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Effect of row spacing and herbicide programs for control of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) in dicamba/glyphosate-resistant soybean

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Abstract

Glyphosate-resistant (GR) Palmer amaranth is one of the most difficult to control weeds in soybean production fields in Nebraska and the United States. An integrated approach is required for effective management of GR Palmer amaranth. Cultural practices such as narrow row spacing might augment herbicide efficacy for management of GR Palmer amaranth. The objectives of this study were to evaluate the effect of row spacing and herbicide programs for management of GR Palmer amaranth in dicamba/glyphosate-resistant (DGR) soybean. Field experiments were conducted in a grower's field with a uniform population of GR Palmer amaranth near Carleton, Nebraska, in 2018 and 2019. Year-by-herbicide program-by-row spacing interactions were significant for all variables; therefore, data were analyzed by year. Herbicides applied PRE controlled GR Palmer amaranth ≥95% in both years 14 d after PRE (DAPRE). Across soybean row-spacing, most PRE followed by (fb) early-POST (EPOST) herbicide programs provided 84% to 97% control of Palmer amaranth compared with most EPOST fb late-post (LPOST) programs, excluding dicamba in single and sequential applications (82% to 95% control). Mixing microencapsulated acetochlor with a POST herbicide in PRE fb EPOST herbicide programs controlled Palmer amaranth ≥93% 14 d after EPOST and ≥96% 21 d after LPOST with no effect on Palmer amaranth density. Interaction of herbicide program-by-row spacing on Palmer amaranth control was not significant; however, biomass reduction was significant at soybean harvest in 2019. The herbicide programs evaluated in this study caused no soybean injury. Due to drought conditions during a majority of the 2018 growing season, soybean yield in 2018 was reduced compared with 2019.

Introduction

Native to the American Southwest, Palmer amaranth has spread across the continental United States since the beginning of the 20th century due to seed and equipment transportation and agricultural expansion (Sauer 1957; Ward et al. 2013). Historically, Palmer amaranth was not a management concern in Nebraska due to its limited geographical distribution; however, the prevalence of Palmer amaranth has increased since the previous decade, with confirmed populations in most Nebraska counties. A survey conducted in Nebraska reported Palmer amaranth as the fourth most troublesome weed to manage in agronomic crops in the Panhandle and West Central regions of Nebraska and sixth most troublesome weed across the state (Sarangi and Jhala 2018). Reports from this survey are similar to trends in the southeastern United States, where herbicide-resistant (HR), particularly glyphosate-resistant (GR), Palmer amaranth has progressively become a troublesome weed to manage in cotton (*Gossypium hirsutum* L.), corn (*Zea mays* L.), and soybean production fields (Webster and Nichols 2012).

Palmer amaranth is a prolific seed producer despite competition with agronomic crops (Burke et al. 2007; Guo and Al-Khatib 2003; Massinga et al. 2001), with female plants producing ≥200,000 seeds per plant (Keeley et al. 1987; Scott and Smith 2011; Sellers et al. 2003). Palmer amaranth has the potential to produce high numbers of seed. Keeley et al. (1987) reported that Palmer amaranth could produce 200,000 to 600,000 seeds per plant, whereas Scott and Smith (2011) reported seed production from 150,000 to 200,000 seeds per plant when Palmer amaranth was grown under competition with cotton or soybean. However, Scott and Smith (2011) indicated that seed production of Palmer amaranth grown without competition can exceed 1.5 million seeds per plant. Like waterhemp (*Amaranthus tuberculatus* Sauer), Palmer amaranth has an extended emergence period (from May to September) in the southeastern United States (Jha et al. 2008), and from May to August in the midwestern United States (Spaunhorst et al. 2014). In addition, Palmer amaranth is a dioecious species primarily pollinated by wind (Franssen et al. 2001; Ward et al. 2013) that can transfer herbicide resistance alleles via pollen-mediated gene flow (Jhala et al. 2021).

Glyphosate, a broad-spectrum systemic herbicide, is the most widely used agricultural pesticide globally (Benbrook 2016). An estimated 8.6 billion kg of glyphosate was applied worldwide between 1974 and 2014, with the United States accounting for 19%, or 1.6 billion kg, of global usage (Benbrook 2016). Glyphosate use in the United States was estimated at 18 million kg per year in 1996, increasing to an estimated 125 million kg in 2013 (USGS 2020). The popularity of glyphosate can be attributed in large part to the widespread adoption of GR crops, low cost, broad spectrum of weed control, and flexibility with crop rotation without carryover injury (Woodburn 2000). Glyphosate was ranked as the most commonly used herbicide in GR corn-soybean cropping systems in Nebraska in a survey conducted in 2015 (Sarangi and Jhala 2018).

Increased reliance on herbicides resulting from the adoption of reduced/no-tillage cropping systems and continuous use of single site-of-action herbicides has led to the evolution of herbicide-resistant weeds (Chahal et al. 2017, 2018). As of 2020, a total of 262 weeds have evolved resistance to 23 of the 26 available herbicide sites of action (Heap 2020). In the United States, continued use of glyphosate in agronomic cropping systems has led to the evolution of resistance to the 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS) pathway in several weeds, including Palmer amaranth (Gaines et al. 2011). The first instance of GR Palmer amaranth was confirmed in Georgia in 2004 (Culpepper et al. 2006). Since then, GR Palmer amaranth has been confirmed in 39 states (Heap 2020), including Nebraska (Chahal et al. 2017; Vieira et al. 2018). Palmer amaranth biotypes resistant to synthetic auxin growth regulators, acetolactate synthase (ALS)-, photosystem II (PS II)-, hydroxyphenylpyruvate dioxygenase (HPPD)-, microtubule-, long chain fatty acid-, and protoporphyrinogen oxidase (PPO)-inhibiting herbicides have been reported (Heap 2020). A population of dicamba-resistant Palmer amaranth was identified in Tennessee in 2020 (Steckel 2020). Multiple herbicide-resistant Palmer amaranth populations have been reported in multiple states; for example, Schwartz-Lazaro et al. (2017) confirmed a Palmer amaranth population resistant to glyphosate, ALS-, PPO-, and microtubule-inhibiting herbicides in Arkansas. Jhala et al. (2014) reported atrazine and HPPD-inhibiting herbicide resistant Palmer amaranth in Nebraska. Kumar et al. (2019) confirmed Palmer amaranth resistant to atrazine, chlorsulfuron, 2,4-D, glyphosate, and mesotrione in Kansas.

While herbicides are currently the primary tool for weed control in agronomic crops in the United States, integration of nonchemical control methods (i.e., cultural, mechanical, and biological) could provide enhanced weed control. Previous studies have demonstrated the benefits of integrating cultural control methods such as tillage, crop rotation, crop density, row spacing, ground cover, and cover crops with herbicides for control of GR horseweed (*Conyza canadensis* L.), burclover (*Medicago polymorpha* L.), common lambsquarters (*Chenopodium album* L.), littleseed canarygrass (*Phalaris minor* Retz.), scarlet pimpernel (*Anagallis arvensis* L.), toothed dock (*Rumex dentatus* L.), and GR giant ragweed (*Ambrosia trifida* L. Bhullar et al. 2015; Chahal and Jhala 2019; Ganie et al. 2016). Narrow row spacing has been shown previously to enhance weed control and reduce weed seed production in GR soybean, glufosinate-resistant soybean, and sweet potato (Bell et al. 2015; Meyers et al. 2010; Whitaker et al. 2010).

The adoption of dicamba/glyphosate-resistant (DGR) soybean has been high since its commercialization, with Beckie et al. (2019) reporting >50% market share in the United States by 2019. This trend corresponds with survey results that reported that DGR soybean adoption increased from 20% in 2017 to almost 80% in 2019 in Nebraska (Chahal and Jhala 2019; Werle et al. 2018). Given the continued spread of HR weeds such as GR Palmer amaranth, this adoption trend is indicative of producers' search for alternative weed management options in soybean. Due to the lack of scientific literature on integration of narrow row spacing with dicamba-based herbicide programs for control of GR Palmer amaranth in DGR soybean, the objectives of this study were to determine the effects of soybean row spacing (38 or 76 cm) and herbicide programs for GR Palmer amaranth control, density, and biomass as well as soybean injury and yield in DGR soybean in a rainfed grower's field in Nebraska.

Materials and Methods

Study Site and Experimental Design

Field experiments were conducted during the summer of 2018 and 2019 in a grower's rainfed field in Thayer County, Carleton, NE (40.30°N, 97.67°W). The field was naturally infested with Palmer amaranth with 37-fold to 40-fold resistance to glyphosate (Chahal et al. 2017). The soil texture at the research site was Crete silt loam (montmorillonitic, mesic, Pachic Argiustolls) with a pH of 6.0, 19% sand, 63% silt, 18% clay, and 2.6% organic matter content. Palmer amaranth was the primary weed in the field with sporadic presence of horseweed, green foxtail (*Setaria viridis* P. Beauv.), and giant foxtail (*S. faberi* Herrm.).

The producer's field had been in a GR corn-soybean rotation with reliance on glyphosate for weed control in a no-till production system for the previous 10 yr. Corn residue from the previous cropping season was retained and the study was conducted using no-till practices. Paraquat (Gramoxone® SL; Syngenta Crop Protection, Greensboro, NC) at 840 g ai ha^{-1} plus 2,4-D ester (Weedone® LV6; Nufarm Inc., Burr Ridge, IL) at 386 g ae ha^{-1} plus a nonionic surfactant (Induce®; Helena Chemical, Collierville, TN) at 0.25% vol/vol was applied 2 wk before soybean planting with a tractor-mounted sprayer calibrated to deliver 140 L ha^{-1} at 276 kPa for control of winter annual weeds. Dicamba/glyphosate-resistant soybean (Northern King NK S29K3X) was planted on May 10, 2018, and May 15, 2019 at 346,000 seeds ha^{-1} at a depth of 3.0 cm.

Treatments were arranged in a randomized split-block design with four replications (Federer and King 2006). Herbicide programs were assigned as the whole plot factor (Table 1) in a randomized complete block, whereas row spacing (38 or 76 cm) was assigned as the subplot factor, which resulted in nonstandard incomplete "column" blocks, each containing 15 herbicide programs across the four replications. An incomplete blocking factor was added to simplify the field operation of planting soybean in 38-cm and 76-cm row spacing and reduce field traffic to avoid soil compaction. Plots were 3 m wide by 9 m long with four soybean rows spaced 76 cm apart or six soybean rows spaced 38 cm apart. In total, 15 herbicide programs were evaluated: two early-POST (EPOST), four EPOST followed by (fb) late-POST (LPOST), four

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Table 1. Herbicides and application timings, rates, and products used for control of glyphosate-resistant Palmer amaranth in dicamba/glyphosate-resistant soybean in field experiments conducted near Carleton, NE, in 2018 and 2019.

Herbicide program	Timing[a]	Rate[a]	Trade name	Manufacturer[b]	Adjuvants[a,c]
		(g ai/ae ha^{-1})			
Nontreated control	–	–	–	–	–
Dicamba	EPOST	560	XtendiMax	Bayer	DRA + WC
Glyphosate	EPOST	1,260	Roundup	Bayer	AMS
Dicamba	EPOST fb LPOST	560 fb 560	XtendiMax	Bayer	DRA + WC
fb dicamba			XtendiMax		DRA + WC
Glyphosate	EPOST fb LPOST	1,260	Roundup	Bayer	AMS
fb glyphosate		1,260	Roundup		AMS
Imazethapyr	EPOST fb LPOST	70	Pursuit	BASF	AMS
fb dicamba		560	XtendiMax	Bayer	DRA + WC
Imazethapyr + fomesafen/*S*-metolachlor fb dicamba	EPOST fb LPOST	70 + 1,480	Pursuit + Prefix	BASF, Syngenta	AMS + NIS
		560	XtendiMax	Bayer	DRA + WC
Dicamba	EPOST fb LPOST	560	XtendiMax	Bayer	DRA + WC
fb dicamba		560	XtendiMax		DRA + WC
Dicamba + chlorimuron/flumioxazin	PRE fb EPOST	560 + 85	XtendiMax + Rowel FX	Bayer	–
fb dicamba		560	XtendiMax		DRA + WC
Flumioxazin/metribuzin/pyroxasulfone fb dicamba	PRE fb EPOST	475	Fierce MTZ	Valent	–
		560	XtendiMax	Bayer	DRA + WC
Imazethapyr/pyroxasulfone/saflufenacil fb dicamba	PRE fb EPOST	135	Zidua PRO	BASF	–
		560	XtendiMax	Bayer	DRA + WC
Dicamba	PRE fb EPOST	560	XtendiMax	Bayer	DRA + WC
fb dicamba + acetochlor		560 + 1,600	XtendiMax + Warrant		DRA + WC
Dicamba + chlorimuron/flumioxazin	PRE fb EPOST + RH	560 + 85	XtendiMax + Rowel FX	Bayer	DRA + WC
fb dicamba + acetochlor		560 + 1,600	XtendiMax + Warrant		DRA + WC
Flumioxazin/metribuzin/pyroxasulfone	PRE fb EPOST + RH	475	Fierce MTZ	Valent	–
fb dicamba + acetochlor		560 + 1,600	XtendiMax + Warrant	Bayer	DRA + WC
Imazethapyr/pyroxasulfone/saflufenacil	PRE fb EPOST + RH	215	Zidua PRO	BASF	–
fb dicamba + acetochlor		560 + 1,600	XtendiMax + Warrant	Bayer	DRA + WC

[a]Abbreviations: ai, active ingredient; ae, acid equivalent; AMS, ammonium sulfate (N-Pak AMS Liquid, Winfield United, LLC., St. Paul, MN 55164); DRA, drift reducing agent (Intact, Precision Laboratories, Waukegan, IL 60085); EPOST, early POST-emergence; fb, followed by; LPOST, late POST-emergence; NIS, nonionic surfactant (Induce, Helena Chemical, Collierville, TN 38017); RH, residual herbicide; WC, water conditioner (Class Act Ridion, Winfield United, Arden Hills, MN, 55126).
[b]Bayer CropScience, Research Triangle Park, NC; BASF Corporation, Research Triangle Park, NC; Syngenta Crop Protection, LLC., Greensboro, NC; Valent USA Corporation, Walnut Creek, CA.
[c]AMS at 3% vol/vol, DRA at 0.5% vol/vol, NIS at 0.25% and WC at 1% vol/vol were mixed with herbicide treatments based on label recommendations.

PRE fb EPOST, four PRE fb EPOST plus a residual herbicide (RH), and a nontreated control (Table 1). PRE herbicides were applied on the same day after planting DGR soybean, and EPOST herbicides were applied on June 18, 2018, and June 25, 2019, when soybean was at the V3 to V4 growth stage and Palmer amaranth was 7.5 to 10.5 cm tall. LPOST herbicides were applied on July 6, 2018, and July 2, 2019, when soybean was at the R1 growth stage. The PRE, EPOST, and LPOST herbicides were applied using a handheld CO_2 pressurized backpack sprayer fitted with an AIXR 110015 flat-fan or TTI 11005 flat-angle nozzles (TeeJet®, Spraying Systems Co., Wheaton, IL) based on label requirements and calibrated to deliver 140 L ha^{-1} at 276 kPa.

Data Collection

Palmer amaranth control from PRE-applied herbicides was visually assessed 14 and 28 d after PRE (DAPRE) herbicide applications using a scale of 0% to 100%, with 0% representing no control and 100% representing complete control. Likewise, Palmer amaranth control from POST herbicides was visually assessed at 14 and 21 d after early-POST (DAEPOST) applications, 21 d after late-POST (DALPOST) applications, and prior to soybean harvest using the same scale at which PRE-applied herbicides were evaluated. Palmer amaranth density was recorded 14 DAPRE, 14 DAEPOST, and 14 DALPOST by counting Palmer amaranth plants in two 0.5-m^2 quadrats placed randomly between the two or four center soybean rows (76- or 38-cm row spacing, respectively) in each plot and converting to plants per square meter. Soybean injury was visually assessed at 14 DAPRE, 14 DAEPOST, and 14 DALPOST on a scale of 0% to 100%, with 0% representing no injury and 100% representing complete plant death. Aboveground biomass of Palmer amaranth was collected 14 DAEPOST and 21 DALPOST. Biomass samples were oven-dried at 65 C for 14 d, with Palmer amaranth aboveground biomass data converted into percent biomass reduction compared with the nontreated control using the following equation (Wortman 2014):

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

where C is equal to the aboveground biomass of the nontreated control plot and B is equal to the biomass of an individual treated plot. Soybean yield was taken from the center two or four rows in each plot (for 76- and 38-cm row spacing, respectively) using a plot combine (Gleaner K2; AGCO, Duluth, GA) and adjusted to 13% moisture content.

Statistical Analysis

Statistical analysis was performed using R statistical software version 4.0.3 (R Core Team 2018) using the GLMMTMB package (Brooks et al. 2017) and LME4 package (Bates et al. 2015), with subsequent contrast analysis preformed using the GMODELS package (Warnes et al. 2018). Year-by-treatment and year-by-treatment-by-row spacing interactions were evaluated, and if significant, data were analyzed separately by year. In the models separated by year, the interaction of herbicide treatment and row spacing were considered fixed effects, whereas the interaction of replication by herbicide treatment, column, and column by row spacing were considered random effects.

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Normality assumptions were tested for each variable using Shapiro-Wilk tests and Normal Q-Q plots. Total aboveground Palmer amaranth biomass reduction and Palmer amaranth control ratings were log(x+1) or logit-transformed and fit to generalized linear mixed-effect models using GLMMTMB functions with gaussian (link = "identity") and beta (link = "logit") error distributions, respectively (Stroup 2015). Likewise, soybean yield and weed density data were log(x+1) or square root transformed and fit to linear mixed-effect models using the *lmer* function (Kniss and Streibig 2018). Selection for final GLMMTMB models was based on model dispersion parameter estimates and Akaike information criterion (AIC) values, with log(x+1) or logit transformation with beta and gaussian error distributions selected for all response variables, respectively. Likewise, final *lmer* models were selected based on restricted maximum likelihood (REML) criterion at convergence values and AIC values. Prior to conducting ANOVA, variance assumptions were tested for each variable at $\alpha = 0.05$ using Bartlett and Fligner-Killen tests (Kniss and Streibig 2018). Variables that failed variance assumptions were subsequently assessed for outliers and heterogeneity of variance by plotting residual values (Knezevic et al. 2003; Ritz et al. 2015).

The ANOVA was performed using the CAR package (Fox and Weisberg 2019). For *lmer* models, ANOVA was conducted with Type III Wald *F*-tests, whereas GLMMTMB models used Type III Wald chi-square tests. After conducting ANOVA, treatment estimated marginal means were separated using the EMMEANS package (Lenth 2019) and MULTCOMP package (Hothorn et al. 2008). Estimated marginal means included post hoc Tukey P-value adjustments and Sidak method confidence-level adjustments, with compact letter display generated via the *multcomp:cld* function. A priori contrasts were performed using the GMODELS package (Warnes et al. 2018) to compare EPOST, EPOST fb LPOST, and PRE fb EPOST herbicide programs. In the first set of a priori contrasts, PRE fb EPOST programs were pooled together regardless of the inclusion of a RH at EPOST. Following these sets of contrasts, PRE fb EPOST herbicide programs were further separated into PRE fb EPOST, and PRE fb EPOST plus RH to evaluate the addition of acetochlor as an overlapping residual herbicide. Following treatment means separation and contrast analysis, data were back-transformed for the presentation of results.

Results and Discussion

Year-by-herbicide program-by-row spacing interactions were significant for all experimental variables; therefore, data were separated and presented by year.

Temperature and Precipitation

Growing conditions differed between the 2018 and 2019 growing seasons (Figure 1). In both years, field experiments were conducted under rainfed conditions. During 2018, cumulative precipitation received was below the 30-yr average (517 mm) for most of the growing season. In contrast, during 2019, cumulative precipitation received during the growing season exceeded the 30-yr average by 221 mm. Average daily temperatures in 2018 exceeded the 30-yr average during the early growing season, whereas they closely resembled the 30-yr average in 2019 (Figure 1). Herbicide programs evaluated in this study displayed excellent safety in DGR soybean, with no observable injury across both years (data not shown).

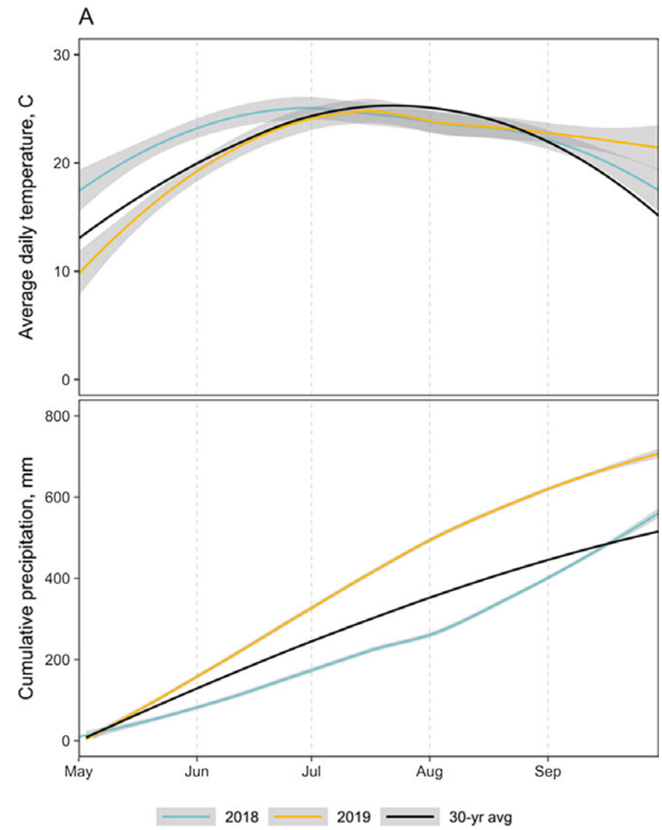

Figure 1. Average daily air temperature (ºC) and total cumulative precipitation (mm) received during the 2018 and 2019 growing seasons compared to the 30-year average for dryland field experiments conducted to determine the effect of row spacing and herbicide programs for control of glyphosate-resistant Palmer amaranth in dicamba/glyphosate-resistant soybean near Carleton, Nebraska, in 2018 and 2019.

Palmer Amaranth Control

Herbicides applied PRE controlled GR Palmer amaranth ≥95% in both years 14 DAPRE (Table 2). The PRE herbicides controlled Palmer amaranth 91% to 96% in 2018, whereas in 2019, flumioxazin/metribuzin/pyroxasulfone and imazethapyr/pyroxasulfone/saflufenacil provided 95% and 93% control, respectively, at 21 DAPRE. In 2019, dicamba plus chlorimuron/flumioxazin applied PRE controlled Palmer amaranth 80% compared to 45% control with dicamba (Table 2). Reduced control of Palmer amaranth with dicamba applied alone in 2019 can be attributed primarily to the shorter residual control by dicamba compared to other PRE herbicide programs evaluated as observed by Hedges et al. (2019). Efficacy of premixed and tank-mixed PRE herbicides with multiple effective sites of action on Palmer amaranth control were previously evaluated in soybean fields in Nebraska, with Striegel et al. (2020) and Shyam et al. (2021) reporting 93% to 99% control 14 and 28 DAPRE. Results from the current study are similar to those reported by Meyer et al. (2015), when flumioxazin/pyroxasulfone, metribuzin, dicamba, *S*-metolachlor, *S*-metolachlor/fomesafen, acetochlor, isoxaflutole, and *S*-metolachlor/mesotrione applied PRE provided 95% to 99% control of Palmer amaranth 21 DAPRE in field experiments conducted in Arkansas, Illinois, Indiana, Missouri, Nebraska, and Tennessee.

At 14 DAEPOST, the interaction of herbicide program-by-row spacing and the main effect of row spacing for Palmer amaranth control were not significant for either year. For both years, EPOST and EPOST fb LPOST herbicide programs provided

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Table 2. Effect of row spacing and herbicide programs on control of glyphosate-resistant Palmer amaranth in dicamba/glyphosate-resistant soybean 14 and 21 DAPRE in rainfed field experiments conducted near Carleton, NE, in 2018 and 2019.

PRE herbicide	Rate[a]	14 DAPRE[a,b,c,d]		21 DAPRE[a,b,c,d]	
		2018	2019	2018	2019
	(g ai/ae ha^{-1})	%			
Dicamba	560	97	99	91	45 c
Dicamba + chlorimuron/flumioxazin	560 + 85	96	99	95	80 b
Flumioxazin/metribuzin/pyroxasulfone	475	97	99	96	95 a
Imazethapyr/pyroxasulfone/saflufenacil	215	95	99	95	93 ab
Row spacing					
38 cm		96	99	96	84
76 cm		96	99	92	86
Treatment P-value		0.655	0.859	0.324	< 0.001
Row spacing P-value		0.195	0.999	0.097	0.131
Treatment*row spacing P-value		0.527	0.999	0.522	0.821

[a]Abbreviations: ai, active ingredient; ae, acid equivalent; DAPRE, days after pre-emergence herbicide; PRE, pre-emergence herbicide; RH, residual herbicide.
[b]PRE fb EPOST and PRE fb EPOST + RH treatments were combined (n = 8) for analysis of 14 and 28 DAPRE control.
[c]Data for each year were logit transformed before analysis; however back-transformed values are presented based on interpretations of transformed data.
[d]Means presented within the same column with no common letters are significantly different according to estimated marginal means with Sidak confidence-level adjustments and Tukey P-value adjustments.

reduced control of Palmer amaranth compared with PRE fb EPOST application of dicamba or dicamba plus acetochlor. Imazethapyr applied EPOST provided 15% and 4% Palmer amaranth control in 2018 and 2019, respectively. Likewise, EPOST or EPOST fb LPOST applications of glyphosate provided 10% to 30% control across both years. Reduced Palmer amaranth control with imazethapyr and glyphosate observed in this study can be attributed primarily to the prevalence of ALS-inhibitor-resistant and GR Palmer amaranth biotypes present at the study location (Chahal et al. 2017). In EPOST and EPOST fb LPOST herbicide programs where dicamba was applied, Palmer amaranth control from EPOST programs varied from 36% to 68% in 2018 and 85% to 89% in 2019 (Table 3). A priori contrasts comparing the main effect of herbicides on Palmer amaranth control were significant ($P < 0.05$) 14 DAEPOST for both years, with PRE fb EPOST herbicide programs providing 90% and 99% Palmer amaranth control in 2018 and 2019, respectively. The addition of acetochlor with EPOST herbicides increased Palmer amaranth control 14 DAEPOST in 2018 and 2019 (88% vs. 93% and 83% vs. 94%, respectively).

At 21 DAEPOST, PRE fb EPOST and PRE fb EPOST + RH (acetochlor) programs controlled Palmer amaranth 84% to 97% in both years, with comparable control also provided by most EPOST or EPOST fb LPOST dicamba applications (Table 3). Conversely, glyphosate provided 36% to 43% control in 2018 and 7% to 8% control in 2019. This indicates the level of glyphosate resistance and demonstrates that even two applications of glyphosate could not provide >45% control. Imazethapyr applied EPOST controlled Palmer amaranth by 58% in 2018 and by 3% in 2019, whereas mixing fomesafen/*S*-metolachlor with imazethapyr improved control to 75% and 61% 21 DAEPOST in 2018 and 2019, respectively (Table 3). A priori contrasts comparing the main effects of herbicide programs on Palmer amaranth control were significant ($P < 0.001$) 21 DAEPOST, with PRE fb EPOST and PRE fb EPOST + RH providing the highest Palmer amaranth control. Averaged across PRE herbicides, mixing acetochlor with dicamba applied EPOST increased Palmer amaranth control 21 DAEPOST in 2018 (97%) compared to dicamba alone (92%), but not in 2019 (Table 3).

At 21 DALPOST, most PRE fb EPOST and PRE fb EPOST + RH programs continued to provide 91% to 99% Palmer amaranth control in 2018, with the exception of dicamba PRE fb dicamba EPOST (84%), results for which were similar to those of EPOST-only programs (82%). In contrast, dicamba applied EPOST fb LPOST controlled Palmer amaranth by 91%, similar to that controlled by PRE fb EPOST programs. These results were similar at 21 DALPOST in 2019, with PRE fb EPOST, PRE fb EPOST + RH, and stand-alone applications of dicamba applied EPOST or EPOST fb LPOST providing 85% to 95% control of Palmer amaranth. Dicamba applied LPOST following imazethapyr or imazethapyr plus fomesafen/*S*-metolachlor applied EPOST controlled Palmer amaranth by 58% to 85%.

A priori contrasts comparing the main effects of herbicide programs on Palmer amaranth control were significant 21 DALPOST with PRE fb EPOST herbicide programs providing ≥92% Palmer amaranth control. Tank-mixing acetochlor with POST herbicides increased Palmer amaranth control 21 DALPOST (Table 3). In 2018, the interaction of herbicide program by row spacing was significant ($P < 0.001$) for Palmer amaranth control 21 DALPOST, although comparisons of estimated marginal means across row spacing was only significant for EPOST applications of glyphosate, which provided 53% and 26% Palmer amaranth control in 38- and 76-cm row spacing, respectively (Table 4). In both years, contrasts comparing the main effects of herbicide programs on Palmer amaranth control were significant 21 DALPOST, with PRE fb EPOST herbicide programs providing 92% and 88% control in 2018 and 2019, respectively. Mixing acetochlor with POST herbicides increased Palmer amaranth control 21 DALPOST (Table 3). The increased Palmer amaranth control via the inclusion of acetochlor as an overlapping residual herbicide is similar to results reported by Sarangi and Jhala (2019) in which overlapping residual herbicides increased Palmer amaranth control and biomass reductions in conventional soybean 28 DAPOST in a field study in Nebraska.

Prior to soybean harvest, most PRE fb EPOST and PRE fb EPOST + RH programs controlled GR Palmer amaranth by 91% to 99%, with the exception of dicamba fb dicamba in 2018, which provided 76% control (Table 5). These results are similar to those reported by Bell et al. (2015) in a 2-yr study in which

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Table 3. Control of glyphosate-resistant Palmer amaranth at 14 and 21 DAEPOST and 21 DALPOST in dryland field experiments conducted near Carleton, NE to determine the effect of row spacing and herbicide programs in dicamba/glyphosate-resistant soybean in 2018 and 2019.

Herbicide Program	Timing	14 DAEPOST [a,b,c]		21 DAEPOST [a,b,c]		21 DALPOST [a,b,c]	
		2018	2019	2018	2019	2018	2019
		%					
Nontreated control	–	0	0	0	0	0	0
Dicamba	EPOST	36 d	85 abc	90 ab	94 a	82 cd	95 a
Glyphosate	EPOST	30 d	13 d	43 ef	5 c	38 f	2 c
Dicamba fb dicamba	EPOST fb LPOST	68 bc	89 abc	91 ab	94 a	91 abc	95 a
Glyphosate fb glyphosate	EPOST fb LPOST	21 d	10 d	36 f	5 c	37 f	9 c
Imazethapyr fb dicamba	EPOST fb LPOST	15 d	4 d	58 de	3 c	58 e	48 b
Imazethapyr + fomesafen/*S*-metolachlor fb dicamba	EPOST fb LPOST	64 c	72 c	75 cd	59 b	74 d	85 ab
Dicamba fb dicamba	PRE fb EPOST	79 abc	81 bc	86 bc	90 ab	84 bcd	90 a
Dicamba + chlorimuron/flumioxazin fb dicamba	PRE fb EPOST	90 abc	86 abc	95 ab	96 a	96 abc	96 a
Flumioxazin/metribuzin/pyroxasulfone fb dicamba	PRE fb EPOST	92 ab	95 ab	96 a	96 a	98 ab	87 ab
Imazethapyr/pyroxasulfone/saflufenacil fb dicamba	PRE fb EPOST	89 abc	94 abc	92 ab	91 ab	91 abc	86 ab
Dicamba fb dicamba + acetochlor	PRE fb EPOST + RH	92 ab	89 abc	94 ab	89 a	94 abc	85 ab
Dicamba + chlorimuron/flumioxazin fb dicamba + acetochlor	PRE fb EPOST + RH	93 ab	89 abc	96 a	84 ab	97 ab	89 a
Flumioxazin/metribuzin/pyroxasulfone fb dicamba + acetochlor	PRE fb EPOST + RH	95 a	96 a	97 a	94 a	99 a	93 a
Imazethapyr/pyroxasulfone/saflufenacil fb dicamba + acetochlor	PRE fb EPOST + RH	92 ab	90 abc	96 a	88 ab	98 ab	93 a
Row spacing							
38 cm		69	76	89	75	81	83
76 cm		68	77	87	75	78	78
Treatment P-value		< 0.001	0.020	< 0.001	< 0.001	< 0.001	< 0.001
Row spacing P-value		0.599	0.891	0.959	0.611	0.052	0.461
Treatment*row spacing P-value		0.980	0.263	0.182	0.995	< 0.001	0.163
Contrasts[d]							
EPOST vs EPOST fb LPOST		32 vs 42 ***	NS	NS	NS	NS	NS
EPOST vs PRE fb EPOST		32 vs 90 ***	81 vs 99 ***	66 vs 94 ***	47 vs 93 ***	61 vs 94 ***	48 vs 92 ***
EPOST fb LPOST vs PRE fb EPOST		42 vs 90 ***	81 vs 99 ***	64 vs 94 ***	37 vs 93 ***	65 vs 94 ***	59 vs 92 ***
PRE fb EPOST vs. PRE fb EPOST + RH		88 vs 93 ***	83 vs 94 *	92 vs 97 ***	NS	92 vs 97 ***	88 vs 96 *

[a]Abbreviations: DAEPOST, days after early-POST emergence; DALPOST, days after late-POST emergence; DAPRE, days after pre-emergence; EPOST, early-POST emergence; fb, followed by; LPOST, late-POST emergence; RH, residual herbicide.
[b]Data for each year were logit transformed before analysis; however back-transformed values are presented based on interpretations of transformed data.
[c]Means presented within the same column with no common letters are significantly different according to estimated marginal means with Sidak confidence-level adjustments and Tukey P-value adjustments.
[d]A priori contrasts; * = significant ($P < 0.05$); **= significant ($P < 0.01$); ***= significant ($P < 0.001$); NS, nonsignificant ($P \geq 0.05$)

herbicide programs receiving PRE herbicides controlled Palmer amaranth by ≥95% regardless of row spacing when evaluated prior to harvest. The EPOST and EPOST fb LPOST applications of dicamba provided similar control to PRE fb EPOST herbicide programs, with the exception of dicamba applied EPOST in 2018 (72%). As observed at 21 DALPOST, imazethapyr fb dicamba and imazethapyr mixed with fomesafen/*S*-metolachlor fb dicamba provided 60% to 78% Palmer amaranth control. A priori contrasts comparing the main effects of herbicide programs on Palmer amaranth control were significant for preharvest Palmer amaranth control with PRE fb EPOST herbicide programs providing 92% to 99% Palmer amaranth control. Mixing acetochlor with EPOST herbicide increased Palmer amaranth control at preharvest in 2018, but not in 2019 (Table 5). While the effect of acetochlor applied POST in soybean is well documented (Bell et al. 2015; Manuchehri et al. 2017; Sarangi and Jhala 2018), the effect of including acetochlor with dicamba in DGR soybean applied POST for Palmer amaranth control is limited. The inconsistency of preharvest Palmer amaranth control with acetochlor has been reported elsewhere. For example, Spaunhorst et al. (2014) reported that the inclusion of acetochlor applied EPOST or LPOST did not provide additional control of waterhemp compared to programs without acetochlor in DGR soybean in Missouri. Likewise, including acetochlor in an overlapping residual herbicide program did not increase Palmer amaranth control compared to programs lacking acetochlor in cotton (Manuchehri et al. 2017). In contrast, research conducted in Nebraska with multiple HR Palmer amaranth in corn has indicated that acetochlor applied POST in a PRE fb POST herbicide program was an effective management strategy (Chahal et al. 2018). An important distinction to note is that the inclusion of acetochlor with POST herbicides did not result in reduced Palmer amaranth control (via antagonistic effects) compared to corresponding programs that did not include acetochlor.

Palmer Amaranth Biomass Reduction

The main effect of row spacing and the interaction of herbicide-by-row spacing were not significant 14 DAEPOST in 2018 (Table 6). The PRE fb EPOST and PRE fb EPOST plus RH programs provided the highest reduction of Palmer amaranth biomass (91% to 100%) compared to EPOST (23% to 78%) and EPOST fb

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Table 4. Interaction of herbicide programs and row spacing (38 cm or 76 cm) for control of glyphosate-resistant Palmer amaranth at 21 DAEPOST and 21 DALPOST and biomass reduction at pre-harvest in rainfed field experiments conducted near Carleton, NE, in dicamba/glyphosate-resistant soybean in 2018 and 2019.

Herbicide program	Timing	2018[a,b,c] 21 DALPOST control		2019[a,b,c] Preharvest biomass reduction	
		38 cm	76 cm	38 cm	76 cm
		———————%———————			
Nontreated control	–	–	–	–	–
Dicamba	EPOST	87 abcd	76 cde	34 abc	91 a
Glyphosate	EPOST	53 fg	26 i	2 c	3 c
Dicamba fb dicamba	EPOST fb LPOST	95 abc	88 abc	100 a	100 a
Glyphosate fb glyphosate	EPOST fb LPOST	31 hi	42 gh	74 ab	20 bc
Imazethapyr fb dicamba	EPOST fb LPOST	54 fg	62 ef	100 a	100 a
Imazethapyr + fomesafen/*S*-metolachlor fb dicamba	EPOST fb LPOST	70 def	79 bcde	100 a	100 a
Dicamba fb dicamba	PRE fb EPOST	88 abc	80 abcd	100 a	100 a
Dicamba + chlorimuron/flumioxazin fb dicamba	PRE fb EPOST	96 ab	95 abc	96 a	94 a
Flumioxazin/metribuzin/pyroxasulfone fb dicamba	PRE fb EPOST	99 ab	97 ab	100 a	100 a
Imazethapyr/pyroxasulfone/saflufenacil fb dicamba	PRE fb EPOST	95 abc	87 abcd	100 a	100 a
Dicamba fb dicamba + acetochlor	PRE fb EPOST + RH	93 abc	94 abc	100 a	100 a
Dicamba + chlorimuron/flumioxazin fb dicamba + acetochlor	PRE fb EPOST + RH	99 a	94 abc	100 a	100 a
Flumioxazin/metribuzin/pyroxasulfone fb dicamba + acetochlor	PRE fb EPOST + RH	99 a	98 a	100 a	100 a
Imazethapyr/pyroxasulfone/saflufenacil fb dicamba + acetochlor	PRE fb EPOST + RH	98 ab	98 ab	100 a	100 a
Treatment*row spacing P-value		< 0.001		0.004	

[a]Abbreviations: GR, glyphosate-resistant; DGR, dicamba/glyphosate-resistant; DAEPOST, days after early-POST emergence herbicide; DALPOST, days after late-POST emergence herbicide; DAPRE, days after pre-emergence herbicide; EPOST, early-POST emergence herbicide; fb, followed by; LPOST, late-POST emergence herbicide; PRE, pre-emergence herbicide; RH, residual herbicide.
[b]Data for each year were logit transformed before analysis; however back-transformed values are presented based on interpretations of transformed data.
[c]Means presented within the same column with no common letters are significantly different according to estimated marginal means with Sidak confidence-level adjustments and Tukey P-value adjustments.

Table 5. Pre-harvest control of glyphosate-resistant Palmer amaranth and soybean yield in rainfed field experiments conducted near Carleton, NE to determine the effect of row spacing and herbicide program in dicamba/glyphosate-resistant soybean in 2018 and 2019.

Herbicide Program	Timing	Palmer amaranth control[a,b,c]		Soybean yield (±SEM)[a,b,c]	
		2018	2019	2018	2019
		———%———		———kg ha^{-1}———	
Nontreated control	–	0	0	379 ± 51 cd	2,284 ± 199 c
Dicamba	EPOST	72 b	95 a	655 ± 85 abc	4,220 ± 368 ab
Glyphosate	EPOST	28 c	4 c	459 ± 61 bcd	3,176 ± 269 bc
Dicamba fb dicamba	EPOST fb LPOST	90 a	96 a	564 ± 75 abcd	4,613 ± 390 a
Glyphosate fb glyphosate	EPOST fb LPOST	39 c	10 c	314 ± 42 d	4,396 ± 383 ab
Imazethapyr fb dicamba	EPOST fb LPOST	60 b	63 b	357 ± 46 d	3,647 ± 318 ab
Imazethapyr + fomesafen/*S*-metolachlor fb dicamba	EPOST fb LPOST	74 b	78 b	572 ± 77 abcd	5,037 ± 439 a
Dicamba fb dicamba	PRE fb EPOST	76 b	99 a	695 ± 93 abc	4,350 ± 377 ab
Dicamba + chlorimuron/flumioxazin fb dicamba	PRE fb EPOST	92 a	99 a	835 ± 108 ab	4,479 ± 390 ab
Flumioxazin/metribuzin/pyroxasulfone fb dicamba	PRE fb EPOST	96 a	99 a	895 ± 116 a	4,997 ± 436 a
Imazethapyr/pyroxasulfone/saflufenacil fb dicamba	PRE fb EPOST	91 a	99 a	929 ± 125 a	4,765 ± 414 a
Dicamba fb dicamba + acetochlor	PRE fb EPOST + RH	93 a	99 a	825 ± 107 ab	4,358 ± 381 ab
Dicamba + chlorimuron/flumioxazin fb dicamba + acetochlor	PRE fb EPOST + RH	95 a	99 a	896 ± 132 a	4,950 ± 432 a
Flumioxazin/metribuzin/pyroxasulfone fb dicamba + acetochlor	PRE fb EPOST + RH	97 a	99 a	925 ± 120 a	5,105 ± 443 a
Imazethapyr/pyroxasulfone/saflufenacil fb dicamba + acetochlor	PRE fb EPOST + RH	96 a	99 a	847 ± 110 ab	4,653 ± 393 a
Row spacing					
38 cm		84	91	466 ± 37	4,607 ± 238 a
76 cm		86	89	871 ± 70	3,930 ± 203 b
Treatment P-value		< 0.001	< 0.001	< 0.001	< 0.001
Row spacing P-value		0.595	0.399	0.521	0.003
Herbicide*row spacing P-value		0.053	0.672	0.179	0.793
Contrasts[d]					
EPOST vs. EPOST fb LPOST		53 vs 66 *	53 vs 61 *	NS	3,824 vs 4,536 **
EPOST vs. PRE fb EPOST		53 vs 92 ***	53 vs 99 ***	598 vs 938 ***	3,824 vs 4,753 ***
EPOST fb LPOST vs. PRE fb EPOST		66 vs 92 ***	61 vs 99 ***	507 vs 938 ***	NS
PRE fb EPOST vs. PRE fb EPOST + RH		88 vs 96 ***	NS	NS	NS

[a]Abbreviations: EPOST, early-POST emergence; fb, followed by; LPOST, late-POST emergence; RH, residual herbicide; SEM, standard error of the mean.
[b]Data for each year were log or logit transformed before analysis; however back-transformed values are presented based on interpretations of transformed data.
[c]Means presented within the same column with no common letters are significantly different according to estimated marginal means with Sidak confidence-level adjustments and Tukey P-value adjustments.
[d]A priori contrasts; * = significant ($P < 0.05$); **= significant ($P < 0.01$); ***= significant ($P < 0.001$); NS, nonsignificant ($P \geq 0.05$).

Table 6. Effect of row spacing and herbicide programs on glyphosate-resistant Palmer amaranth biomass reduction at 14 DAEPOST, 14 DALPOST, and pre-harvest in rainfed field experiments conducted near Carleton, NE in dicamba/glyphosate-resistant soybean in 2018 and 2019.

Herbicide program	Timing	14 DAEPOST [a,b,c] 2018	14 DAEPOST [a,b,c] 2019	14 DALPOST [a,b,c] 2019	Preharvest [a,b,c] 2019
		%			
Nontreated control	–	–	–	–	–
Dicamba	EPOST	78 ab	85 a	98 a	60 ab
Glyphosate	EPOST	23 d	23 b	7 b	3 c
Dicamba fb dicamba	EPOST fb LPOST	68 abc	78 a	99 a	104 a
Glyphosate fb glyphosate	EPOST fb LPOST	22 d	29 b	40 ab	44 b
Imazethapyr fb dicamba	EPOST fb LPOST	33 cd	0 b	61 ab	106 a
Imazethapyr + fomesafen/*S*-metolachlor fb dicamba	EPOST fb LPOST	59 bcd	73 a	44 ab	100 a
Dicamba fb dicamba	PRE fb EPOST	91 ab	96 a	84 a	100 a
Dicamba + chlorimuron/flumioxazin fb dicamba	PRE fb EPOST	98 ab	85 a	85 ab	95 a
Flumioxazin/metribuzin/pyroxasulfone fb dicamba	PRE fb EPOST	97 ab	99 a	101 a	100 a
Imazethapyr/pyroxasulfone/saflufenacil fb dicamba	PRE fb EPOST	88 ab	100 a	85 a	100 a
Dicamba fb dicamba + acetochlor	PRE fb EPOST + RH	97 ab	96 a	77 ab	100 a
Dicamba + chlorimuron/flumioxazin fb dicamba + acetochlor	PRE fb EPOST + RH	95 ab	97 a	96 a	100 a
Flumioxazin/metribuzin/pyroxasulfone fb dicamba + acetochlor	PRE fb EPOST + RH	100 a	99 a	100 a	100 a
Imazethapyr/pyroxasulfone/saflufenacil fb dicamba + acetochlor	PRE fb EPOST + RH	96 ab	98 a	100 a	100 a
Row spacing					
38 cm		80	74	80	84 a
76 cm		70	76	74	83 a
Treatment P-value		< 0.001	< 0.001	0.047	< 0.001
Row Spacing P-value		0.554	0.299	0.960	0.010
Treatment*Row Spacing P-value		0.108	0.212	0.173	0.128
Contrasts[d]					
EPOST vs. EPOST fb LPOST		NS	NS	NS	36 vs 91 ***
EPOST vs. PRE fb EPOST		45 vs 95 ***	54 vs 97 ***	53 vs 90 **	36 vs 100 ***
EPOST fb LPOST vs. PRE fb EPOST		50 vs 95 ***	43 vs 97 ***	62 vs 90 **	NS
PRE fb EPOST vs. PRE fb EPOST + RH		NS	94 vs 99 *	NS	NS

[a]Abbreviations: DAEPOST, days after early-POST emergence; DALPOST, days after late-POST emergence; EPOST, early-POST emergence; fb, followed by; LPOST, late-POST emergence; RH, residual herbicide.
[b]Data for each year were logit transformed before analysis; however back-transformed values are presented based on interpretations of transformed data.
[c]Means presented within the same column with no common letters are significantly different according to estimated marginal means with Sidak confidence-level adjustments and Tukey P-value adjustments.
[d]A priori contrasts; * = significant ($P < 0.05$); **= significant ($P < 0.01$); ***= significant ($P < 0.001$); NS, nonsignificant ($P \geq 0.05$).

LPOST (22% to 68%) 14 DAEPOST (Table 6). A priori contrasts in 2018 comparing the main effect of herbicide programs on Palmer amaranth biomass reduction were significant, with PRE fb EPOST programs providing the greatest reduction of Palmer amaranth biomass. The addition of acetochlor as an RH was not significant 14 DAEPOST in 2018 (Table 6).

A priori contrasts in 2019 comparing the main effect of herbicide program on Palmer amaranth biomass reduction were significant 14 DAEPOST and 14 DALPOST, with PRE fb EPOST programs providing 97% and 90% biomass reductions, respectively. The addition of acetochlor as an RH was significant 14 DAEPOST in 2019 (99% vs. 94% biomass reduction), but not 14 DALPOST ($P < 0.05$; Table 6). Acetochlor has been previously shown to provide >80% control of Palmer amaranth up to 50 d after application (Cahoon et al. 2015), while mixing acetochlor with glufosinate has been shown to provide ≥93% biomass reduction of GR common ragweed (*Ambrosia artemisiifolia* L.) in glufosinate-resistant soybean (Barnes et al. 2017) and ≥84% control applied alone or tank-mixed with fluometuron, diuron, fomesafen, or diuron/fomesafen (Cahoon et al. 2015).

Prior to harvest in 2019 (e.g., 88 DALPOST), PRE fb EPOST and PRE fb EPOST plus RH programs reduced Palmer amaranth biomass by 98% to 100%. The EPOST fb LPOST programs, excluding glyphosate fb glyphosate (62%), reduced Palmer amaranth biomass 100%, whereas glyphosate and dicamba applied EPOST reduced Palmer amaranth biomass only 2% and 68%, respectively (Table 6). A priori contrasts comparing the main effects of herbicide program for Palmer amaranth biomass reduction were significant, with PRE fb EPOST and EPOST fb LPOST programs providing similar reductions of Palmer amaranth biomass (Table 6). The interaction of herbicide program by row spacing on Palmer amaranth biomass reduction was significant ($P = 0.026$) at preharvest in 2019, with most herbicide programs providing similar biomass reductions with the exception of dicamba applied EPOST (97% and 40% biomass reductions for 38-cm and 76-cm row spacings, respectively) and glyphosate applied EPOST fb LPOST (76% and 48% biomass reductions for 38-cm and 76-cm row spacing, respectively; Table 4). The effect of row spacing on Palmer amaranth biomass reduction in herbicide programs consisting of dicamba applied EPOST and glyphosate applied EPOST fb LPOST can be partially attributed to the effects that narrower row spacing has on achieving canopy closure more quickly compared to wider row spacing. With rapid canopy closure, late-emerging Palmer amaranth growth is suppressed, limiting biomass and seed production (Buehring et al. 2002; Jha and Norsworthy 2009; Norsworthy et al. 2007).

Palmer Amaranth Density

Palmer amaranth density was higher in EPOST and EPOST fb LPOST herbicide programs compared to programs containing PRE herbicides 14 DAEPOST in both years (Table 7). However, the interaction of herbicide by row spacing was significant 14 DAEPOST ($P = 0.028$ and $P = 0.04$, respectively), although after

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Table 7. Effect of row spacing and herbicide programs on glyphosate-resistant Palmer amaranth density at 14 DAEPOST and 14 DALPOST in rainfed field experiments conducted near Carleton, NE in dicamba/glyphosate-resistant soybean in 2018 and 2019.

Herbicide Program	Timing	14 DAEPOST [a,b,c]		14 DALPOST [a,b,c]
		2018	2019	2019
		plants m^{-2}		
Nontreated control	–	145 e	212 cd	30
Dicamba	EPOST	118 de	85 cd	2
Glyphosate	EPOST	155 e	365 cd	56
Dicamba fb dicamba	EPOST fb LPOST	147 e	75 cd	0
Glyphosate fb glyphosate	EPOST fb LPOST	161 e	575 d	36
Imazethapyr fb dicamba	EPOST fb LPOST	175 e	804 d	35
Imazethapyr + fomesafen/*S*-metolachlor fb dicamba	EPOST fb LPOST	69 de	30 bc	10
dicamba fb dicamba	PRE fb EPOST	86 de	12 bc	7
dicamba + chlorimuron/flumioxazin fb dicamba	PRE fb EPOST	9 bc	2 ab	6
Flumioxazin/metribuzin/pyroxasulfone fb dicamba	PRE fb EPOST	0 a	0 a	0
Imazethapyr/pyroxasulfone/saflufenacil fb dicamba	PRE fb EPOST	9 bc	0 a	6
Dicamba fb dicamba + acetochlor	PRE fb EPOST + RH	21 cd	0 a	13
Dicamba + chlorimuron/flumioxazin fb dicamba + acetochlor	PRE fb EPOST + RH	3 abc	0 a	1
Flumioxazin/metribuzin/pyroxasulfone fb dicamba + acetochlor	PRE fb EPOST + RH	2 ab	0 a	0
Imazethapyr/pyroxasulfone/saflufenacil fb dicamba + acetochlor	PRE fb EPOST + RH	4 abc	0 a	0
Treatment P-value		< 0.001	< 0.001	0.178
Row spacing				
38 cm		28	13	1 a
76 cm		29	14	15 b
Row spacing P-value		0.065	0.383	0.002
Treatment*row spacing P-value		0.028	0.040	0.083
Contrasts[d]				
EPOST vs. EPOST fb LPOST		NS	325 vs 497 *	NS
EPOST vs. PRE fb EPOST		199 vs 32 ***	325 vs 3 ***	123 vs 25 **
EPOST fb LPOST vs. PRE fb EPOST		162 vs 32 ***	497 vs 3 ***	133 vs 25 ***
PRE fb EPOST vs. PRE fb EPOST + RH		NS	NS	NS

[a]Abbreviations: DAEPOST, days after early-POST emergence; DALPOST, days after late-POST emergence; EPOST, early-POST emergence; fb, followed by; LPOST, late-POST emergence; RH, residual herbicide.
[b]Data for each year were square root or log transformed before analysis; however back-transformed values are presented based on interpretations of transformed data.
[c]Means presented within the same column with no common letters are significantly different according to estimated marginal means with Sidak confidence-level adjustments and Tukey P-value adjustments.
[d]A priori contrasts; * = significant ($P < 0.05$); **= significant ($P < 0.01$); ***= significant ($P < 0.001$); NS, nonsignificant ($P \geq 0.05$).

adjusting for multiple comparisons, estimated marginal mean groupings were similar for herbicide programs and row spacing (Table 8). This is likely attributed to the large variance in Palmer amaranth densities across herbicide programs and row spacings, or the conservative nature of post hoc Tukey P-value adjustments and Sidak method confidence-level adjustments used during estimated marginal mean separation. For the analysis of main effects, a priori contrasts comparing Palmer amaranth density 14 DAEPOST for both years were significant with reduced Palmer amaranth density in PRE fb EPOST herbicide programs compared to EPOST and EPOST fb LPOST herbicide programs. The addition of acetochlor with a POST herbicide did not reduce Palmer amaranth density in PRE fb EPOST herbicide programs, indicating that an RH at EPOST is not needed in every field and that careful herbicide selection is necessary based on weed density and moisture availability to avoid extra cost (Table 7).

At 14 DALPOST in 2019 (e.g., 36 DAEPOST), density of Palmer amaranth was not significant by herbicide or herbicide-by-row spacings. Row spacing was significant ($P = 0.002$), with 1.0 Palmer amaranth plant per square meter in 38-cm row spacing compared with 15 Palmer amaranth plants in 76-cm row spacing across the herbicide programs evaluated. Mixing acetochlor did not reduce Palmer amaranth density compared to PRE fb EPOST herbicide programs without acetochlor (Table 7). Inclusively, findings from the current study at 14 DALPOST are similar to the results reported by Spaunhorst et al. (2014) that acetochlor with EPOST or LPOST herbicides did not reduce waterhemp density in DGR soybean in Missouri compared to EPOST and LPOST herbicides that did not include acetochlor.

Soybean Yield

Due to drought conditions during a majority of the growing season in 2018, soybean yield was reduced compared with 2019 (Figure 1; Table 5). In 2018, the main effect of herbicide program was significant for soybean yield, whereas row spacing and the interaction effect of herbicide-by-row spacing were not significant. Yield was consistently higher in PRE fb EPOST (695 kg ha^{-1}) and PRE fb EPOST plus RH programs (925 kg ha^{-1}) compared to most EPOST and EPOST fb LPOST herbicide programs with the exception of dicamba applied EPOST (655 ± 55 kg ha^{-1}) and dicamba applied EPOST fb LPOST (564 ± 75 kg ha^{-1}). A priori contrasts comparing soybean yield in 2018 were significant, with the highest yield occurring in treatments that received PRE fb EPOST herbicides, which is consistent with literature indicating the economic importance of PRE fb POST herbicide programs (Barnes et al. 2017; Rosenbaum et al. 2013) as well as multiple applications to control Palmer amaranth (Cahoon et al. 2015).

The main effects of row spacing and herbicide programs were significant for soybean yield, with 4,607 ± 238 and 3,930 ± 203 kg ha^{-1} in 38-cm and 76-cm row spacing, respectively, in 2019 (Table 5). Across row spacings, soybean yield was similar for most herbicide programs, excluding glyphosate applied EPOST (3,176 ± 269 kg ha^{-1}). Wax and Pendleton (1968) reported soybean yield

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Table 8. Interaction of herbicide programs and row spacing for glyphosate-resistant Palmer amaranth density at 14 DAEPOST in rainfed field experiments conducted near Carleton, NE in dicamba/glyphosate-resistant soybean in 2018 and 2019.

Herbicide program	Timing	2018 [a,b,c] 14 DAEPOST 38 cm	2018 [a,b,c] 14 DAEPOST 76 cm	2019 [a,b,c] 14 DAEPOST 38 cm	2019 [a,b,c] 14 DAEPOST 76 cm
		plants m^{-2}			
Nontreated control	–	290 h	72 e-h	294 def	153 c-f
Dicamba	EPOST	144 gh	97 e-h	146 c-f	49 b-f
Glyphosate	EPOST	75 e-h	316 h	415 ef	319 def
Dicamba fb dicamba	EPOST fb LPOST	178 h	121 fgh	211 def	26 a-f
Glyphosate fb glyphosate	EPOST fb LPOST	116 fgh	222 h	707 f	466 ef
Imazethapyr fb dicamba	EPOST fb LPOST	291 h	106 fgh	840 f	770 f
Imazethapyr + fomesafen/*S*-metolachlor fb dicamba	EPOST fb LPOST	124 fgh	38 c-h	17 a-e	54 b-f
Dicamba fb dicamba	PRE fb EPOST	78 e-h	96 e-h	10 a-d	14 a-d
Dicamba + chlorimuron/flumioxazin fb dicamba	PRE fb EPOST	22 b-h	3 a-d	0 a	4 abc
Flumioxazin/metribuzin/pyroxasulfone fb dicamba	PRE fb EPOST	0 a	1 ab	0 a	0 a
Imazethapyr/pyroxasulfone/saflufenacil fb dicamba	PRE fb EPOST	10 a-g	7 a-f	0 a	0 a
Dicamba fb dicamba + acetochlor	PRE fb EPOST + RH	9 a-g	49 d-h	0 a	0 a
Dicamba + chlorimuron/flumioxazin fb dicamba + acetochlor	PRE fb EPOST + RH	1 abc	6 a-e	0 a	1 ab
Flumioxazin/metribuzin/pyroxasulfone fb dicamba + acetochlor	PRE fb EPOST + RH	1 ab	3 a-d	1 ab	0 a
Imazethapyr/pyroxasulfone/saflufenacil fb dicamba + acetochlor	PRE fb EPOST + RH	2 abc	9 a-g	0 a	0 a
Herbicide*row spacing P-value		0.028		0.040	

[a]Abbreviations: DAEPOST, days after early-POST emergence; DALPOST, days after late-POST emergence; EPOST, early-POST emergence; fb, followed by; LPOST, late-POST emergence; RH, residual herbicide.
[b]Data for each year were logit transformed before analysis; however back-transformed values are presented based on interpretations of transformed data.
[c]Means presented within the same column with no common letters are significantly different according to estimated marginal means with Sidak confidence-level adjustments and Tukey P-value adjustments.

increases of 10%, 18%, and 20% in 76-cm, 50-cm, and 25-cm row spacing compared with 101-cm row spacing in field experiments conducted in Illinois. A priori contrasts comparing soybean yield in 2019 were significant with the highest yield in PRE fb EPOST or EPOST fb LPOST herbicide programs, indicating the importance of using PRE herbicide programs in DGR soybean; however, mixing acetochlor with POST herbicides did not result in increased soybean yield (Table 5). While soybean grain yield reduction of up to 79% due to Palmer amaranth interference has previously been reported (Bensch et al. 2003; Klingaman and Oliver 1994; Monks and Oliver 1988), the control of Palmer amaranth provided by most of the herbicide programs in this research was substantial enough to avoid the yield reductions that occurred to the nontreated control (2,284 kg ± 199 kg ha^{-1}).

Practical Implications

Results of this study indicate that herbicide programs and their subsequent application timing had a greater impact on control of GR Palmer amaranth than row spacing in DGR soybean. Although significantly higher reductions to Palmer amaranth biomass occurred preharvest in 38-cm row spacings compared to 76-cm row spacings in EPOST applications of dicamba and EPOST fb LPOST programs of glyphosate, other inconsistent results in this research pertaining to Palmer amaranth density/main effects of row spacing along with other variable results reported in the literature suggests additional research may be needed. Results from this research indicate that the use of PRE fb POST herbicide programs in DGR soybean provide higher levels of Palmer amaranth control than PRE-only herbicide programs, and also that dicamba applied POST provides effective control of GR Palmer amaranth. The efficacy of acetochlor applied EPOST on Palmer amaranth control, density, and biomass reduction varied across site-years and evaluation periods.

The importance of herbicide programs that use multiple sites of action is reaffirmed through this research. For example, EPOST applications of dicamba provided 68% GR Palmer amaranth biomass reduction at preharvest when averaged across row spacings, which was a stark contrast compared to the 98% to 100% biomass reductions that occurred in PRE fb EPOST and PRE fb EPOST plus RH programs. These results are similar to the findings reported by Cahoon et al. (2015) in DGR cotton that sequential applications of dicamba were more effective than a single application; however, selection pressure on Palmer amaranth and other weeds should be considered when using sequential applications of the same herbicide, and such sequential applications should be avoided if other options are available, especially considering the recent confirmation of dicamba-resistant Palmer amaranth in Tennessee (Steckel 2020).

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