipitation		
Timing[b]	2016	2017	30-yr average	2016	2017	30-yr average
	C			mm		
1 to 10 DAPRE	16.6	8.5	——	16.8	76.5	——
11 to 20 DAPRE	20.2	19.9	——	71.1	22.9	——
21 to 30 DAPRE	25.3	13.8	——	0.0	135.6	——
June	24.8	23.7	21.8	10.9	40.9	103.6
July	24.6	25.6	24.2	66.3	51.3	102.4
August	23.4	21.3	23.1	55.4	91.7	93.7
September	19.8	19.8	18.5	90.2	61.5	59.9
October	14.3	12.4	11.6	46.5	112.8	60.7
Annual	12.2	11.7	10.3	623.8	723.6	748.5

[a] Air temperature and precipitation data were obtained from HPRCC, the High Plains Regional Climate Center (2017).

[b] DAPRE, days after PRE herbicide application.

Table 3. Palmer amaranth and velvetleaf control and density as affected by PRE herbicide treatments in no-till non-GE soybean in Nebraska.[a,b]

	Palmer amaranth control[c]		Palmer amaranth density[d]	Velvetleaf control[c]		Velvetleaf density[d]
PRE herbicide program	14 DAPRE	28 DAPRE	14 DAPRE	14 DAPRE	28 DAPRE	14 DAPRE
	——— % ———		—— no. plants m^{-2} ——	——— % ———		—— no. plants m^{-2} ——
Nontreated control	0	0	32 a	0	0	29 a
Chlorimuron-ethyl/flumioxazin/metribuzin	99 a	97 a	1 b	98 a	96 a	1 b
Saflufenacil/imazethapyr + dimethenamid-P	100 a	98 a	0 b	99 a	97 a	0 b
Flumioxazin/chlorimuron-ethyl	100 a	98 a	0 b	98 a	97 a	0 b
Flumioxazin/pyroxasulfone	100 a	98 a	0 b	98 a	98 a	0 b
Sulfentrazone/metribuzin	100 a	98 a	0 b	97 a	95 a	2 b
P-value	0.70	0.09	< 0.001	0.06	0.13	< 0.001

[a] Abbreviation: DAPRE, d after PRE herbicide application.

[b] Data presented in this table were pooled across both years (2016 and 2017).

[c] Data were arc-sine square-root transformed before analysis; however, back-transformed original mean values are presented based on the interpretation of the transformed data, and the weed control data for the nontreated control plots were not included in the analysis.

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

Table 4. Palmer amaranth control, density, and aboveground biomass reduction as affected by herbicide programs in no-till non-GE soybean in Nebraska.[a,b]

Herbicide program		Palmer amaranth control[c,d]			Density[d]	Biomass reduction[c,d]
PRE	POST	14 DAPOST	28 DAPOST	At harvest	28 DAPOST	56 DAPOST
		——— % ———			— no. plants m^{-2} —	——— % ———
Nontreated control		0	0	0	110 a	0
Chlorimuron-ethyl/flumioxazin/metribuzin	——	76 cd	67 ef	42 ef	37 b	68 e
	Fluthiacet-methyl/fomesafen	97 a	90 cd	85 bc	10 d	89 cd
	Fluthiacet-methyl/fomesafen + acetochlor	99 a	97 ab	95 ab	2 d	98 a
Saflufenacil/imazethapyr + dimethenamid-P	——	77 bcd	61 ef	28 fg	42 b	56 e
	Lactofen	99 a	91 c	81 cd	8 d	90 bcd
	Lactofen + pyroxasulfone	99 a	99 a	97 a	1 d	100 a
Flumioxazin/chlorimuron-ethyl	——	71 d	61 ef	36 efg	38 b	58 e
	Acifluorfen	98 a	88 cd	83 c	9 d	86 d
	Acifluorfen + dimethenamid-P	99 a	97 ab	90 abc	3 d	97 ab
Flumioxazin/pyroxasulfone	——	87 b	83 d	67 d	16 cd	86 d
	Fluthiacet-methyl	96 a	92 c	80 cd	8 d	88 cd
	Fluthiacet-methyl + *S*-metolachlor/fomesafen	99 a	99 a	97 a	1 d	98 a
Sulfentrazone/metribuzin	——	71 d	58 f	22 g	47 b	60 e
	Cloransulam-methyl	83 bc	70 e	45 e	33 bc	68 e
	Cloransulam-methyl + pyroxasulfone/fluthiacet-methyl	97 a	94 bc	82 c	9 d	96 abc
P-value		< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Contrasts[e]						
PRE-only vs. PRE fb POST		76 vs. 95**	66 vs. 86**	39 vs. 75**	36 vs. 14**	66 vs. 84**
PRE fb POST vs. PRE fb POST-WR		95 vs. 99*	86 vs. 97**	75 vs. 92**	14 vs. 3*	84 vs. 98**

[a] Abbreviations: DAPOST, d after POST herbicide application; POST-WR, POST with residual.

[b] Data presented in this table were pooled across both years (2016 and 2017).

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

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

[e] A priori orthogonal contrasts; ** = significant ($P < 0.01$) and * = significant ($P < 0.05$).

Averaged across herbicide programs, PRE fb POST programs controlled Palmer amaranth 95% at 14 DAPOST compared with 76% control with PRE-only programs (Table 4). The PRE fb POST-WR programs controlled Palmer amaranth 99% at 14 DAPOST. Due to a decline in the residual activities of the PRE soil-applied herbicides, PRE-only programs resulted in 66% control of Palmer amaranth at 28 DAPOST compared with 86% control for PRE fb POST programs (Table 4). Most of the PRE fb POST-WR programs resulted in ≥97% control of Palmer amaranth at 28 DAPOST. Similarly, Chahal et al. (2018) reported that mixing soil-residual herbicides with foliar-active POST herbicides controlled HPPD and PSII inhibitor–resistant Palmer amaranth season-long in Nebraska. Averaged across programs, PRE-only herbicide programs reduced Palmer amaranth density by 67% at 28 DAPOST compared with the nontreated control (36 plants m^{-2} with PRE-only programs vs. 110 plants m^{-2} in nontreated control; Table 4). The PRE fb POST-WR programs resulted in 3 Palmer amaranth plants m^{-2} compared with 14 plants m^{-2} in PRE fb POST programs. Due to the availability of sufficient soil moisture early in the season in 2017, Palmer amaranth emergence was more than two times higher in 2017 compared with 2016. Palmer amaranth density was 48 to 76 plants m^{-2} in 2016 compared with 108 to 220 plants m^{-2} in 2017 in nontreated control (data not shown).

PRE fb POST-WR herbicide programs including saflufenacil/imazethapyr plus dimethenamid-P fb lactofen plus pyroxasulfone, and flumioxazin/pyroxasulfone fb fluthiacet-methyl plus *S*-metolachlor/fomesafen resulted in 97% control of Palmer amaranth at harvest, which was comparable to the control obtained with chlorimuron-ethyl/flumioxazin/metribuzin fb fluthiacet-methyl/fomesafen plus acetochlor (95% control), and flumioxazin/chlorimuron-ethyl fb acifluorfen plus dimethenamid-P (90% control) (Table 4). Orthogonal contrasts showed that PRE fb POST herbicide programs resulted in higher Palmer amaranth control (75%) than PRE-only programs (39% control) at harvest and that PRE fb POST-WR programs improved Palmer amaranth control over PRE fb POST programs (92% vs. 75% control). In a statewide survey of growers and extension agents in Georgia, Sosnoskie and Culpepper (2014) reported that growers often use overlapping residual herbicides to obtain season-long Palmer amaranth control in cotton (*Gossypium hirsutum* L.). Data on reduction in aboveground biomass followed similar trends as Palmer amaranth control and density (Table 4). The PRE fb POST-WR programs resulted in higher biomass reduction (96% to 100%) compared with other herbicide programs.

Several studies reported improved Palmer amaranth control by PRE fb POST herbicide programs in soybean (Butts et al. 2016; Meyer et al. 2015; Whitaker et al. 2010), though it is expected that

Table 5. Velvetleaf control and density as affected by herbicide programs in no-till non-GE soybean in Nebraska.[a,b]

Herbicide program		Velvetleaf control[c,d]		Density[d]
PRE	POST	14 DAPOST	28 DAPOST	28 DAPOST
		——— % ———		—— no. plants m^{-2} ——
Nontreated control		0	0	45 a
Chlorimuron-ethyl/flumioxazin/metribuzin	——	93 bc	92 abc	7 bc
	Fluthiacet-methyl/fomesafen	97 ab	94 abc	4 c
	Fluthiacet-methyl/fomesafen + acetochlor	97 ab	97 ab	2 c
Saflufenacil/imazethapyr + dimethenamid-P	——	89 cd	88 bc	9 b
	Lactofen	99 a	96 ab	3 c
	Lactofen + pyroxasulfone	99 a	99 a	0 c
Flumioxazin/chlorimuron-ethyl	——	93 bc	93 abc	8 bc
	Acifluorfen	98 ab	94 abc	4 c
	Acifluorfen + dimethenamid-P	97 ab	97 ab	1 c
Flumioxazin/pyroxasulfone	——	89 cd	85 c	10 b
	Fluthiacet-methyl	98 ab	95 abc	3 c
	Fluthiacet-methyl + *S*-metolachlor/fomesafen	99 a	98 a	1 c
Sulfentrazone/metribuzin	——	79 d	67 d	15 b
	Cloransulam-methyl	96 ab	91 bc	6 c
	Cloransulam-methyl + pyroxasulfone/fluthiacet-methyl	94 abc	94 abc	5 c
P-value		< 0.001	< 0.001	< 0.001
Contrasts[e]				
PRE-only vs. PRE fb POST		89 vs. 98**	85 vs. 94**	10 vs. 4**
PRE fb POST vs. PRE fb POST-WR		98 vs. 97 NS	94 vs. 97 NS	4 vs. 2 NS

[a] Abbreviations: DAPOST, d after POST herbicide application; POST-WR, POST with residual.
[b] Data presented in this table were pooled across both years (2016 and 2017).
[c] Data were arc-sine square-root transformed before analysis; however, back-transformed original mean values are presented based on the interpretation of the transformed data.
[d] Means presented within each column with no common letter(s) are significantly different according to Fisher's protected LSD, where $\alpha = 0.05$.
[c] A priori orthogonal contrasts; ** = significant ($P < 0.01$); NS, nonsignificant ($P \geq 0.05$).

the extended emergence period of Palmer amaranth will allow later-emerging cohorts to escape in-crop POST treatments. Neve et al. (2011) proposed that mixing foliar-active POST herbicides with soil-residual herbicides can provide season-long control of Palmer amaranth in row crops. To achieve residual control of Palmer amaranth later in the season, very-long-chain fatty acid (VLCFA)-inhibiting herbicides (such as acetochlor, dimethenamid-P, pyroxasulfone, and *S*-metolachlor) were applied POST in this study along with foliar-active herbicides (ALS and protoporphyrinogen oxidase [PPO] inhibiting). The VLCFA-inhibiting herbicides are known for the residual control of small-seeded broadleaf weed species, including *Amaranthus* spp. (Geier et al. 2006; Grey et al. 2014; Hay 2017; Sarangi et al. 2015b, 2017).

Velvetleaf Control and Density

The PRE herbicides tested in this study controlled velvetleaf 95% or greater at 14 and 28 DAPRE and resulted in 0 to 2 velvetleaf plants m^{-2} at 14 DAPRE (Table 3). Similarly, Peterson et al. (2017) reported 94% to 100% control of velvetleaf at 18 DAPRE with flumioxazin/chlorimuron-ethyl, flumioxazin/pyroxasulfone, and sulfentrazone/metribuzin in a field study conducted in Manhattan, KS. Mahoney et al. (2014) also reported that PRE application of flumioxazin/pyroxasulfone at 200 g ai ha^{-1} in no-till soybean controlled velvetleaf 94% at 28 DAPRE in Ontario, Canada.

The PRE fb POST herbicide programs substantially improved velvetleaf control (98%) over the PRE-only herbicide programs (89% control) at 14 DAPOST (Table 5). However, averaged across herbicide programs, velvetleaf control was similar in PRE fb POST-WR and PRE fb POST programs at 14 and 28 DAPOST. The majority of soil-residual herbicides included in POST herbicide programs were VLCFA inhibitors, and these herbicides showed partial velvetleaf control (Anonymous 2016; Belfry et al. 2015; Robinson et al. 2008). Therefore, the selection of residual herbicides for POST application should be based on the weed species present in the field. Velvetleaf density data at 28 DAPOST followed a similar trend as velvetleaf control, and PRE fb POST programs considerably reduced velvetleaf density to 4 plants m^{-2}, while velvetleaf density was 10 and 45 plants m^{-2} in the PRE-only programs and nontreated control, respectively (Table 5).

Soybean Injury and Yield

At 14 DAPRE, soybean injury caused by PRE herbicides was minimal. No difference in soybean stand ($P = 0.38$) was also observed at 28 DAPRE (Table 6). However, at 7 DAPOST, 8% to

Table 6. Soybean stand count and yield as affected by herbicide programs in no-till non-GE soybean in Nebraska.[a]

Herbicide program		Soybean stand	Soybean yield[b,c]	
PRE	POST	28 DAPRE	2016	2017
		—— no. plants m^{-1} row ——	—————— kg ha^{-1}	——————
Nontreated control		16 a	2,247 g	560 e
Chlorimuron-ethyl/flumioxazin/ metribuzin	——	17 a	3,617 def	1,273 cd
	Fluthiacet-methyl/fomesafen	17 a	3,805 bcdef	1,733 bc
	Fluthiacet-methyl/fomesafen + acetochlor	19 a	4,187 abc	2,811 a
Saflufenacil/imazethapyr + dimethenamid-P	——	17 a	3,377 f	1,127 d
	Lactofen	16 a	3,950 bcde	1,793 b
	Lactofen + pyroxasulfone	18 a	4,526 a	2,479 a
Flumioxazin/chlorimuron-ethyl	——	18 a	3,757 cdef	933 de
	Acifluorfen	18 a	3,963 bcde	1,704 bc
	Acifluorfen + dimethenamid-P	18 a	4,061 abcd	1,935 b
Flumioxazin/pyroxasulfone	——	18 a	3,543 ef	1,687 bc
	Fluthiacet-methyl	17 a	3,852 bcdef	1,915 b
	Fluthiacet-methyl + *S*-metolachlor/ fomesafen	17 a	4,321 ab	2,719 a
Sulfentrazone/metribuzin	——	19 a	3,467 ef	940 de
	Cloransulam-methyl	17 a	3,955 bcde	1,254 cd
	Cloransulam-methyl + pyroxasulfone/ flumioxazin-methyl	17 a	3,875 bcdef	1,802 b
P-value		0.38	< 0.001	< 0.001
Contrasts[d]				
PRE-only vs. PRE fb POST		——	3,552 vs. 3,905**	1,192 vs. 1,680**
PRE fb POST vs. PRE fb POST-WR		——	3,905 vs. 4,194*	1,680 vs. 2,349**

[a] Abbreviations: DAPRE, d after PRE herbicide application; POST-WR, POST with residual.

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

[c] Year-by-treatment interaction was significant for soybean yield; therefore, data from both years are presented separately.

[d] A priori orthogonal contrasts; ** = significant ($P < 0.01$), and * = significant ($P < 0.05$).

12% soybean injury was observed with all POST herbicides, although, injury symptoms were transitory and dissipated at 21 DAPOST (data not shown). The POST application of PPO-inhibiting herbicides (acifluorfen, fomesafen, and lactofen) is known to cause a low to moderate level of soybean injury (Sarangi and Jhala 2015). However, several studies have reported that low levels of herbicide injury do not impact soybean yield (Legleiter et al. 2009; Patton 2013; Riley and Bradley 2014; Sarangi et al. 2017).

The year-by-treatment interaction was significant for soybean yield; therefore, yield data from 2016 and 2017 are presented separately. It is believed that the higher Palmer amaranth density in 2017 led to the lower soybean yield in all the treatments and nontreated control. Averaged across herbicide programs, PRE fb POST programs resulted in higher soybean yield (3,905 and 1,680 kg ha^{-1} in 2016 and 2017, respectively) compared with the PRE-only herbicide programs (3,552 and 1,192 kg ha^{-1} in 2016 and 2017, respectively) (Table 6). The PRE fb POST-WR program improved soybean yield by 7% and 40% in 2016 and 2017, respectively, over the PRE fb POST program. Therefore, it is evident that if Palmer amaranth is the major weed in a no-till non-GE soybean field, herbicide strategies that include overlapping soil-residual herbicides as tested in this study may result in season-long control and higher soybean yield. Whitaker et al. (2010) noted that PRE fb POST/POST-WR herbicide programs are necessary for effective management of Palmer amaranth and higher soybean yield. Moreover, Chahal et al. (2018) showed that inclusion of soil-residual herbicides in POST treatments increased corn yield and net economic returns. Butts et al. (2016) also reported that a PRE fb POST/POST-WR herbicide strategy is an important component in integrated weed management that can effectively manage *Amaranthus* spp. and increase grain yield. Studies conducted in Nebraska also showed that PRE fb POST/POST-WR herbicide programs resulted in higher waterhemp control and soybean yield in GR and glufosinate-resistant soybean (Jhala et al. 2017; Sarangi et al. 2017).

Economics

Weed management costs for the PRE fb POST and PRE fb POST-WR herbicide programs ranged between US\$104.8 and US\$205.9 ha^{-1} (Table 7). Gross profit margins with PRE fb POST-WR programs varied from US\$895.3 to US\$1,184.3 ha^{-1}, whereas for the PRE fb POST programs, gross profit margins ranged from US\$857.5 to US\$972.4 ha^{-1}. The results of the benefit–cost ratio analysis showed that greater economic benefit was obtained with the PRE-only program of flumioxazin/chlorimuron-ethyl (benefit–cost ratio = 6.1), flumioxazin/pyroxasulfone (5.6), and chlorimuron/flumioxazin/metribuzin (5.5) due to the lower weed management cost (Table 7); however, the PRE-only programs resulted in poor control of Palmer amaranth (an average of 39% control at harvest) and velvetleaf (85% control at 28 DAPOST) compared with the PRE fb POST/ POST-WR programs. Therefore, application of POST herbicides following a PRE treatment is recommended for long-term sustainable weed

Table 7. Gross profit margin and benefit–cost ratio of herbicide programs for control of Palmer amaranth and velvetleaf in no-till non-GE soybean in Nebraska.

Herbicide program					
PRE	POST	Gross revenue[a]	Weed management cost[b]	Gross profit margin[c]	Benefit–cost ratio[d]
		US\$ ha^{-1}			
Nontreated control		533.3	0.0	533.3	——
Chlorimuron-ethyl/flumioxazin/ metribuzin	——	929.1	72.1	857.1	5.5
	Fluthiacet-methyl/fomesafen	1,052.2	126.0	926.2	4.1
	Fluthiacet-methyl/fomesafen + acetochlor	1,329.6	175.4	1,154.2	4.5
Saflufenacil/imazethapyr + dimethenamid-P	——	855.8	82.0	773.8	3.9
	Lactofen	1,091.2	157.4	933.8	3.5
	Lactofen + pyroxasulfone	1,331.0	205.9	1,125.0	3.9
Flumioxazin/chlorimuron-ethyl	——	891.1	58.6	832.5	6.1
	Acifluorfen	1,076.7	104.8	972.0	5.2
	Acifluorfen + dimethenamid-P	1,139.2	141.1	998.2	4.3
Flumioxazin/pyroxasulfone	——	993.7	82.1	911.6	5.6
	Fluthiacet-methyl	1,095.7	123.3	972.4	4.6
	Fluthiacet-methyl + *S*-metolachlor/ fomesafen	1,337.6	153.3	1,184.3	5.2
Sulfentrazone/metribuzin	——	837.3	78.2	759.2	3.9
	Cloransulam-methyl	989.7	132.2	857.5	3.5
	Cloransulam-methyl + pyroxasulfone/ fluthiacet-methyl	1,078.6	183.3	895.3	3.0

[a] Gross revenue was calculated by multiplying average soybean yield (from 2016 and 2017) with the average grain price for non-GE soybean at harvest in 2017 (US\$0.38 kg^{-1}).

[b] Weed management cost included the cost of herbicides, adjuvants, and custom applications (US\$18.11 ha^{-1} application^{-1}); herbicide price was averaged from three independent commercial sources in Nebraska.

[c] Gross profit margin was calculated as gross revenue minus weed management cost.

[d] Benefit–cost ratio for a program (US\$/US\$) = (gross revenue of a program – gross revenue of nontreated control)/ weed management cost.

management and to reduce the weed seedbank in the soil. In this study, flumioxazin/pyroxasulfone fb fluthiacet-methyl plus *S*-metolachlor/fomesafen resulted in the highest gross profit margin (US$1,184.3) and a benefit–cost ratio of 5.2.

Practical Implications

Weed management in no-till non-GE soybean is mostly herbicide dependent; therefore, herbicide programs should be selected carefully to provide season-long weed control and high soybean yield. Unlike GR or glufosinate-resistant soybean systems, there are few "rescue" POST herbicides available in non-GE soybean, meaning that a PRE herbicide application is even more critical. In this study, PRE fb POST-WR programs controlled Palmer amaranth 82% to 99% throughout the season and resulted in higher soybean yields (4,194 and 2,349 kg ha^{-1} in 2016 and 2017, respectively) compared with the PRE-only and PRE fb POST programs. The PRE fb POST herbicide programs controlled velvetleaf 94% at 28 DAPOST, which was similar to the control obtained with the PRE fb POST-WR programs. Although the inclusion of soil-residual herbicides in PRE fb POST programs slightly increased gross profit margins and mostly did not improve the benefit–cost ratio compared with the PRE fb POST programs, this weed management approach is important for season-long management of *Amaranthus* spp. such as waterhemp and Palmer amaranth. A recent report by USDA-APHIS (2018) stated that inspection officials in China, the largest importer of U.S.-grown soybean (GE and non-GE), have detected considerable weed seed contamination in soybean shipments from the United States, with 80% of those seeds coming from four major weeds, including *Amaranthus* spp. Therefore, to ensure uninterrupted soybean trade with China, it is essential to control Palmer amaranth season-long to reduce seed contamination in soybean.

POST broadleaf weed control in non-GE soybean is often achieved through ALS- and PPO-inhibiting herbicides. However, ALS inhibitor–resistant *Amaranthus* spp. and horseweed (*Erigeron canadensis* L.) are widespread in Nebraska (Jhala 2018; Lawrence 2017; Sarangi and Jhala 2018; Sarangi et al. 2015a), and recently a waterhemp biotype from southeast Nebraska has been confirmed resistant to PPO inhibitors (Heap 2018a; Stephens et al. 2017). Therefore, overlapping residual herbicides not only can provide season-long control of Palmer amaranth, but also can include an additional site of action (if not used previously) in the herbicide program that will mitigate/reduce the selection pressure associated with a single herbicide or site of action.

Author ORCIDs. Debalin Sarangi, http://orcid.org/0000-0002-1876-8400; Amit J. Jhala, http://orcid.org/0000-0001-8599-4996.

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