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ARTICLE

Pest Interactions in Agronomic Systems

Economics of reducing Palmer amaranth seed production in dicamba/glufosinate/glyphosate-resistant soybean

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Abstract

Increased prevalence of glyphosate-resistant (GR) weeds within agronomic cropping systems has led to the readoption of pre-emergence (PRE) herbicides and use of multiple herbicide-resistant soybean [*Glycine max* (L.) Merr.] cultivars. Herbicide programs were evaluated in the recently commercialized dicamba/glyphosate/glufosinate-resistant (DGGR) soybean for weed control, reduction of Palmer amaranth (*Amaranthus palmeri* S. Watson) seed production, crop safety, and economic performance. At 35 days after pre-emergence herbicides, acetochlor plus dicamba plus metribuzin, acetochlor/fomesafen plus dicamba, dicamba plus flumioxazin, and imazethapyr/pyroxasulfone/saflufenacil provided 80–99% control of velvetleaf (*Abutilon theophrasti* Medik.), Palmer amaranth, common lambsquarters (*Chenopodium album* L.), and *Poaceae* species. Evaluation at 14 days after early postemergence herbicides indicated PRE followed by (fb) POST applications of mixtures of acetochlor, dicamba, glufosinate, and glyphosate provided 80–99% weed control compared with 67–93% control in POST-only programs. Most herbicide programs provided 83–99% control of grass and broadleaf weeds, with 85–91% weed biomass reductions at 28 days after late-POST. The PRE fb POST programs reduced Palmer amaranth seed production by 94–99%, whereas POST-only programs provided 75–83% reduction. In 2020, most programs provided gross profit margins ≥US\$1,000 ha^{-1}, with glufosinate fb glufosinate and imazethapyr/pyroxasulfone/saflufenacil fb acetochlor plus glufosinate providing \$1,481 and \$1,466 ha^{-1}, respectively. Benefit/cost ratios ranged between 0.3 and 3.9 in 2019 due to hail but increased to 2.9–10.9 in 2020. Results of this study support use of PRE herbicides with multiple sites of action in DGGR soybean and indicate that glufosinate can provide POST control of GR Palmer amaranth.

Abbreviations: DAEPOST, days after early postemergence; DALPOST, days after late postemergence; DAPRE, days after pre-emergence; DGGR, dicamba/glyphosate/glufosinate-resistant; DGR, dicamba/glyphosate-resistant; EPOST, early-postemergence; fb, followed by; GR, glyphosate-resistant; HR, herbicide-resistant; LPOST, late postemergence; POST, postemergence; PRE, pre-emergence; SOA, site of action.

1 | INTRODUCTION

Core Ideas

- Weed control was improved in most PRE fb POST herbicide programs compared with POST-only programs.
- Programs that included dicamba in POST applications had reduced Palmer amaranth seed production.
- Glufosinate provided effective control of glyphosate-resistant Palmer amaranth.

Weed management programs in agronomic cropping systems have shifted dramatically since the commercialization of herbicide-resistant (HR) crops due to flexibility in applying broad-spectrum postemergence (POST) herbicides that would previously have caused significant phytotoxic injuries to sensitive crop species. In the United States, glyphosate-resistant (GR) soybean [*Glycine max* (L.) Merr.], corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), and canola (*Brassica napus* L.) were the principal genetically engineered crops from 1996 to 2000 (James, 2003). The rapid adoption of HR crops originally observed during this time period was ultimately sustained throughout the following two decades, with the USDA Economic Research Service estimating that 94% of domestic soybean and 90% of domestic corn acreage in 2014 carried HR traits (USDA-ERS, 2018). Whereas HR crops initially conferred resistance to a single herbicide site of action (SOA) or active ingredient, in recent years, HR traits conferring resistance to multiple SOAs via multiple insertion events were commercialized in crops such as corn (Nandula, 2019; Que et al., 2010). Despite these successes, offerings of multiple-HR soybean cultivars lagged behind until recently, when stacks of existing glyphosate or glufosinate HR traits with synthetic auxin herbicide 2,4-D (2,4-dichlorophenoxyacetic acid), or dicamba (3,6-dichloro-2-methoxybenzoic acid) resistance were commercialized in the United States (Beckie et al., 2019). Likewise, a stacked soybean trait resistant to glyphosate, glufosinate, and isoxaflutole, a hydroxyphenyl-pyruvate-dioxygenase–inhibiting herbicide, was also released during the same time period (Jhala, 2020). In late 2020, the USEPA approved the commercialization of a stacked soybean trait resistant to glyphosate, glufosinate, and dicamba (Jhala, 2020; USEPA, 2020).

Since the initial commercialization, the market share of dicamba/glyphosate-resistant (DGR) soybean and other multiple-HR trait soybean have increased considerably (Beckie et al., 2019), including in Nebraska (Werle et al., 2018). It has been previously reported that many producers have concerns regarding off-target movement of dicamba (Bish & Bradley, 2017). However, many producers are adopting multiple-HR traits such as DGR soybean for management of GR weeds, primarily waterhemp [*Amaranthus tuberculatus* (Moq.) J. D. Sauer], kochia [*Bassia scoparia* (L.) A. J. Scott], horseweed (*Erigeron canadensis* L.), and Palmer amaranth (Sarangi & Jhala, 2018). Across the Midwestern United States, GR weeds have become increasingly difficult to manage with conventional POST herbicides available for use in soybean. Nearly 60% of surveyed corn and soybean producers in Nebraska reported the use of soil-applied residual herbicides at planting to manage GR weeds early in the season (Sarangi & Jhala, 2018), which follows adoption trends in the United States in soybean that increased to nearly 70% in 2015 (Beckie et al., 2019).

Economic information comparing DGR soybean with glufosinate-resistant and conventional soybean has previously been reported in Nebraska (Striegel et al., 2020). However, information on pre-emergence (PRE) and POST herbicide programs in dicamba/glyphosate/glufosinate-resistant (DGGR) soybean on weed control efficacy and crop safety is not readily available. Furthermore, POST herbicide programs comprising of combinations or sequential applications of dicamba, glufosinate, and glyphosate to control GR weeds such as Palmer amaranth ave not been evaluated for economic performance or weed control efficacy. Use of overlapping soil-applied residual herbicides has previously been shown to provide season-long control of Palmer amaranth and velvetleaf in conventional, no-tillage soybean in Nebraska (Sarangi & Jhala, 2019). However, due to the recent release of DGGR soybean, an economic comparison of PRE followed by (fb) POST herbicide programs that include and exclude the use of overlapping residual herbicides has not been reported. Furthermore, the effects of these herbicide programs on Palmer amaranth soil seed-bank dynamics has not been determined. The objectives of this study were to evaluate herbicide programs in DGGR soybean for weed control, their effect on reducing Palmer amaranth seed production, crop safety and response, and grain yield, as well as an economic comparison of gross profit margins and benefit/cost ratios.

2 | MATERIALS AND METHODS

2.1 | Site description

Field experiments were conducted over a two-year period (2019 and 2020) at the University of Nebraska-Lincoln's South Central Agricultural Laboratory, located near Clay Center, NE (40.575256° N, −98.137824° W). Soil classifications at the research sites consisted of a Hastings silt loam (montmorillonitic, mesic, Pachic Argiustolls) with a pH of

6.5, 17% sand, 58% silt, 25% clay, and 3% organic matter. In both years, the study sites were in long-term corn–soybean crop rotation fields with corn preceding the field experiments. In both years, study sites had access to aboveground lateral move irrigation. Herbicide treatments were arranged in a randomized complete block design with four replications, with an individual plot size of 3 m wide by 9 m long each comprised of four soybean rows spaced 0.76 m apart. The soybean cultivar Asgrow AG26XF0 was planted on 1 May 2019 and 14 May 2020 at 345,000 seeds ha^{-1} under no-tillage conditions (De Bruin & Pedersen, 2008; Specht, 2016). Field sites selected had been used previously for other weed science research, leading to substantially high weed pressure. The primary summer annual weeds present during both years were Palmer amaranth (documented to be glyphosate-resistant), velvetleaf, common lambsquarters, and a mixture of green foxtail [*Setaria viridis* (L.) Beauv.], giant foxtail (*Setaria faberi* Hermm.) and large crabgrass [*Digitaria sanguinalis* (L.) Scop.].

2.2 | Herbicide treatments

Immediately following planting, PRE herbicides (Table 1) were applied using a CO_2-pressurized backpack sprayer comprised of a five-nozzle boom fitted with AIXR 110015 or TTI 11005 (for treatments containing dicamba) flat-fan nozzles (TeeJet Spraying Systems Co.) calibrated to deliver 140 L ha^{-1} at 276 kPa. Likewise, early-POST (EPOST; 28–35 days after pre-emergence [DAPRE]) and late-POST (LPOST; 60–75 DAPRE) herbicides were applied in a similar fashion, with a CO_2-pressurized backpack sprayer comprised of a five-nozzle boom fitted with AIXR 11002, XR 11002, or TTI 11002 flat-fan nozzles calibrated to deliver 140 L ha^{-1} at 276 kPa. The EPOST herbicide applications were made when the soybean plants were at the two to three trifoliate stage (e.g., V2 to V3) when the average weed height from the soil surface ranged from 5 to 10.2 cm. The LPOST herbicide applications were made when the soybean were at least at the four trifoliate stage (e.g., V4) but prior to flowers reaching the uppermost two nodes (e.g., R1, prior to R2) when the average weed height from the soil surface ranged from 7.6 to 17.8 cm. Herbicide programs were comprised of 15 standalone herbicides or mixtures of four herbicides (acetochlor, dicamba, glyphosate, and glufosinate) at labeled rates (Table 1), with a nontreated control included for comparison. Prior to study initiation in both years, the entire experimental area received an early-spring application of glyphosate (Roundup PowerMax, Bayer Crop Science; at 840 g acid equivalent [a.e.] ha^{-1}) plus liquid ammonium sulfate (3% v/v) plus a nonionic surfactant (Induce, Helena Chemical; at 0.25% v/v) plus 2,4-D ester (Weedone LV6, Nufarm Inc.; at 386 g a.e. ha^{-1}) using a tractor-mounted sprayer calibrated to deliver 140 L ha^{-1} at 276 kPa for control of winter annual weeds such as henbit (*Lamium amplexicaule* L.), field pennycress (*Thlaspi arvense* L.), and horseweed (*Erigeron canadensis* L.).

2.3 | Data collection

Soybean plant stand was assessed at 28 DAPRE by randomly counting the number of plants in 1-m linear length of the middle two rows. Estimates of visible control and density of Palmer amaranth, common lambsquarters, velvetleaf, and grass weeds were recorded at 35 DAPRE, 14 DAEPOST, 14 and 28 d after LPOST (DALPOST), and prior to harvest (140–154 DAPRE). Weed control was assessed based on a 0–100% scale, where 0% equals no control and 100% equals all plant death. Soybean injury was rated based on a 0–100% scale at 14 DAPRE, 28 DAPRE, 14 DAEPOST, 14 and 28 DALPOST, where 0% equals no injury and 100% equals total soybean plant death. Weed plant density was collected within the middle two soybean rows in each plot using two randomly placed 0.5 m^2 quadrats. At 35 DAPRE and 28 DALPOST, the aboveground weed biomass within the two 0.5 m^2 quadrats was severed at the soil surface and collected, with weed biomass from the grass and broadleaf weeds subsequently separated and oven-dried at 70 ˚C for 10 d. Dry grass and broadleaf weed biomass was recorded and converted into g m^{-2}, after which the percent weed biomass reduction was calculated using Equation 1:

$$Y = \left[\frac{(B_{\text{con}} - B_{\text{plot}})}{B_{\text{con}}}\right] \times 100 \tag{1}$$

where B_{con} represents the weed biomass from the nontreated control and B_{plot} represents the weed biomass from the treated plot (Wortman, 2014).

Prior to soybean harvest, three randomly selected female Palmer amaranth plants (if available) within the center two rows of each plot were sampled by severing the plants at the soil surface and placed into one paper bag. Under laboratory conditions, seed heads were removed from each collected plant, with seeds subsequently separated by passing the threshed material through a series of laboratory sieves with mesh opening sizes ranging from 0.5 to 3.35 mm. The material collected from the 0.5-mm sieve was further processed using a seed cleaner that used air to remove the lighter floral chaff from Palmer amaranth seeds (Sosnoskie & Culpepper, 2014). Seeds were thoroughly cleaned, and the seed weight and number of seeds per female plant were determined. The weight of 100 seeds from each of the 10 female plants was used to determine the average number of seeds per female plant.

For both years, daily weather data were collected from a local High Plains Regional Climate Center Automated

TABLE 1 Herbicide programs and rates used to evaluate weed control in dicamba/glufosinate/glyphosate-resistant soybean in Nebraska in 2019 and 2020

Herbicide program	Rate	Timing	Trade names	Manufacturer[a]	Adjuvants[b]
	g a.e. or a.i. ha^{-1}				
Acetochlor + dicamba + metribuzin fb	1,680 + 560 + 210	PRE fb	Warrant, Xtendimax, Mauler	Bayer, Bayer, Valent	DRA, WC
Acetochlor + dicamba + glyphosate	1,680 + 560 + 1,540	EPOST	Warrant, XtendiMax, Roundup	Bayer	DRA, WC
Acetochlor + dicamba + metribuzin fb	1,680 + 560 + 210	PRE fb	Warrant, Xtendimax, Mauler	Bayer, Bayer, Valent	DRA, WC
Acetochlor + dicamba + glyphosate fb	1,680 + 560 + 1,540	EPOST fb	Warrant, XtendiMax, Roundup	Bayer	DRA, WC
Glufosinate	656	LPOST	Liberty	BASF	AMS
Acetochlor + dicamba + metribuzin fb	1,680 + 560 + 210	PRE fb	Warrant, Xtendimax, Mauler	Bayer, Bayer, Valent	DRA, WC
Acetochlor + glufosinate + glyphosate	1,680 + 656 + 1,540	EPOST	Warrant, Liberty, Roundup	Bayer, BASF, Bayer	AMS
Acetochlor + dicamba + metribuzin fb	1,680 + 560 + 210	PRE fb	Warrant, Xtendimax, Mauler	Bayer, Bayer, Valent	DRA, WC
Acetochlor + glyphosate fb	1,680 + 1,540	EPOST fb	Warrant, Roundup	Bayer	AMS
Glufosinate	656	LPOST	Liberty	BASF	AMS
Acetochlor/fomesafen + dicamba fb	1,525 + 560	PRE fb	Warrant Ultra, Xtendimax	Bayer	DRA, WC
Acetochlor + dicamba + glyphosate	1,680 + 560 + 1,540	EPOST	Warrant, Xtendimax, Roundup	Bayer	DRA, WC
Acetochlor/fomesafen + dicamba fb	1,525 + 560	PRE fb	Warrant Ultra, Xtendimax	Bayer	DRA, WC
Acetochlor + glufosinate + glyphosate	1,680 + 656 + 1,540	EPOST	Warrant, Liberty, Roundup	Bayer, BASF, Bayer	AMS
Dicamba + flumioxazin fb	560 + 72	PRE fb	Xtendimax, Valor SX	Bayer, BASF	DRA, WC
Acetochlor + dicamba + glyphosate	1,680 + 560 + 1,540	EPOST	Warrant, Xtendimax, Roundup	Bayer	DRA, WC
Dicamba + flumioxazin fb	560 + 72	PRE fb	Xtendimax, Valor SX	Bayer, BASF	DRA, WC
Acetochlor + glufosinate + glyphosate	1,680 + 656 + 1,540	EPOST	Warrant, Liberty, Roundup	Bayer, BASF, Bayer	AMS
Acetochlor + glufosinate + glyphosate	1,680 + 656 + 1,540	EPOST	Warrant, Liberty, Roundup	Bayer, BASF, Bayer	AMS
Acetochlor + glufosinate	1,680 + 656	EPOST	Warrant, Liberty	Bayer, BASF	AMS
Acetochlor + dicamba fb	1,680 + 560	EPOST fb	Warrant, Xtendimax	Bayer	DRA, WC
Glufosinate + glyphosate	656 + 1,540	LPOST	Liberty, Roundup	BASF, Bayer	AMS
Glyphosate fb	1,540	EPOST fb	Roundup	Bayer	AMS, COC
Glyphosate	1,540	LPOST	Roundup	Bayer	AMS, COC
Glufosinate fb	656	EPOST fb	Liberty	BASF	AMS
Glufosinate	656	LPOST	Liberty	BASF	AMS
Imazethapyr/pyroxasulfone/saflufenacil fb	215	PRE fb	Zidua Pro	BASF	—
Acetochlor + dicamba	1,680 + 560	LPOST	Warrant, Xtendimax	Bayer	DRA, WC
Imazethapyr/pyroxasulfone/saflufenacil fb	215	PRE fb	Zidua Pro	BASF	—
Acetochlor + glufosinate	1,680 + 656	LPOST	Warrant, Liberty	Bayer, BASF	AMS

Note. a.e., acid equivalent; AMS, ammonium sulfate (Amsol); COC, crop oil concentrate (Agri-Dex); DRA, drift-reducing agent (Intact); EPOST, early postemergent herbicide; fb, followed by; LPOST, late postemergent herbicide; PRE, pre-emergence herbicide; WC, non-AMS water conditioner (Class Act Ridion).

[a] Bayer CropScience, BASF Corporation, and Valent U.S.A. Corporation.

[b] AMS at 3% (v/v), COC at 1% v/v, DRA at 0.5% v/v, and WC at 1% v/v were mixed with PRE, EPOST, and LPOST herbicide treatments according to label recommendations.

Weather Data Network weather station located in Harvard, NE (40.566667° N, −98.149296° W), with cumulative precipitation received and average daily temperature recorded from 1 May to 1 October in 2019 and 2020. Plots were harvested at crop maturity in both years, with soybean grain from the center two rows harvested using a small-plot combine. Grain weight and moisture content were recorded and adjusted to the industry standard of 13%.

2.4 | Economic analysis

Price estimates for herbicides and spray adjuvants were obtained from three independent commercial sources in Nebraska (Central Valley Ag Cooperative, Frontier Cooperative, Nutrien Ag Solutions), which were averaged prior to economic analysis. Price estimates for custom application were obtained from the aforementioned sources, with an average cost of US\$17.30 ha^{-1} application^{-1} for PRE herbicides, \$18.95 ha^{-1} application^{-1} for nondicamba POST herbicide programs, and \$31.71 ha^{-1} application^{-1} for POST herbicide programs containing dicamba. Weed management programs were then assessed for profitability, with gross profit margin for each program calculated using Equation 2 (Sarangi & Jhala, 2019):

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

where R is the gross revenue calculated by multiplying soybean grain yield for each treatment by the average price received for soybean in Nebraska in 2019 (\$0.3095 kg^{-1}) and 2020 (\$0.3154 kg^{-1}), and W is the weed management program cost consisting of the cost of herbicides and spray adjuvants with custom application.

Following gross profit margin analysis, benefit/cost ratio were calculated using the gross revenue and cost of each herbicide program using Equation 3 (Sarangi & Jhala, 2019):

$$\text{Benefit/cost ratio for a program}\ (\text{US\$/US\$}) = (R_\text{T} - R_\text{C})/W \tag{3}$$

where R_T is the overall gross revenue for each weed management program, R_C is the gross revenue for the nontreated control, and W is the cost of each weed management program including the average cost of herbicides and spray adjuvants with custom application.

2.5 | Statistical analysis

Statistical analysis was performed using R statistical software (Version 4.0.3) (R Core Team, 2018) using "glmmTMB" package (Version 1.0.2.1) (Brooks et al., 2017), with subsequent contrast analysis performed using the "gmodels" package (Version 2.18.1) (Warnes et al., 2018). The interaction of year × treatment was not significant for most experimental variables; therefore, years were combined for most variables, excluding soybean yield and Palmer amaranth seed production. In both the combined and single-year models, herbicide treatment was considered a fixed effect, whereas the replication nested within year was considered a random effect. Discrete variables (e.g., weed density, soybean yield, and Palmer amaranth seed production), were fit to generalized linear mixed-effect models with gaussian (link = "identity") error distributions. Three iterations of each model for discrete variables were compared: nontransformed, square-root transformed, and log(x+1) transformed. Likewise, continuous variables (e.g., weed control and biomass reduction) were fit to generalized linear mixed-effect models with gaussian (link = "identity") and beta (link = "logit") error distributions (Stroup, 2015). Two iterations of each model for continuous variables were compared: nontransformed and logit-transformed. For both discrete and continuous variables, the final model selection was based on model dispersion parameter estimates and Akaike information criterion (AIC) values, with square-root, log(x+1) and logit transformations with gaussian and beta error distributions selected for most response variables, respectively.

Prior to conducting ANOVA, normality assumptions were evaluated using Shapiro-Wilk tests and normal Q–Q plots, while variance assumptions were evaluated at $\alpha = .05$ using Bartlett and Fligner-Killen tests (Kniss & Streibig, 2018). Variables that failed variance assumptions were visually assessed for outliers, and heterogeneity of variance was examined by plotting residual values (Knezevic et al., 2003) using base functions (R Core Team, 2018).

An ANOVA was performed using the "car" package (Version 3.0-10) using Type II Wald Chi-Square Tests (Fox & Weisberg, 2019). After conducting the ANOVA, treatment-estimated marginal means were separated using the "emmeans" package (Version 1.5.1) (Lenth, 2019) and "multcomp" package (Version 1.4-14) (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. To determine the significance of PRE-applied herbicides, contrast analyses were preformed comparing PRE fb POST herbicide programs (e.g., PRE fb EPOST, PRE fb EPOST fb LPOST, and PRE fb LPOST) to POST-only programs (e.g., EPOST and EPOST fb LPOST). Likewise, to determine the significance of POST herbicide application timing, subsequent contrast analysis was performed to compare POST herbicide timing (e.g., EPOST, EPOST fb LPOST, or LPOST). Due to the presence of GR Palmer amaranth, data used in POST contrast analyses were subset

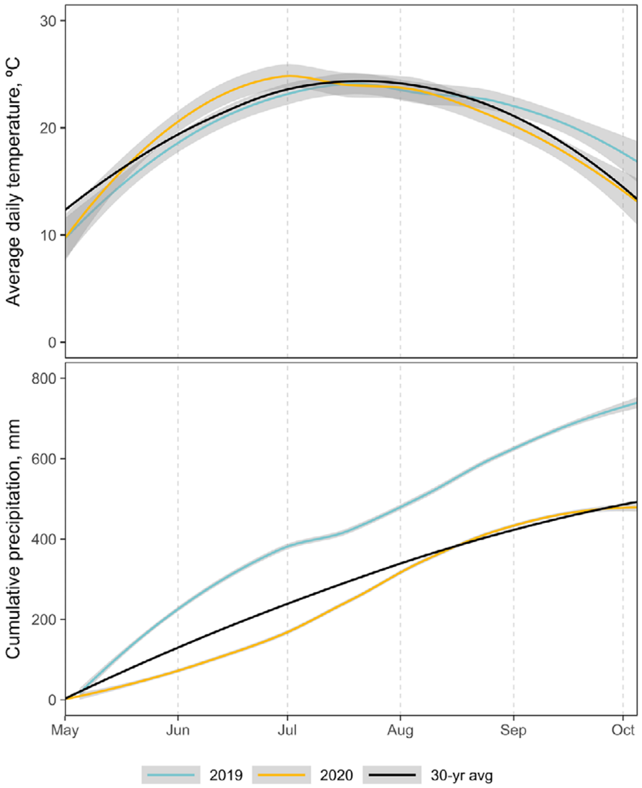

FIGURE 1 Average daily air temperature (°C) and total cumulative precipitation (mm) (including supplemental irrigation) received during the 2019 and 2020 growing seasons compared with the 30-year average at South Central Agricultural Laboratory near Clay Center, Nebraska, USA

prior to analysis to exclude data from glyphosate fb glyphosate programs for Palmer amaranth control, density, and 28 DALPOST broadleaf weed biomass reduction. Following treatment means separation and contrast analysis, data that received logit, log(x+1), or square-root transformations were back-transformed for the presentation of results.

3 | RESULTS

3.1 | Average daily temperature and precipitation

Average daily temperatures in 2019 and 2020 were overall similar to the 30-yr average (Figure 1). In contrast, the cumulative precipitation recorded from 1 May to 1 October at the study location in 2019 and 2020 differed from the 30-yr average. In 2019, cumulative precipitation received (709 mm) exceeded the 30-yr average (486 mm), whereas in 2020, the cumulative precipitation was drastically reduced (234 mm). To overcome dry conditions in 2020, seven irrigation events totaling 237 mm were applied via a lateral moving aboveground irrigation system, in contrast to only two irrigation events totaling 65 mm in 2019. The increased amount of irrigation water applied in 2020 was sufficient to return the cumulative precipitation (471 mm) to similar levels as the 30-yr average (Figure 1).

3.2 | Soybean stand and injury

Soybean plant population stand (339,500 plants ha^{-1}) was not significantly different ($P > .05$) for herbicide program, year, or the interaction of year and herbicide program (data not shown).

The DGGR soybean cultivar Asgrow AG26XF0 displayed a high margin of tolerance to all PRE-applied herbicides evaluated in this study, with no visible soybean injury at 14 or 28 DAPRE across both years (data not shown). Similarly, a high margin of tolerance to all POST-applied herbicides evaluated in this study was also observed, with no visible soybean injury at 14 DAEPOST or at 14 or 28 DALPOST (data not shown).

3.3 | PRE herbicide: Weed control, weed density, and weed biomass reduction

Averaged across years, PRE-applied herbicides provided 94–98% control of Palmer amaranth, 95–97% control of velvetleaf, 95–97% control of common lambsquarters, and 88–98% control of grass weed species 35 DAPRE (Table 2). The PRE-applied herbicides evaluated in this study reduced the density of Palmer amaranth, velvetleaf, and grass weed species to 0–1 plant m^{-2} compared with the nontreated control (26, 11, and 13 plants m^{-2}, respectively). Also, PRE-applied herbicides provided 95–100% biomass reductions for grass and broadleaf weeds (Table 2).

3.4 | POST herbicide: Weed control, weed density, and weed biomass reduction

When following PRE herbicide, POST treatments provided 86–99% control of Palmer amaranth 14 DAEPOST, 14 and 28 DALPOST, and prior to harvest. POST-only programs (e.g., EPOST, EPOST fb LPOST, which did not follow PRE-applied herbicides) provided similar control of Palmer amaranth (80–94%) across all evaluation times with the exception of glyphosate fb glyphosate (27–67% control) due to the prevalence of GR Palmer amaranth (Table 3). Contrast statements indicated no significant difference between POST herbicide programs for most evaluation times. Inversely, contrast analyses comparing Palmer amaranth control in PRE fb POST and POST-only programs were significant at 14 and 28 DALPOST and prior to harvest. The PRE fb POST herbicide programs provided 96% control of Palmer amaranth

TABLE 2 Effect of pre-emergence herbicides on weed control, weed density, and weed biomass reduction 35 days after pre-emergence in dicamba/glufosinate/glyphosate-resistant soybean in field experiments conducted in Nebraska in 2019 and 2020

Herbicide Program	Control				Population density			Biomass Reduction	
	Palmer amaranth	Velvetleaf	Common lambsquarters	Grass	Palmer amaranth	Velvetleaf	Grass	Broadleaf	Grass
	%				no. plants m^{-2}			%	
Nontreated control	—	—	—	—	26 c	11 b	13 c	—	—
Acetochlor + dicamba + metribuzin	95	95	95	96	0 a	1 a	0 a	97	96
Acetochlor/fomesafen + dicamba	97	97	97	97	1 b	1 a	0 a	99	97
Dicamba + flumioxazin	94	96	96	88	1 b	1 a	1 b	99	96
Imazethapyr/pyroxasulfone/saflufenacil	98	97	97	98	0 a	0 a	0 a	100	100
P-value	.083	.738	.296	.122	<.001	<.001	<.001	.200	.167

Note. Grass weed pressure was composed of green foxtail and giant foxtail with minor pressure from other *Poaceae* species including large crabgrass. Prior to analysis, control data were logit transformed, and density data were log(x+1) transformed and fit to generalized linear mixed models and compared with nontransformed models. Back transformed values are presented based on interpretations of transformed data. 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.

compared with 82 and 89% control with POST-only programs (Table 3). Most herbicide programs evaluated reduced the density of Palmer amaranth compared with the nontreated control (18–24 plants m^{-2}). Contrast analysis comparing density of Palmer amaranth by application timing was not significant, whereas the use of PRE herbicides provided the lowest density of Palmer amaranth at all evaluation timings (Table 3).

All POST herbicide programs provided 87–99% control of velvetleaf (Table 4). At most evaluation timing, a priori contrasts comparing the POST herbicide programs were not significant. However, contrasts comparing LPOST to EPOST and EPOST fb LPOST programs were significant at 28 DALPOST and prior to harvest. In both instances, imazethapyr/pyroxasulfone/saflufenacil PRE fb LPOST applications of dicamba or acetochlor plus glufosinate provided better control (99 vs. 94–95%) than other programs. Similarly, programs that contained PRE-applied herbicides provided increased control (97–98%) of velvetleaf ($P < .01$) than POST-only programs (90–93%) at most evaluation timings (Table 4).

Evaluations at 14 and 28 DALPOST, as well as prior to harvest, indicated all POST herbicide programs reduced velvetleaf density to ≤6 plants m^{-2} compared with the nontreated control (3–16 plants m^{-2}). All herbicide programs reduced velvetleaf density to 0–2 plants m^{-2}, except for EPOST applications of acetochlor plus glufosinate plus glyphosate (3 plants m^{-2} at prior to harvest) (Table 4). Similar to the contrast analysis results in velvetleaf control, imazethapyr/pyroxasulfone/saflufenacil PRE fb dicamba or acetochlor plus glufosinate reduced velvetleaf density to 0 plants m^{-2} at 28 DALPOST or prior to harvest compared with 1 plants m^{-2} for EPOST programs (Table 4).

Herbicide programs evaluated in this study provided 70–99% control of common lambsquarters at 14 DAEPOST (Table 5). Most PRE fb POST programs provided increased control (>90%) compared with most POST-only programs (70–89%) at 14 DAEPOST. The PRE applications of imazethapyr/pyroxasulfone/saflufenacil continued to provide 95–99% control of common lambsquarters at 14 DAEPOST despite no POST herbicide being applied until LPOST (Table 5). As the seasons progressed, PRE fb POST programs continued to provide increased control of common lambsquarters compared with POST-only programs when evaluated at 14 and 28 DALPOST, as well as prior to harvest (Table 5). Contrast statements comparing PRE fb POST vs. POST herbicide programs that were significant ($P \leq .01$) at all evaluation timings, further support the improved control by PRE fb POST (96–98%) programs compared with POST-only programs (83–89%). These differences were also observed in the density reduction of common lambsquarters. Common lambsquarters density was the highest early in the season at 14 DAEPOST, where POST-only programs and dicamba plus

TABLE 3 Effect of pre-emergence followed by postemergence (PRE fb POST) herbicide programs for control and density of Palmer amaranth in dicamba/glufosinate/glyphosate-resistant soybean in field experiments conducted in Nebraska in 2019 and 2020

Herbicide Program		**Palmer amaranth control**				**Palmer amaranth density**			
PRE	**POST (EPOST fb LPOST)**	**14 DAEPOST**	**14 DALPOST**	**28 DALPOST**	**Prior to harvest**	**14 DAEPOST**	**14 DALPOST**	**28 DALPOST**	**Prior to harvest**
		%				no. plants m^{-2}			
Nontreated control	—	—	—	—	—	24 e	18 d	23 d	18 d
Acetochlor + dicamba + metribuzin	Acetochlor + dicamba + glyphosate	94 ab	99 a	94 a	96 a	2 b	0 a	0 a	0 a
Acetochlor + dicamba + metribuzin	Acetochlor + dicamba + glyphosate fb glufosinate	98 a	99 a	94 a	95 a	0 a	0 a	0 a	1 ab
Acetochlor + dicamba + metribuzin	Acetochlor + glufosinate + glyphosate	91 ab	91 a	90 a	90 a	2 ab	2 ab	2 ab	2 abc
Acetochlor + dicamba + metribuzin	Acetochlor + glyphosate fb glufosinate	94 ab	95 a	91 a	90 a	2 ab	1 ab	1 ab	2 abc
Acetochlor/fomesafen + dicamba	Acetochlor + dicamba + glyphosate	90 ab	99 a	94 a	94 a	2 ab	0 a	0 a	1 ab
Acetochlor/fomesafen + dicamba	Acetochlor + glufosinate + glyphosate	90 ab	90 a	89 a	87 a	2 b	2 ab	2 ab	3 bc
Dicamba + flumioxazin	Acetochlor + dicamba + glyphosate	86 abc	99 a	94 a	94 a	3 bc	0 a	0 a	1 ab
Dicamba + flumioxazin	Acetochlor + glufosinate + glyphosate	86 abc	96 a	92 a	90 a	3 b	1 ab	1 a	2 abc

(Continues)

TABLE 3 (Continued)

Herbicide Program		Palmer amaranth control				Palmer amaranth density			
PRE	**POST (EPOST fb LPOST)**	**14 DAEPOST**	**14 DALPOST**	**28 DALPOST**	**Prior to harvest**	**14 DAEPOST**	**14 DALPOST**	**28 DALPOST**	**Prior to harvest**
—	Acetochlor + glufosinate + glyphosate	86 abc	87 a	84 a	80 a	4 bc	4 bc	3 bc	4 bcd
—	Acetochlor + glufosinate	91 ab	85 a	83 a	79 a	5 bcd	4 bc	4 bc	4 bcd
—	Acetochlor + dicamba fb glufosinate + glyphosate	78 bc	90 a	90 a	87 a	9 cde	1 ab	1 ab	2 abc
—	Glyphosate fb glyphosate	67 c	52 b	27 b	39 b	12 de	8 cd	8 c	9 cd
—	Glufosinate fb glufosinate	92 ab	94 a	91 a	85 a	2 ab	1 ab	1 ab	3 bc
Imazethapyr/pyroxasulfone/ saflufenacil	– fb acetochlor + dicamba	80 abc	95 a	92 a	94 a	24 e	2 ab	1 ab	1 ab
Imazethapyr/pyroxasulfone/ saflufenacil	– fb acetochlor + glufosinate	77 bc	99 a	94 a	96 a	2 b	1 ab	0 a	1 ab
P value		<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001
Contrasts[a]									
PRE fb POST vs. POST only		NS	96 vs. 82**	96 vs. 89**	92 vs. 83*	4 vs. 6*	1 vs. 3**	1 vs. 3**	2 vs. 4**
EPOST vs. EPOST fb LPOST		NS	NS	NS	NS	NS	NS	NS	NS
EPOST vs. LPOST		90 vs. 79**	NS	NS	NS	NS	NS	NS	NS
EPOST fb LPOST vs. LPOST		91 vs. 79**	NS	NS	89 vs. 95*	NS	NS	NS	NS

Note. DAEPOST, days after EPOST; DALPOST, days after LPOST; EPOST, early POST; LPOST, late POST; NS, nonsignificant ($P \geq .05$). Prior to analysis, control data were logit transformed and density data were log(x+1) transformed and fit to generalized linear mixed models and compared with nontransformed models. 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. Back transformed values are presented based on interpretations of transformed data.

[a] Selected a priori contrasts.

*Significant at $P < .05$. ** Significant at $P < .01$.

TABLE 4 Effect of pre-emergence followed by postemergence (PRE fb POST) herbicide programs for control and density of velvetleaf in dicamba/glufosinate/glyphosate-resistant soybean in field experiments conducted in Nebraska in 2019 and 2020

Herbicide program		Velvetleaf control				Velvetleaf density			
PRE	POST (EPOST fb LPOST)	14 DAEPOST	14 DALPOST	28 DALPOST	Prior to harvest	14 DAEPOST	14 DALPOST	28 DALPOST	Prior to harvest
		%				no. plants m^{-2}			
Nontreated control	—	—	—	—	—	3 bcd	4 c	4 b	16 d
Acetochlor + dicamba + metribuzin	Acetochlor + dicamba + glyphosate	99 ab	99 ab	98 a	99 a	1 abc	0 a	0 a	0 ab
Acetochlor + dicamba + metribuzin	Acetochlor + dicamba + glyphosate fb glufosinate	99 a	99 a	99 a	99 a	0 a	0 a	0 a	0 a
Acetochlor + dicamba + metribuzin	Acetochlor + glufosinate + glyphosate	98 ab	98 ab	94 ab	95 ab	2 bcd	1 ab	1 ab	1 abc
Acetochlor + dicamba + metribuzin	Acetochlor + glyphosate fb glufosinate	99 ab	99 ab	96 a	97 a	1 abc	0 ab	0 a	0 ab
Acetochlor/fomesafen + dicamba	Acetochlor + dicamba + glyphosate	99 ab	99 ab	98 a	99 a	1 abc	0 a	0 a	0 ab
Acetochlor/fomesafen + dicamba	Acetochlor + glufosinate + glyphosate	95 abc	95 abc	91 ab	91 ab	2 abcd	1 ab	1 ab	1 abc
Dicamba + flumioxazin	Acetochlor + dicamba + glyphosate	98 ab	98 ab	98 a	99 a	3 bcd	0 a	0 a	0 ab
Dicamba + flumioxazin	Acetochlor + glufosinate + glyphosate	98 ab	98 ab	94 ab	95 ab	4 cd	0 a	1 ab	1 abc
—	Acetochlor + glufosinate + glyphosate	91 bc	91 bc	86 b	87 b	4 bcd	2 bc	3 b	3 c
—	Acetochlor + glufosinate	89 c	89 c	90 ab	91 ab	3 bcd	2 bc	2 ab	2 bc
—	Acetochlor + dicamba fb glufosinate + glyphosate	94 abc	94 abc	90 ab	91 ab	6 d	1 ab	1 ab	1 abc
—	Glyphosate fb glyphosate	99 a	99 a	91 ab	92 ab	2 bcd	0 a	1 ab	1 abc
—	Glufosinate fb glufosinate	99 ab	99 ab	94 ab	95 ab	1 ab	0 a	1 ab	1 abc

(Continues)

TABLE 4 (Continued)

Herbicide program		Velvetleaf control				Velvetleaf density			
PRE	POST (EPOST fb LPOST)	14 DAEPOST	14 DALPOST	28 DALPOST	Prior to harvest	14 DAEPOST	14 DALPOST	28 DALPOST	Prior to harvest
Imazethapyr/pyroxasulfone/ saflufenacil	– fb acetochlor + dicamba	99 a	99 a	99 a	99 a	3 bcd	0 a	0 a	0 a
Imazethapyr/pyroxasulfone/ saflufenacil	– fb acetochlor + glufosinate	98 ab	98 ab	98 a	99 a	1 abc	0 a	0 a	0 a
P value		<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001
Contrasts[a]									
PRE fb POST vs. POST only		NS	98 vs. 93**	97 vs. 90**	97 vs. 90**	3 vs. 5*	0 vs. 2**	1 vs. 2**	1 vs. 2**
EPOST vs. EPOST fb LPOST		NS	NS	NS	NS	NS	0 vs 1*	NS	NS
EPOST vs. LPOST		NS	NS	94 vs. 99*	94 vs. 99*	NS	NS	1 vs. 0*	1 vs. 0*
EPOST fb LPOST vs. LPOST		NS	NS	NS	95 vs. 99*	NS	NS	NS	NS

Note. DAEPOST, days after EPOST; DALPOST, days after LPOST; EPOST, early POST; LPOST, late POST; NS, nonsignificant ($P \geq .05$). Prior to analysis, control data were logit transformed and density data were log(x+1) transformed and fit to generalized linear mixed models and compared with nontransformed models. 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. Back transformed values are presented based on interpretations of transformed data.

[a] Selected a priori contrasts.

*Significant at $P < .05$. ** Significant at $P < .01$.

TABLE 5 Effect of herbicide programs for control and density of common lambsquarters in dicamba/glufosinate/glyphosate-resistant soybean in field experiments conducted in Nebraska in 2019 and 2020

Herbicide program		Common lambsquarters control				Common lambsquarters density			
PRE	POST (EPOST fb LPOST)	14 DAEPOST	14 DALPOST	28 DALPOST	Prior to harvest	14 DAEPOST	14 DALPOST	28 DALPOST	Prior to harvest
		%				no. plants m^{-2}			
Nontreated control	—	—	—	—	—	17 d	18 e	25 d	23 d
Acetochlor + dicamba + metribuzin	Acetochlor + dicamba + glyphosate	95 ab	99 a	99 a	98 a	1 ab	0 a	0 a	0 a
Acetochlor + dicamba + metribuzin	Acetochlor + dicamba + glyphosate fb glufosinate	99 a	99 a	99 a	98 a	0 a	0 a	0 a	0 a
Acetochlor + dicamba + metribuzin	Acetochlor + glufosinate + glyphosate	79 efg	99 a	95 a	96 a	6 bcd	0 a	1 ab	1 ab
Acetochlor + dicamba + metribuzin	Acetochlor + glyphosate fb glufosinate	92 abc	99 a	96 a	97 a	1 abc	0 a	1 ab	1 ab
Acetochlor/fomesafen + dicamba	Acetochlor + dicamba + glyphosate	83 cde	99 a	99 a	98 a	4 abcd	0 a	0 a	0 a
Acetochlor/fomesafen + dicamba	Acetochlor + glufosinate + glyphosate	80 def	91 b	88 abc	92 ab	7 bcd	1 b	3 abc	3 abc
Dicamba + flumioxazin	Acetochlor + dicamba + glyphosate	71 gh	99 a	99 a	98 a	14 d	0 a	0 a	0 a
Dicamba + flumioxazin	Acetochlor + glufosinate + glyphosate	70 h	99 a	93 ab	94 ab	15 d	0 a	1 ab	1 ab
—	Acetochlor + glufosinate + glyphosate	72 fgh	84 c	78 c	78 b	12 cd	4 cd	7 c	7 c
—	Acetochlor + glufosinate	89 abcd	76 d	81 c	80 b	4 abcd	6 d	6 c	6 c
—	Acetochlor + dicamba fb glufosinate + glyphosate	70 h	89 bc	80 c	79 b	20 d	2 bc	4 bc	4 bc
—	Glyphosate fb glyphosate	85 cde	99 a	82 bc	81 b	10 cd	0 a	4 bc	4 bc
—	Glufosinate fb glufosinate	89 bcde	99 a	99 a	98 a	1 abc	0 a	0 a	0 a

(Continues)

TABLE 5 (Continued)

Herbicide program		Common lambsquarters control				Common lambsquarters density			
PRE	POST (EPOST fb LPOST)	14 DAEPOST	14 DALPOST	28 DALPOST	Prior to harvest	14 DAEPOST	14 DALPOST	28 DALPOST	Prior to harvest
Imazethapyr/pyroxasulfone/ saflufenacil	– fb acetochlor + dicamba	95 ab	99 a	99 a	98 a	4 abcd	0 a	0 a	0 a
Imazethapyr/pyroxasulfone/ saflufenacil	– fb acetochlor + glufosinate	99 a	99 a	99 a	98 a	1 ab	0 a	0 a	0 a
P value		<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001
Contrasts[a]									
PRE fb POST vs. POST only		NS	98 vs. 89**	96 vs. 83**	97 vs. 84**	6 vs. 10*	0 vs. 2**	0 vs. 4**	0 vs. 4**
EPOST vs. EPOST fb LPOST		80 vs. 86*	NS	NS	NS	NS	NS	NS	NS
EPOST vs. LPOST		80 vs. 89*	NS	NS	NS	NS	NS	NS	NS
EPOST fb LPOST vs. LPOST		NS	NS	NS	NS	NS	NS	NS	NS

Note. DAEPOST, days after EPOST; DALPOST, days after LPOST; EPOST, early POST; LPOST, late POST; POST, postemergence herbicide; PRE, pre-emergence herbicide; NS, nonsignificant ($P \geq .05$). Prior to analysis, control data were logit transformed and density data were log(x+1) transformed and fit to generalized linear mixed models and compared with nontransformed models. 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. Back transformed values are presented based on interpretations of transformed data.

[a] Selected a priori contrasts.

*Significant at $P < .05$. ** Significant at $P < .01$.

flumioxazin fb POST programs recorded the highest plant densities. At 14 and 28 DALPOST, common lambsquarters density was greatly reduced in PRE fb POST programs, again with the exception of dicamba plus flumiozazin fb POST herbicides (4 plants m^{-2}). The POST herbicide contrast statements were not significant at any evaluation time, whereas contrast statements comparing PRE fb POST vs. POST herbicide programs were significant ($P \leq .01$) for all evaluation times (Table 5). Use of PRE herbicide programs consistently provided complete control of common lambsquarters (0 plants m^{-2}) compared with POST-only programs (2–4 plants m^{-2}).

At 14 DAEPOST, all herbicide programs provided 80–98% control of grass weeds except for POST-only applications of acetochlor plus dicamba (57%). Grass weed control provided by acetochlor plus dicamba increased to 96% following LPOST applications of glufosinate plus glyphosate (Table 6). Consequently, all herbicide programs provided similar control of grass weeds both at 28 DALPOST and prior to harvest (87–99%, Table 6). Contrast statements for grass weed control were not significant at any evaluation period. The PRE fb POST programs reduced grass weed density the most (0–1 plant m^{-2}) at all evaluation periods (Table 6). Despite many POST-only programs providing similar density reductions as PRE fb POST programs, contrast statements were significant ($P \leq .01$) at most evaluation times, with the use of PRE herbicides providing better control and reduced grass weed density compared with POST-only programs (Table 6).

At 28 DALPOST, all evaluated herbicide programs provided significant biomass reduction to both grass and broadleaf weeds compared with the nontreated control. With the exception of glyphosate fb glyphosate, all herbicide programs provided 90–100% reduction of broadleaf weed species biomass (Table 7). Reductions to grass weed biomass were similar across herbicide systems, with all herbicide programs providing 85–100% reduction in biomass, with the exception of EPOST applications of acetochlor, glufosinate, and glyphosate (76%). In both cases, contrast statements comparing PRE fb POST and POST-only programs were significant ($P \leq .01$) with PRE fb POST programs providing greater reductions to grass (99%) and broadleaf (89%) weed biomass compared with POST-only programs (88 and 85%, respectively) (Table 7).

3.5 | Palmer amaranth seed production

In late August of 2019, the research site experienced a severe hail event that effected Palmer amaranth seed production measured prior to soybean harvest. Palmer amaranth seed production in most treatments was significantly reduced in 2019 compared with 2020, with the exception of the nontreated control (28,703 and 22,550 seeds plant^{-1}, respectively). Therefore, the Palmer seed production was separated and analyzed by year. In 2019, Palmer amaranth seed production was reduced to 0–325 seeds plant^{-1} across PRE fb POST programs, with POST-only programs providing similar reductions (85–4,786 seeds plant^{-1}) (Table 7). This excludes glyphosate fb glyphosate (17,804 seeds plant^{-1}), which was an ineffective herbicide program due to the presence of GR Palmer amaranth at the research site. In 2020, various herbicide programs reduced Palmer amaranth seed production to 0 seeds plant^{-1} (Table 7). However, contrary to the results in 2019, contrast analysis for POST-only programs in 2020 resulted in significantly higher ($P < .01$) Palmer amaranth seed production compared with PRE fb POST programs (7,544 vs. 1,634 seeds plant^{-1}, respectively). Several PRE fb POST herbicide programs provided smaller reductions to Palmer amaranth seed production in 2020 compared with 2019. For example, acetochlor plus dicamba plus metribuzin or acetochlor/fomesafen plus dicamba applied PRE fb POST herbicide programs (which excluded dicamba) reduced seed production to 1,000–4,500 seeds plant^{-1}, a significant increase compared with results from 2019. In total, seven of the evaluated herbicide programs reduced seed production to ≤350 seeds female Palmer amaranth plant^{-1} in both years, and 12 programs reduced seed production to ≤350 seeds plant^{-1} in one or both years (Table 7).

3.6 | Soybean yield

Soybean grain yield was considerably reduced in 2019 due to a hail event at the R4-R5 growth stage that resulted in significant dropped pods and >50% defoliation. Soybean yield was similar across herbicide programs, with an overall range of 1,356–2,461 kg ha^{-1}, compared with the nontreated control (1,089 kg ha^{-2}).

Soybean yield in 2020 was higher compared with 2019. Nonetheless, soybean yield was similar for most PRE fb POST and POST-only programs, with a range of 4,125–5,121 kg ha^{-1} (Table 7). In 2020, the lowest yields were observed in POST-only programs, including acetochlor plus glufosinate plus glyphosate (3,338 kg ha^{-2}), acetochlor plus glufosinate (3,302 kg ha^{-2}) and glyphosate fb glyphosate (4,006 kg ha^{-2}). These results are corroborated by contrast statements comparing yield in PRE fb POST vs. POST-only programs (4,675 and 3,959 kg ha^{-1}, respectively). Contrast analyses comparing soybean yield in EPOST vs. LPOST herbicide programs were significant ($P < .05$), with LPOST application of dicamba or acetochlor plus glufosinate following imazethapyr/pyroxasulfone/saflufenacil outperforming EPOST programs (4,979 and 4,296 kg ha^{-2}, respectively).

TABLE 6 Effect of pre-emergence followed by postemergence (PRE fb POST) herbicide programs for control and density of grass weed species in dicamba/glufosinate/glyphosate-resistant soybean in field experiments conducted in Nebraska in 2019 and 2020

Herbicide program		Grass control				Grass density			
PRE	POST (EPOST fb LPOST)	14 DAEPOST	14 DALPOST	28 DALPOST	Prior to harvest	14 DAEPOST	14 DALPOST	28 DALPOST	Prior to harvest
		%				no. plants m^{-2}			
Nontreated control	—	—	—	—	—	10 d	5 c	14 c	5 c
Acetochlor + dicamba + metribuzin	Acetochlor + dicamba + glyphosate	80 ab	98 a	97	99	1 ab	0 a	0 a	0 a
Acetochlor + dicamba + metribuzin	Acetochlor + dicamba + glyphosate fb glufosinate	97 a	98 a	97	99	0 a	0 a	0 a	0 a
Acetochlor + dicamba + metribuzin	Acetochlor + glufosinate + glyphosate	92 a	97 a	97	99	0 a	0 a	0 a	0 a
Acetochlor + dicamba + metribuzin	Acetochlor + glyphosate fb glufosinate	94 a	98 a	97	99	1 abc	0 a	0 a	0 a
Acetochlor/fomesafen + dicamba	Acetochlor + dicamba + glyphosate	90 a	98 a	97	99	1 ab	0 a	0 a	0 a
Acetochlor/fomesafen + dicamba	Acetochlor + glufosinate + glyphosate	90 a	98 a	97	99	0 a	0 a	0 a	0 a
Dicamba + flumioxazin	Acetochlor + dicamba + glyphosate	86 ab	98 a	95	99	1 ab	0 a	0 a	0 a
Dicamba + flumioxazin	Acetochlor + glufosinate + glyphosate	85 ab	97 a	90	95	1 abc	0 a	1 ab	0 a
—	Acetochlor + glufosinate + glyphosate	86 ab	93 b	94	87	4 bcd	2 bc	3 b	3 bc
—	Acetochlor + glufosinate	91 a	96 ab	93	81	4 bcd	1 ab	1 ab	1 abc
—	Acetochlor + dicamba fb glufosinate + glyphosate	57 b	96 ab	93	93	5 cd	1 ab	1 ab	1 abc
—	Glyphosate fb glyphosate	92 a	96 ab	97	93	2 abc	0 a	1 ab	1 ab
—	Glufosinate fb glufosinate	93 a	98 a	95	99	2 abc	0 a	0 a	0 a

(Continues)

TABLE 6 (Continued)

Herbicide program		Grass control				Grass density			
PRE	POST (EPOST fb LPOST)	14 DAEPOST	14 DALPOST	28 DALPOST	Prior to harvest	14 DAEPOST	14 DALPOST	28 DALPOST	Prior to harvest
Imazethapyr/pyroxasulfone/ saflufenacil	– fb acetochlor + dicamba	90 a	96 ab	97	93	2 abc	1 abc	1 ab	1 abc
Imazethapyr/pyroxasulfone/ saflufenacil	– fb acetochlor + glufosinate	94 a	98 a	97	99	1 ab	0 a	0 a	0 a
P value		<.001	.034	.059	.065	<.001	<.001	<.001	<.001
Contrasts[a]									
PRE fb POST vs. POST only		NS	98 vs. 94**	98 vs. 92**	98 vs. 90**	1 vs. 4**	0 vs. 1**	0 vs. 2**	0 vs. 2**
EPOST vs. EPOST fb LPOST		NS	NS	NS	NS	NS	NS	NS	NS
EPOST vs. LPOST		NS	NS	NS	NS	NS	NS	NS	NS
EPOST fb LPOST vs. LPOST		NS	NS	NS	NS	NS	NS	NS	NS

Notes. DAEPOST, days after EPOST; DALPOST, days after LPOST; EPOST, early POST; LPOST, late POST; NS, nonsignificant ($P \geq .05$). Grass weed pressure was composed namely of green foxtail and giant foxtail with minor pressure from other *Poaceae* species including large crabgrass. Prior to analysis, control data were logit transformed and density data were log(x+1) transformed and fit to generalized linear mixed models and compared with nontransformed models. Back transformed values are presented based on interpretations of transformed data. 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.

[a] Selected a priori contrasts.

*Significant at $P < .05$. ** Significant at $P < .01$.

TABLE 7 Effect of pre-emergence followed by postemergence (PRE fb POST) herbicide programs for weed biomass reduction measured at 28 days after late post-emergence herbicide (DALPOST), Palmer amaranth seed production measured prior to harvest, soybean yield, and gross revenue in field experiments conducted in Nebraska in 2019 and 2020

Herbicide Program[a]		28 DALPOST biomass reduction		Palmer amaranth seed production		Soybean yield		Gross revenue[a]	
PRE	POST (EPOST fb LPOST)	Broadleaf	Grass	2019	2020	2019	2020	2019	2020
		%		no. seeds plant^{-1}		kg ha^{-1}		\$ ha^{-1}	
Nontreated control	—	—	—	28,703 b	22,550 c	1,089 b	1,548 d	337.12	488.27
Acetochlor + dicamba + metribuzin	Acetochlor + dicamba + glyphosate	100 a	100 a	0 a	0 a	1,356 ab	4,648 ab	419.78	1,466.06
Acetochlor + dicamba + metribuzin	Acetochlor + dicamba + glyphosate fb glufosinate	100 a	100 a	21 ab	0 a	2,154 ab	4,323 ab	666.81	1,363.55
Acetochlor + dicamba + metribuzin	Acetochlor + glufosinate + glyphosate	94 a	100 a	62 ab	1,159 bc	2,439 a	4,512 ab	755.04	1,423.16
Acetochlor + dicamba + metribuzin	Acetochlor + glyphosate fb glufosinate	97 a	100 a	94 ab	3,264 bc	2,426 a	4,725 ab	751.02	1,490.34
Acetochlor/fomesafen + dicamba	Acetochlor + dicamba + glyphosate	100 a	99 a	115 ab	0 a	2,250 a	4,981 ab	696.53	1,571.09
Acetochlor/fomesafen + dicamba	Acetochlor + glufosinate + glyphosate	93 a	100 a	96 ab	4,653 bc	1,892 ab	4,373 ab	585.71	1,379.32
Dicamba + flumioxazin	Acetochlor + dicamba + glyphosate	100 a	100 a	121 ab	0 a	1,902 ab	4,824 ab	588.80	1,521.57
Dicamba + flumioxazin	Acetochlor + glufosinate + glyphosate	98 a	96 ab	325 ab	142 b	2,084 ab	4,318 ab	645.14	1,361.97
—	Acetochlor + glufosinate + glyphosate	92 a	76 b	1,068 ab	4,809 bc	1,838 ab	3,338 c	568.99	1,052.86
—	Acetochlor + glufosinate	90 a	85 ab	4,786 ab	10,463 c	1,475 ab	3,302 c	456.62	1,041.51
—	Acetochlor + dicamba fb Glufosinate + glyphosate	93 a	88 ab	85 ab	1,129 bc	2,104 ab	4,125 abc	651.34	1,301.09
—	Glyphosate fb glyphosate	48 b	95 ab	17,804 b	7,826 c	1,660 ab	4,006 bc	513.89	1,263.56
—	Glufosinate fb glufosinate	97 a	99 a	346 ab	2,759 bc	2,357 a	5,015 ab	729.66	1,581.82

(Continues)

TABLE 7 (Continued)

Herbicide Program[a]		28 DALPOST biomass reduction		Palmer amaranth seed production		Soybean yield		Gross revenue[a]	
PRE	**POST (EPOST fb LPOST)**	**Broadleaf**	**Grass**	**2019**	**2020**	**2019**	**2020**	**2019**	**2020**
Imazethapyr/pyroxasulfone/ saflufenacil	– fb acetochlor + dicamba	98 a	94 ab	119 ab	0 a	2,050 ab	4,816 ab	634.62	1,519.05
Imazethapyr/pyroxasulfone/ saflufenacil	– fb acetochlor + glufosinate	100 a	100 a	58 ab	0 a	2,461 a	5,121 a	761.85	1,615.25
P value		0.002	< 0.00	< 0.001	< 0.001	< 0.001	< 0.001	—	—
Contrasts[b]									
PRE fb POST vs. POST only		89 vs. 85**	99 vs. 88**	NS	1,634 vs. 7,544**	NS	4,675 vs. 3,959**	—	—
EPOST vs. EPOST fb LPOST		NS	NS	NS	NS	1,947 vs. 2,265*	NS	—	—
EPOST vs. LPOST		NS	NS	NS	NS	NS	4,296 vs. 4,979*	—	—
EPOST fb LPOST vs. LPOST		NS	NS	NS	NS	NS	NS	—	—

Note. DAEPOST, days after EPOST; EPOST, early POST; LPOST, late POST; POST, postemergence herbicide; PRE, pre-emergence herbicide; NS, nonsignificant ($P \geq .05$). Prior to analysis, biomass reduction, seed production, and yield data were logit, log(x+1) and square-root transformed, respectively. Variables were fit to generalized linear mixed models and compared with nontransformed models. Back transformed values are presented based on interpretations of transformed data. 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.

[a] Gross Revenue was calculated by multiplying soybean yield by the average price received in Nebraska from in 2019 (\$0.3095 kg^{-1}) and 2020 (\$0.3154 kg^{-1}).

[b] Selected a priori contrasts.

*Significant at $P < .05$. ** Significant at $P < .01$.

3.7 | Economic analysis

Gross revenues were lower in 2019 due to reduced soybean grain yield compared with 2020, with an overall experimental range of US\$419–\$762 ha^{-1} in 2019, and \$1,041–\$1,615 ha^{-1} in 2020 (Table 7). The total cost of weed management programs was the lowest for POST-only programs, with the minimum and maximum costs of \$84 and \$163 ha^{-1}, respectively, and an overall average cost of \$108 ha^{-1}. In contrast, the total cost for PRE fb POST herbicide programs was higher, with the minimum and maximum costs of \$168 and \$305 ha^{-1}, respectively, and an overall average cost of \$224 ha^{-1}.

As a consequence of reduced soybean yield in 2019 due to late-season hail, the gross profit margins in 2019 were considerably reduced compared with 2020. Despite the differences in soybean yield between years, imazethapyr/pyroxasulfone/saflufenacil fb acetochlor plus glufosinate (\$593.50 and \$1,446.90) and glufosinate fb glufosinate (\$629.04 and \$1,481.20) provided the highest gross profit margin in 2019 and 2020, respectively. The gross profit margins for most of the herbicide programs were similar in 2019, whereas in 2020, most PRE fb POST programs had higher gross profit margins than POST-only programs (Table 8).

The benefit/cost ratios in this study varied between years and herbicide programs. In 2019, reductions to yield potential due to late-season hail resulted in decreased benefit/cost ratios compared with 2020. Across herbicide programs, EPOST fb LPOST programs had the highest average benefit/cost ratios in 2019 (2.64) and 2020 (8.37) due to better performance of glufosinate fb glufosinate program (3.90 and 10.87, respectively) (Table 8). The benefit/cost ratios for the other PRE fb POST and POST-only programs ranged from 1.38 to 2.02 in 2019, and 3.45 to 5.98 in 2020. Despite widespread prevalence of GR Palmer amaranth in both years, the benefit/cost ratio in 2020 for glyphosate fb glyphosate was the second-highest observed, at 9.26 (Table 8); primarily due to the low cost of glyphosate combined with the high level of control it provided for all grass and other broadleaf weed species.

4 | DISCUSSION

Results of this study support the recommendation of PRE herbicides with multiple effective SOA in DGGR soybean, and are consistent with previously reported results for control of grass and broadleaf weeds. A mixture of acetochlor and dicamba, flumioxazin, fomesafen, and metribuzin has been reported to provide excellent control of GR Palmer amaranth. In a multistate trial conducted in soybean, Meyer et al. (2015) reported that tank-mixed and premixed combinations of acetochlor, dicamba, flumioxazin, fomesafen, and metribuzin along with pyroxasulfone or *S*-metolachlor provided ≥93% control of Palmer amaranth 21 DAPRE. These results were similar to the findings of Cahoon et al. (2015) in cotton, where microencapsulated formulation of acetochlor provided 84% control of GR Palmer amaranth 21–28 DAPRE in North Carolina. Control of other broadleaf and grass weeds observed in this study was similar to previous findings in Nebraska where acetochlor mixed with flumioxazin, fomesafen, and sulfentrazone plus chlorimuron provided 99% control of velvetleaf and grass weeds at 15 DAPRE (Aulakh & Jhala, 2015). Biomass reduction at 35 DAPRE for all evaluated weed species (≤97%) was similar to those reported by Schultz et al. (2015), in which PRE fb POST programs provided greater than 98% biomass reductions compared with POST-only programs.

The results of this study support the efficacy of mixtures of acetochlor, glufosinate, and dicamba at EPOST and LPOST in DGGR soybean. However, special care must be taken to ensure any LPOST applications are applied within updated use restrictions. Across PRE fb POST and POST-only programs, control of most grass and broadleaf weeds was similar for glufosinate and dicamba 14 DAEPOST, with the exception of common lambsquarters, which was reduced in programs that received glufosinate, or glufosinate mixed with acetochlor. These results stand in contrast with the findings of Everman et al. (2007), in which glufosinate provided ≥90% control of broadleaf weeds, including common lambsquarters. However, reduced control of common lambsquarters by glufosinate applied EPOST (70–80%) in this study is similar to results previously reported by Aulakh and Jhala (2015) in Nebraska, where EPOST applications of glufosinate alone or mixed with very long chain fatty acid inhibitors (e.g., acetochlor, pyroxasulfone, *S*-metolachlor) at EPOST provided ≤82% control at the end of the season. Furthermore, control of common lambsquarters was highest in PRE fb POST programs compared with POST-only programs, further indicating the importance of PRE herbicides for control of broadleaf weeds, as reported by Schultz et al. (2015).

Despite the presence of GR Palmer amaranth at these sites, the high efficacy of glyphosate at EPOST or LPOST for control of non-GR weeds was also identified in the current study. For programs that received glufosinate at EPOST and glyphosate at LPOST, common lambsquarters control at 14 and 28 DALPOST increased to comparable levels of programs that received glyphosate at EPOST. Likewise, the control of velvetleaf at 14 and 28 DALPOST further highlighted the value of glyphosate or glufosinate following EPOST applications of dicamba. In a study evaluating the interaction of dicamba, fluthiacet-methyl, and glyphosate in DGR soybean, De Sanctis and Jhala (2021) reported that dicamba applied alone provided <75% control of velvetleaf when plants were taller than 12 cm at the time of application.

TABLE 8 Herbicide program costs and effect of herbicide program on gross profit margin and benefit/cost ratios in dicamba/glufosinate/glyphosate-resistant soybean in field experiments conducted in 2019 and 2020 in Nebraska

Herbicide program		**Weed management program cost**[a]					**Gross profit margin**[b]		**Benefit/cost ratio**[c]	
PRE	**POST (EPOST fb LPOST)**	**PRE**	**EPOST**	**LPOST**	**APP**	**Total**	**2019**	**2020**	**2019**	**2020**
		$ ha^{-1}					$ ha^{-1}		$ ha^{-1}	
Nontreated control	—	—	—	—	—	—	337.12	488.27	—	—
Acetochlor + dicamba + metribuzin	Acetochlor + dicamba + glyphosate	106.06	99.73	—	49.00	254.78	164.99	1,211.27	0.32	3.84
Acetochlor + dicamba + metribuzin	Acetochlor + dicamba + glyphosate fb glufosinate	106.06	99.73	31.36	67.95	305.09	361.72	1,058.45	1.08	2.87
Acetochlor + dicamba + metribuzin	Acetochlor + glufosinate + glyphosate	106.06	84.95	—	36.25	227.26	527.78	1,195.90	1.84	4.11
Acetochlor + dicamba + metribuzin	Acetochlor + glyphosate fb glufosinate	106.06	55.42	31.36	55.20	248.04	502.98	1,242.31	1.67	4.04
Acetochlor/fomesafen + dicamba	Acetochlor + dicamba + glyphosate	94.89	99.73	—	49.00	243.62	452.92	1,327.48	1.48	4.44
Acetochlor/fomesafen + dicamba	Acetochlor + glufosinate + glyphosate	94.89	84.95	—	36.25	216.09	369.62	1,163.23	1.15	4.12
Dicamba + flumioxazin	Acetochlor + dicamba + glyphosate	56.02	99.73	—	49.00	204.75	384.06	1,316.82	1.23	5.05
Dicamba + flumioxazin	Acetochlor + glufosinate + glyphosate	56.02	84.95	—	36.25	177.22	467.92	1,184.75	1.74	4.93
—	Acetochlor + glufosinate + glyphosate	0.00	84.95	—	18.95	103.91	465.08	948.96	2.23	5.43
—	Acetochlor + glufosinate	0.00	71.49	—	18.95	90.44	366.18	951.07	1.32	6.12
—	Acetochlor + dicamba fb glufosinate + glyphosate	0.00	86.26	44.82	31.70	162.79	488.55	1,138.31	1.93	4.99
—	Glyphosate fb glyphosate	0.00	22.93	22.93	37.91	83.77	430.12	1,179.79	2.11	9.26
—	Glufosinate fb glufosinate	0.00	31.36	31.36	37.91	100.62	629.04	1,481.20	3.90	10.87
Imazethapyr/pyroxasulfone/saflufenacil	– fb acetochlor + dicamba	60.61	—	86.26	49.00	195.88	438.74	1,323.17	1.52	5.26
Imazethapyr/pyroxasulfone/saflufenacil	– fb acetochlor + glufosinate	60.61	—	71.49	36.25	168.35	593.50	1,446.90	2.52	6.69

Notes. APP, custom application cost; EPOST, early POST; LPOST, late POST; POST, postemergence herbicide; PRE, pre-emergence herbicide.

[a] Weed management program costs were averaged from three independent sources in Nebraska and include custom application: PRE (US$17.30 ha^{-1} application^{-1}), non–dicamba-containing POST (US$18.94 ha^{-1} application^{-1}), and dicamba-containing POST (US$31.71 ha^{-1} application^{-1}).

[b] Gross profit margins were calculated as gross revenue minus weed management program cost.

[c] Benefit/cost ratio was calculated as gross revenue minus gross revenue in the nontreated control divided by weed management program cost.

For management of GR Palmer amaranth with POST herbicides, it has been previously reported that standalone dicamba provided the lowest density of GR Palmer amaranth regardless of the inclusion of acetochlor (Inman et al., 2016). The importance of POST herbicide superseding the inclusion of acetochlor as an overlapping residual was also reported in the current study. Selection of a PRE fb POST program (of either dicamba, glufosinate, or both) seemed to have a more significant effect on reducing GR Palmer amaranth density and seed production, as well as for higher soybean yield. However, definitive statements on the value of acetochlor are difficult to make in the current study due to the lack of a PRE fb POST program without an overlapping residuals of acetochlor, and only two POST-only programs (glyphosate fb glyphosate and glufosinate fb glufosinate).

Across most broadleaf and grass weeds, the value of mixing additional PRE or POST herbicides with premixed PRE herbicide products was also identified. In many programs receiving the same EPOST or EPOST fb LPOST programs, control was increased for all evaluated weed species in three-way SOA tank-mixes or premixes compared with two-way SOA mixes (dicamba plus flumioxazin). This mirrors results reported by Jha et al. (2015), in which the inclusion of pendimethalin in a mixture with other premixed residual products provided improved weed control compared with the premixed products alone. The mixtures of multiple effective SOA at PRE or POST is also widely considered to be best management practices for reducing the selection of HR weed populations (Norsworthy et al., 2012).

The reduction of GR Palmer amaranth seed production observed in this study is similar to the findings of Crow et al. (2015), in which residual soil-applied herbicides mixed with paraquat applied after crop harvest reduced escaped GR Palmer amaranth seed production from 1,200 to 0 seeds m^{-2} during a 2-yr study in Tennessee. Likewise, in Arkansas, a deep tillage/cover crop study conducted by Bell et al. (2015) reported that GR Palmer amaranth escapes produced 10,300–17,900 seeds m^{-2} despite the use of a range of herbicide programs including paraquat, glyphosate, glufosinate, fomesafen/*S*-metolachlor, acetochlor, and flumioxazin/pyroxasulfone in a bare-ground study. Due to the sampling differences in this study (e.g., three randomly selected female plants plot^{-1}) compared with previously reported literature, seed reductions observed in this study must be taken in the context of reduction from the nontreated control, of which PRE fb POST programs provided robust reductions to seed production, and thus reduced deposits to the seedbank.

The high gross profit observed in the glufosinate fb glufosinate program supports the effectiveness of glufosinate to control the grass and broadleaf weed spectrum present at the research site in both years. These results are consistent with previous literature that reported glufosinate provided robust weed control in glufosinate-resistant crops (Aulakh & Jhala, 2015; Butts et al., 2016; Everman et al., 2007; Schultz et al., 2015; Striegel et al., 2020). Due in part to the reduced input costs for herbicides, adjuvants, and custom application costs, glufosinate fb glufosinate had the highest gross profit margins and benefit/cost ratios in both 2019 and 2020. However, with the recent report of glufosinate-resistant Palmer amaranth in Arkansas (Barber et al., 2021), special care should be taken to use herbicide programs that include multiple effective sites of action rather than reliance on herbicides of the same SOA.

Previous studies have reported on the importance of using PRE herbicides in soybean and the positive effect they can have on soybean yield and net income (Rosenbaum et al., 2013). With the exception of glufosinate fb glufosinate programs, all PRE fb POST programs provided higher yield, gross profit margins, and benefit/cost ratios compared with the POST-only programs evaluated in this study. As such, adoption and implementation of PRE herbicide programs into DGGR soybean systems should be recommended to producers.

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AUTHOR CONTRIBUTIONS

Adam Striegel: Data curation; Formal analysis; Methodology; Resources; Software; Writing – original draft; Writing – review & editing. Amit Jhala: Conceptualization; Funding acquisition; Methodology; Project administration; Resources; Software; Supervision; Visualization; Writing – review & editing

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