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Economics of herbicide programs for weed control in conventional, glufosinate, and dicamba/glyphosate-resistant soybean across Nebraska

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Abstract

Despite widespread adoption of dicamba/glyphosate-resistant (DGR) soybean [*Glycine max* (L.) Merr.] in Nebraska and across the United States in recent years, economic information comparing herbicide programs with glufosinate-resistant (GLU-R) and conventional soybean is not available. The objectives of this study were to evaluate weed control efficacy, crop safety, gross profit margin, and benefit/cost ratios of herbicide programs with multiple sites of action in DGR, GLUR, and conventional soybean. Field

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experiments were conducted in 2018 and 2019 at three irrigated and two rain-fed locations across Nebraska, for a total of 10 site-years. Herbicides applied pre-emergence (PRE) that included herbicides with three sites of action provided 85–99% control of common lambsquarters (*Chenopodium album* L.), Palmer amaranth (*Amaranthus palmeri* S. Watson), velvetleaf (*Abutilon theophrasti* Medik.), and a mixture of foxtail (*Setaria* spp.) and *Poaceae* species. Pre-emergence herbicides evaluated in this study provided 72–96% weed biomass reduction and 61–79% weed density reductions compared with the nontreated control. Herbicides applied post-emergence (POST; dicamba plus glyphosate, glyphosate, glufosinate, and acetochlor plus clethodim plus lactofen) provided 93–99% control of all weed species 28 d after POST (DAPOST). Herbicides applied POST provided 89–98% weed biomass reduction and 86–96% density reduction at 28 DAPOST. For individual site-years, yield was often similar for PRE followed by POST herbicide programs in herbicide-resistant (HR) and conventional soybean. Gross profit margins and benefit/cost ratios were higher in HR soybean than in conventional soybean, although price premiums for conventional soybean can help compensate for increased herbicide costs.

Core Ideas

- Weed control and yield were similar for most herbicide programs tested in this study.
- Gross profit margin was highest in herbicide-resistant soybean traits.
- Premiums for conventional soybean can compensate increased herbicide cost.

Abbreviations:

DAPOST, days after post-emergence application; **DAPRE**, days after pre-emergence application; **DGR**, dicamba/glyphosate-resistant; **fb**, followed by; **GLU-R**, glufosinate-resistant; **GR**, glyphosate resistant; **HR**, herbicide-resistant; **POST**, post-emergence; **PPO**, protoporphyrinogen oxidase; **PRE**, pre-emergence; **SOA**, site of action

1 Introduction

Over the last few decades, commercialization of herbicide-resistant (HR) crops has led to changes in weed management strategies deployed in agronomic crop production systems in the United States. Herbicide-resistant crops provide flexibility to apply nonselective, post-emergence (POST) herbicides for broad-spectrum weed control, and their adoption rates in the United States have remained high since 2014, with 90 and 94% of domestic corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] acreage, respectively (USDA-ERS, 2018). In recent years, soybean cultivars resistant to multiple herbicide sites of

action (SOA) have been commercialized. These cultivars stack existing glyphosate-resistant (GR) or glufosinate-resistant (GLU-R) traits with synthetic auxin herbicide 2,4-D (2,4-dichlorophenoxyacetic acid) or dicamba (3,6-dichloro-2-methoxybenzoic acid) resistance or provide resistance to isoxaflutole, a hydroxyphenyl-pyruvate-dioxygenase-inhibiting herbicide (Beckie, Ashworth, & Flower, 2019). The use of multiple HR soybean cultivars provides producers additional weed management options; however, confirmation of 48 GR weed species globally and 17 GR species in the United States (Heap, 2020) serve as a reminder of the effects poor stewardship and over-reliance on a single herbicide SOA can have for the evolution of HR weeds. Additionally, it emphasizes the critical role herbicide stewardship will continue to play in preserving the utility of new multiple HR trait technologies, particularly in no-till corn-soybean cropping systems (Gage, Krausz, & Walters, 2019).

In 2015, a statewide survey of corn and soybean producers reported that 60% had incorporated the use of soil-applied residual herbicides in soybean to manage GR weeds (Sarangi & Jhala, 2018). In Nebraska, six GR weed species have been confirmed: common ragweed (*Ambrosia artemisiifolia* L.), waterhemp [*Amaranthus tuberculatus* (Moq.) J. D. Sauer], giant ragweed (*Ambrosia trifida* L.), kochia [*Bassia scoparia* (L.) A. J. Scott], horseweed (*Erigeron canadensis* L.), and Palmer amaranth (*Amaranthus palmeri* S. Watson) (Knezevic et al., 2020; Sarangi & Jhala, 2018). Integration of pre-emergence (PRE) herbicide use by soybean producers in Nebraska is similar to national trends, which have seen PRE herbicide use increase from 25 to 70% of soybean acreage in the United States from 2000 to 2015 (Peterson, Collavo, Ovejero, Shivrain, & Walsh, 2018). A 2015 survey in Nebraska revealed that producers relied primarily on protoporphyrinogen oxidase (PPO)-inhibiting and acetolactate synthase-inhibiting herbicides as PRE herbicides in soybean. The most commonly used herbicides were cloransulam-methyl plus sulfentrazone and flumioxazin alone or in tank-mixture with chlorimuron-ethyl and thifensulfuron-methyl (Sarangi & Jhala, 2018). As more producers adopt soil-applied residual herbicides at crop planting, there will be opportunities to improve herbicide stewardship through the use of robust herbicide rotations in combination with tank-mixtures of herbicides with multiple effective SOAs (Beckie & Reboud, 2009; Busi, Powles, Beckie, & Renton, 2019).

Previous research has indicated that the combination of herbicide rotation and tank-mixtures can delay the evolution of new HR weed biotypes (Beckie et al., 2019; Busi et al., 2019; Gage et al., 2019), and these are endorsed as best management practices in both nonintegrated and integrated weed management programs (Knezevic & Cassman, 2003; Norsworthy et al., 2012). Research on HR weed populations has also shown that tank-mixtures with multiple effective SOAs can control GR weed biotypes, such as common ragweed (Barnes, Knezevic, Sikkema, Lindquist, & Jhala, 2017; Byker et al., 2018), waterhemp (Jhala, Sandell, Sarangi, Kruger, & Knezevic, 2017), horseweed (Chahal & Jhala, 2019), and kochia (Sbatella et al., 2019). Similarly, tank-mixtures with multiple effective SOAs have been shown to control other HR weed biotypes, such as PPO-inhibitor resistant Palmer amaranth (Schwartz-Lazaro, Norsworthy, Scott, & Barber, 2017) or atrazine/hydroxyphenyl-pyruvate-dioxygenase inhibitor-resistant Palmer amaranth (Chahal & Jhala, 2019).

In response to concerns about resistance to soil-applied residual herbicides, pesticide manufacturers have commercialized “ready-to-use” pre-mixture formulations of soil-applied residual herbicides with multiple SOAs for use in many agronomic crops, including soybean (Norsworthy et al., 2012). Although stewardship risks associated with application of pre-mixture products below labeled rates exist (Beckie & Harker, 2017; Owen, 2016), widespread adoption and frequent use of pre-mixture products warrants further study and comparison, particularly in soybean with multiple HR traits. Assessments of economic benefits of incorporating PRE herbicide programs in conventional, GR, and glufosinate-resistant (GLU-R) (LibertyLink) soybean systems were examined in a multiyear study conducted in Missouri comparing combinations of PRE and/or POST herbicide programs (Rosenbaum, Massey, & Bradley, 2013). Results from this study indicated that the use of PRE herbicide programs provided the best opportunities for weed control and higher net returns; however, PRE followed by (fb) POST programs provided greater control of waterhemp regardless of soybean HR trait (Rosenbaum et al., 2013). Likewise, a multi-year study in Nebraska compared pre-plant, PRE, and/or POST herbicide programs for control of GR common ragweed and reported that pre-plant fb POST and PRE fb POST herbicide programs provided the highest and most economical control of GR common ragweed in GLU-R soybean (Barnes et al., 2017).

As producers struggle to manage GR weeds using POST herbicides, many have considered rotation to dicamba/glyphosate-resistant (DGR) or GLU-R soybean traits (Werle, Oliveira, et al., 2018). In a 2015 statewide survey conducted in Nebraska, 34% of row crop producers responded positively toward rotation (Sarangi & Jhala, 2018). The GLU-R cultivars currently make up about 20% of soybean grown in the United States. This has increased substantially over the last 5 yr due to the growing need to control GR weeds and troublesome pigweed (*Amaranthus* spp.) species (Beckie et al., 2019). However, adoption of GLU-R soybean in Nebraska has historically been 5.2% or less of total soybean production (Sarangi & Jhala, 2018). Glufosinate applied alone or in tank-mixture has been shown to be effective for controlling GR weeds such as waterhemp, Palmer amaranth, or common ragweed and remains a viable POST option for producers (Barnes et al., 2017; Butts et al., 2016; Jhala et al., 2017; Schultz, Myers, & Bradley, 2015).

Dicamba/glyphosate-resistant (Roundup Ready 2 Xtend) soybean received USEPA approval in 2017. A statewide survey of Nebraska soybean producers indicated that 8.7% of total soybean planted was DGR soybean in 2017 (Werle, Oliveira, et al., 2018). Popularity of DGR soybean cultivars both in Nebraska and the United States has increased since their introduction. Currently, DGR soybeans are estimated to be the most commonly planted soybean HR trait in the United States (Anonymous, 2020). Beckie et al. (2019) estimated that DGR soybean has at least a 50% market share in the United States.

Producers are continually under pressure to reduce production costs. Studies comparing weed control, crop yield, and economic return in conventional and HR soybean have been conducted (Owen et al., 2010; Peterson, Thompson, & Minihan, 2017; Rosenbaum et al., 2013); however, these studies did not focus on commercially available pre-mixture PRE herbicide products with three SOAs or the economic analysis of DGR, GLU-R, and conventional soybean systems. The objectives of this study were to evaluate PRE fb POST herbicide programs with multiple SOA in DGR, GLU-R, and conventional soybean for weed control efficacy, crop safety, gross profit margin, and benefit/cost ratio at five locations across Nebraska.

2 Materials and methods

2.1 Study locations

In 2018 and 2019, field experiments were conducted in northeastern (Concord), eastern (Lincoln), south-central (Clay Center), west-central (North Platte), and western (Scottsbluff) Nebraska at University of Nebraska-Lincoln Research and Extension Centers and Agricultural Laboratories under irrigated (Clay Center, North Platte, and Scottsbluff) and rain-fed (Concord and Lincoln) conditions. For all site-years, experiments were established in fields following a corn–soybean crop rotation. All locations received reduced tillage or an early spring pre-plant herbicide application to control winter annual weeds. Experimental sites were primarily infested with common lambsquarters (*Chenopodium album* L.); Palmer amaranth; velvetleaf (*Abutilon theophrasti* Medik.); and a mixture of bristly foxtail [*Setaria verticillata* (L.) Beauv.], giant foxtail (*Setaria faberi* Herrm.), green foxtail [*Setaria viridis* (L.) P. Beauv.], yellow foxtail [*Setaria pumila* (Poir.) Roem. & Schult.], large crabgrass [*Digitaria sanguinalis* (L.) Scop.], and field sandbur (*Cenchrus spinifex* Cav.).

2.2 Experimental design

Field experiments were arranged in a split-block design with four replications (Federer & King, 2006). The PRE herbicide program (**Table 2**) was the whole plot factor in a randomized complete block, and soybean-cultivar/trait [Roundup Ready 2 Xtend (RR2X), LibertyLink, conventional] with subsequent POST herbicide program (Table 2) was the subplot factor. This resulted in seven nonstandard incomplete “column” blocks, each containing only four of the seven PRE herbicide treatments across four replications. The incomplete blocking factor was added to accommodate experimental locations without access to research plot/packet planters and to simplify field operations. Plot size was 3m wide (four soybean rows spaced 0.75m apart) by 9 m in length. To protect dicamba-sensitive cultivars from direct spray drift, DGR soybean was planted flanking either side of plots receiving POST herbicide applications of dicamba and treated with POST applications of glyphosate, resulting in a 3-m buffer between dicamba applications and dicamba-sensitive cultivars. In addition to providing a 3-m buffer, glyphosate was

Table 1 Soybean cultivars, planting dates, and pre-emergence (PRE) and postemergence (POST) herbicide application dates in field experiments conducted across five locations in Nebraska to determine economics of herbicide programs for weed control in conventional, glufosinate-resistant, and dicamba/glyphosate-resistant soybean in 2018 and 2019.

Study location ^a	HR-trait ^b	Cultivar ^c	Company	Planting date	PRE herbicide application date	POST herbicide application date
Clay Center	DGR	S29-k3x NK	Syngenta Seeds	7 May 2018, 15 May 2019	7 May 2018, 15 May 2019	4 June 2018, 13 June 2019
	GLU-R CON	P31T02L A3253	Corteva AgriScience Bayer Crop Science			
Concord	DR	27MX8 NK	Syngenta Seeds	5 June 2018, 6 June 2019	6 June 2018; 8 June 2019	20 July 2018, 11 Jul 2019
	GLU-R CON	CZ2601LL P29T50	BASF Corporation Corteva AgriScience			
Lincoln	DGR	S29-k3x NK	Syngenta Seeds	13 May 2018, 17 May 2019	11 May 2018, 17 May 2019	11 June 2018, 21 June 2019
	GLU-R CON	P31T02L A3253	Corteva AgriScience Bayer Crop Science			
North Platte ^d	DGR	28XT58	Loveland Products	20 May 2018, 31 May 2019	18 May 2018, 4 June 2019	26 June 2018, 11 July 2019
	GLU-R CON	CZ2601LL A3253	BASF Corporation Bayer Crop Science			
Scottsbluff ^d	DGR	AG20X7	Bayer Crop Science	21 May 2018, 5 June 2019	21 May 2018, 5 June 2019	18 July 2018, 26 July 2019
	GLU-R CON	H20L3 U11-917032 A2035	Hefty Seed Company Husker Genetics Bayer Crop Science			

a. Soil tests for the study locations: Clay Center (hastings silt loam with pH 6.5; 17% sand, 58% silt, and 25% clay; 3.0% organic matter [OM]); Concord (silt loam with pH 6.4; 20% sand, 54% silt, 26% clay; 3.5% OM; and cation exchange capacity [CEC] of 23.8); Lincoln (silt clay loam with pH 5.6; 19% sand, 54% silt, 27% clay; 3.3% OM); North Platte (sandy loam with pH 7.5; 57% sand, 32% silt, 11% clay; 2.1% OM; and CEC of 11.7); Scottsbluff (sandy loam with pH 7.5; 78% sand, 8% silt, 13% clay; and CEC of 7.8).

b. CON, conventional; DGR, dicamba/glyphosate-resistant; GLU-R, glufosinate-resistant; POST, Post-emergent herbicide; PRE, Pre-emergent herbicide.

c. Soybean cultivar A3253 was replanted on 11 June 2019 due to poor initial crop stand.

d. Prior to planting, 122 kg N and 45 kg P₂O₅ ha⁻¹ were broadcasted, with 4.7 L ha⁻¹ of 6% chelated iron applied in-furrow to reduce iron chlorosis.

applied POST in DGR soybean to represent the production practice of planting DGR soybeans but not applying dicamba POST. Soybean cultivars were selected based on maturity group requirements for each location (1.8–2.3 for Scottsbluff; 2.6–3.2 cultivar for Clay Center, Concord, Lincoln, and North Platte) and iron chlorosis resistance for Scottsbluff. Soybean cultivars were planted at 296,500 seeds ha⁻¹ at Scottsbluff and 333,500 seeds ha⁻¹ (De Bruin & Pedersen, 2008; Specht, 2016) at other locations (**Table 1**).

Table 2 Pre-emergence herbicide (PRE) and postemergence herbicide (POST) herbicide programs in field experiments conducted across five locations in Nebraska to determine economics of herbicide programs for weed control in conventional, glufosinate-resistant, and dicamba/glyphosate-resistant soybean in 2018 and 2019.

<i>Herbicide program</i>	<i>Rate</i>	<i>Trade name</i>	<i>Manufacturer</i>	<i>Adjuvants^a</i>	<i>Herbicide program cost^b</i>	<i>Nozzles, carrier volume</i>
	g ai or ae ha ⁻¹				US\$ ha ⁻¹	L ha ⁻¹
Nontreated control						
Weed-free control	1,680	Warrant	Bayer		118.04	AIXR, 140
	215	Zidua Pro	BASF			
PRE						
Sulfentrazone/ S-metolachlor + metribuzin	1,960	Authority Elite	FMC		134.25	AIXR, 140
	700	Tricor 4F	UPI			
Chlorimuron/ flumioxazin/ thifensulfuron-methyl	94	Enlite	Corteva		58.30	AIXR, 140
Flumioxazin/ pyroxasulfone + metribuzin	160	Fierce	Valent		83.66	AIXR, 140
	210	Tricor 4F	UPI			
Chlorimuron/ flumioxazin/metribuzin	374	Trivence	Corteva		73.48	AIXR, 140
Imazethapyr/ pyroxasulfone/ saflufenacil	215	Zidua Pro	BASF		77.92	AIXR, 140
PRE fb POST						
Dicamba + glyphosate	560 + 1,540	Xtendimax + Roundup Powermax	Bayer	DRA,WC	91.31	TTI, 140
Glyphosate	1,540	Roundup Powermax	Bayer	AMS	33.46	AIXR, 140
Glufosinate	656	Liberty	BASF	AMS	50.31	XR, 187
Acetochlor + clethodim + lactofen	1,680	Warrant	BayerValent	AMS, COC	148.74	AIXR, 140
	119 + 220	Select Max + Cobra				

Note. ai, active ingredient; ae, acid equivalent; AMS, ammoniumsulfate; COC, crop oil concentrate; DRA, drift reducing agent; fb, followed by; POST, Post-emergent herbicide; PRE, Pre- for pre-emergence herbicide; WC, non-AMS water conditioner.

a. AMS at 1–1.25% (wt/v), COC at 1% v/v, DRA at 0.5–1% v/v and WC at 1% v/v were mixed with POST herbicide treatments according to label recommendations.

b. Herbicide 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).

2.3 Herbicide treatments

The PRE herbicides (Table 2) were applied at or following soybean planting (Table 1) at each experimental location with a CO₂-pressurized backpack sprayer consisting of a four- or five-nozzle boom calibrated to deliver 140 L ha⁻¹ at 276 kPa with AIXR 110015 flat-fan nozzles (TeeJet Spraying Systems Co.). For comparison, a nontreated (weedy) control and a weed-free control were included with weed-free control plots maintained by using herbicides and hand-weeding as needed. The POST herbicide programs (Table 2) were applied between 28 and 45 d after soybean planting, depending on site-specific weed pressure. The POST herbicides were applied with a CO₂-pressurized backpack sprayer consisting of a four- or five-nozzle boom fitted with TeeJet AIXR or TTI flat-fan nozzles calibrated to deliver 140 L ha⁻¹ or XR flat-fan nozzles at 187 L ha⁻¹ at 276 kPa, respectively (Table 2).

2.4 Data collection

Visual estimates of control of Palmer amaranth and waterhemp, common lambsquarters, velvetleaf, combined grasses, and other weed species were recorded at 14 and 28 d after PRE (DAPRE) and 14 and 28 d after POST (DAPOST) based on a 0–100% scale, where 0% represented no control and 100% represented plant death. Soybean injury was also assessed at 14 and 28 DAPRE and 14 and 28 DAPOST using a similar 0–100% scale, where 0% represented no crop injury and 100% represented plant death. Density of individual weed species was recorded by counting the number of weeds in two 0.5-m² quadrats that were placed randomly in the center two soybean rows in each plot at 14 and 28 DAPRE and DAPOST and adjusted to plants m⁻². Aboveground weed biomass was collected 1 d prior to POST herbicide applications and 28 DAPOST herbicide applications by randomly sampling two 0.5-m² quadrants from the center two soybean rows of each plot in which plants were cut at the soil surface and recording the weed species present in the biomass sample. Weed biomass samples were oven-dried until constant weight and adjusted to grams weed biomass m⁻². Percentages of aboveground weed biomass and density reductions relative to the nontreated control were calculated by using the following equation (Wortman, 2014):

$$Y = [(C - B)/C] \times 100 \quad (1)$$

where C represents the weed biomass or density from the nontreated control plots, and B represents the weed biomass or density from the treated plots. Crop stand was assessed at 28 d after PRE (DAPRE) herbicide application by counting the number of soybean plants present in 1 or 3 m of the center two rows, depending on study location. Weather data for each study location were collected by on-farm or High Plains Regional Climate Center Automated Weather Data Network weather stations, with cumulative precipitation received and average daily temperature recorded from 1 May to 31 Oct. 2018 and 2019. Soybean grain was harvested from the center two rows in each plot at maturity using a small-plot combine with grain weight and moisture content recorded and adjusted to 13%.

2.5 Economic analysis

Gross profit margins and benefit/cost ratio were calculated to assess the profitability for each weed management program (combination of the herbicide program with the cost for herbicide-resistant or conventional soybean seed). Gross profit margin was calculated for each weed management program using the following equation (Sarangi & Jhala, 2019):

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

where R is the gross revenue calculated by multiplying soybean yield for each treatment by the average price received for genetically modified (GM) HR soybean (US\$0.30 kg⁻¹) or non-GM soybean (US\$0.35 kg⁻¹), and W is the total weed management program cost comprised of the average cost of herbicides and spray adjuvants for each treatment with custom application and the weighted average seed cost for the soybean cultivar/trait planted.

Average market price for GM soybean was derived from the cash prices received in Nebraska as reported by the USDA National Agricultural Statistics Service Information from September to December in 2018 and 2019 (USDANASS, 2019). The price for non-GM soybeans was

calculated with estimated price premiums for non-genetically modified organism feed-grade soybean derived from 20 USDA Agricultural Marketing Service National Weekly Non-GMO/Genetically Engineered Grain Reports dating from September to December in 2018 and 2019 (USDAAMS, 2020).

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) and averaged prior to economic analysis. Custom application price estimates from the previously listed sources were also obtained, with an average cost of US\$17.30 ha⁻¹ application⁻¹ for PRE herbicide programs, US\$18.94 ha⁻¹ application⁻¹ for nondicamba POST herbicide programs, and US\$31.71 ha⁻¹ application⁻¹ for POST herbicide programs containing dicamba.

For each treatment, W included the weighted average seed costs for soybean cultivar/trait used in this study, which were adjusted based on planting density. Seed costs included associated technology fees for HR traits and commercially available discounts for volume and cash/pre-pay but did not include potential herbicide rebate programs. The benefit/cost ratios were calculated for each herbicide program using the following equation (Sarangi & Jhala, 2019):

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

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

2.6 Statistical analysis

Statistical analysis was performed in R statistical software v. 3.6.1 (R Core Team, 2018) using the “lme4” package v. 1.1-21 (Bates, Machler, Bolker, & Walker, 2015) and the “glmmTMB” package v. 1.0.0 (Brooks et al., 2017). Experimental data were analyzed with a combined analysis, excluding soybean yield, which was analyzed by site-year. In the combined model, the interaction of PRE herbicide program, POST herbicide program, and site-year were considered fixed effects, and the interaction

of site-year with replication, replication by PRE, column, and column by POST herbicide were considered random effects. In the separated model, site-year interactions were removed from fixed and random effects.

Total aboveground weed biomass and density reductions, weed control, and crop injury ratings were $\log(x + 1)$, square root, or logit-transformed and fit to generalized linear mixed-effect models using *glmmTMB* functions with Gaussian (link = “identity”) and beta (link = “logit”) error distributions (Stroup, 2015). Final *glmmTMB* models were selected based on comparisons of dispersion parameter estimates and Akaike information criterion values, with $\log(x + 1)$ or square root transformation with Gaussian error distribution selected for most response variables.

Soybean grain yield, plant stand, and weed density data were $\log(x + 1)$ or square root transformed and fit to linear mixed-effect models using the *lmer* function (Kniss & Streibig, 2018). Final *lmer* models were selected based on a comparison of restricted maximum likelihood criterion at convergence values, with default or Nelder-Mead model optimizers used for most response variables.

Prior to conducting ANOVA, variance assumptions were tested by using Levene’s tests (Wang et al., 2017) with the *leveneTest* function at $\alpha=.05$. Variables that failed variance assumptions were transformed, fit to *glmmTMB* and *lmer* models, and visually assessed for outliers and heterogeneity of variance by plotting residual values (Knezevic, Evans, Blankenship, Van Acker, & Lindquist, 2002; Ritz, Kniss, & Streibig, 2015). Normality assumptions were tested using Shapiro-Wilk tests with the *shapiro.test* function (Kniss & Streibig, 2018).

The ANOVA was performed with “car” package v. 3.0- 6 (Fox & Weisberg, 2019) using the *Anova* function. For *glmmTMB* models, ANOVA was conducted with Type III Wald Chi-Square Tests, whereas *lmer* models used Type III Wald F Tests. Treatment-estimated marginal means were separated with “emmeans” package v. 1.4.3 (Lenth, 2019) and “multcomp” package v. 1.4-11 (Hothorn, Bretz, & Westfall, 2008) using the *emmeans* and *cld* functions (Kniss & Streibig, 2018) at $\alpha = .05$, with Sidak method confidence-level adjustment and post hoc Tukey *P* value adjustments. Following treatment means separation, data were back-transformed for the presentation of results.

Results presented in this study exclude data from North Platte in 2018 due to a study-wide planter malfunction and Lincoln in 2019 due to flooding 10 DAPRE. Likewise, due to an 80% defoliating hail event 29 DAPOST at Scottsbluff and a 60% defoliating hail event 51 DAPOST (5 Aug. 2019) during the R5 soybean growth stage in Clay Center in 2019, results presented in this study for crop yield, gross profit margin, and benefit/cost ratio exclude data from these site-years.

3 Results

3.1 Average daily temperature and precipitation

Average daily temperatures during the 2018 and 2019 growing seasons for most study locations were similar to the 30-yr average, with the exception of Clay Center, which were slightly cooler (average temperature, 14.5 °C). Cumulative precipitation amounts recorded in 2018 and 2019 at each study location were similar or slightly exceeded the 30-yr average (**Figure 1**).

3.2 Crop stand

Soybean plant stand for locations at 28 DAPRE did not differ across PRE herbicide program ($P = .994$), soybean HR trait and subsequent POST herbicide program ($P = .948$), PRE by site-year ($P = .900$), and PRE by POST ($P = .676$) or PRE by POST by site-year ($P = .889$), with a study-wide average of 234,250 plants ha⁻¹ (data not shown).

3.3 Pre-emergence herbicide: Weed control, weed density, density reduction, and biomass reduction

Across site-years, PRE herbicide programs provided 93–99% control of Palmer amaranth, 92–99% control of common lambsquarters, 87–94% control of velvetleaf, and 81–97% control of grass weed species (bristly foxtail, giant foxtail, green foxtail, yellow foxtail, large crabgrass, and field sandbur) at 28 DAPRE (**Table 3**). Aboveground weed biomass

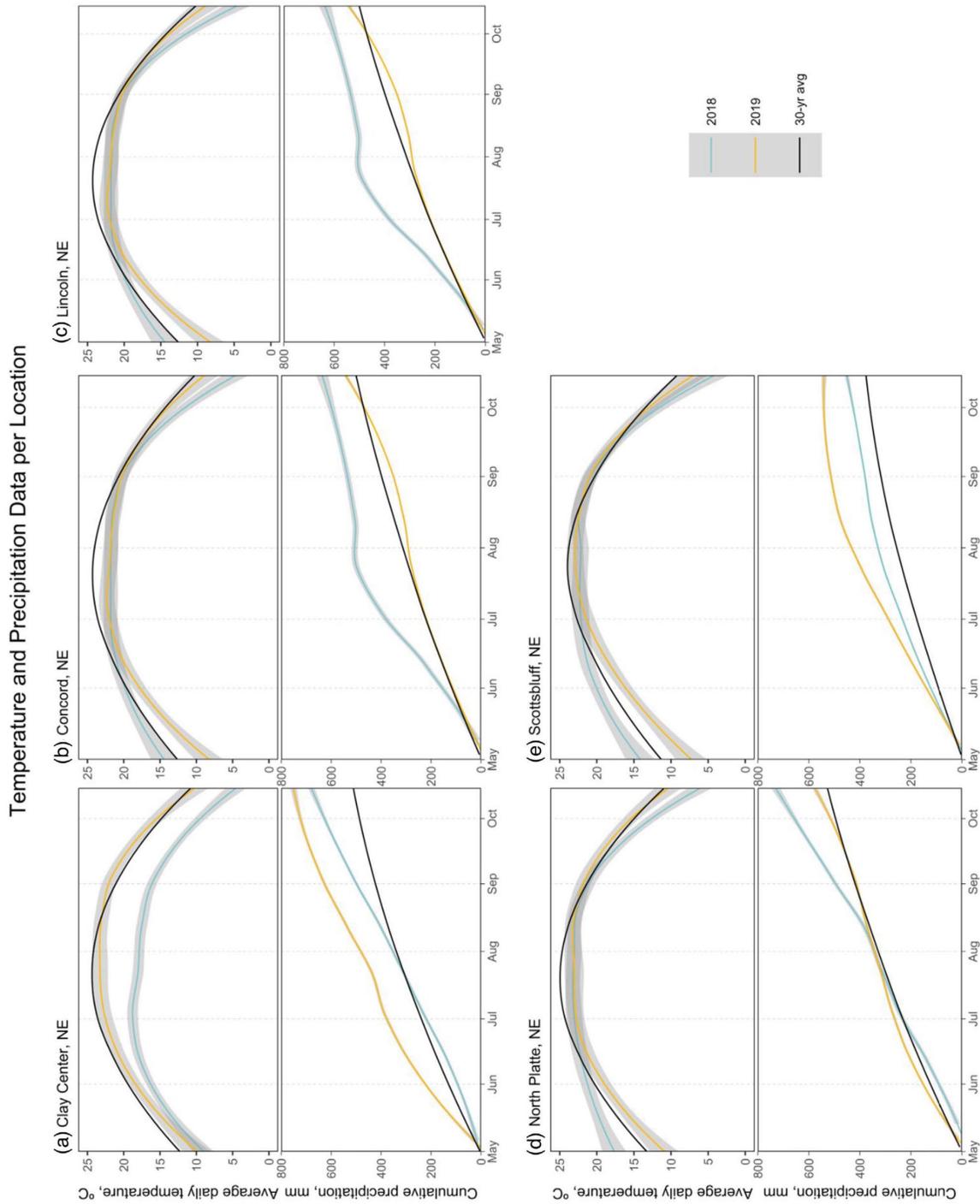


Figure 1 Average daily air temperature ($^{\circ}\text{C}$) and total cumulative precipitation (mm) received during the 2018 and 2019 growing seasons compared with the 30-yr average for field experiments conducted across irrigated (A) Clay Center, NE; (D) North Platte, NE; and (E) Scottsbluff, NE and rainfed conditions in (B) Concord, NE and (C) Lincoln, NE to determine economics of herbicide programs in conventional, glufosinate-resistant, and dicamba/glyphosate-resistant soybean in Nebraska

reduction at 28–45 DAPRE ($P < .001$) showed that PRE herbicide programs offered similar weed biomass reduction relative to the nontreated control (258 g m^{-2}) as the weed-free control (82%) prior to hand removal, where sulfentrazone/*S*-metolachlor plus metribuzin provided 96% weed biomass reduction and imazethapyr/pyroxasulfone/saflufenacil and chlorimuron/flumioxazin/thifensulfuron provided 77 and 72% weed biomass reduction, respectively (Table 3). Palmer amaranth, common lambsquarters, velvetleaf, and the aforementioned grass weed species varied in density at 14 and 28 DAPRE, with most PRE herbicide programs providing similar total weed density reduction to the weed-free control (73%), excluding chlorimuron/flumioxazin/thifensulfuron (61%) (Table 4).

3.4 Post-emergence herbicide: Weed control, weed density, density reduction, and biomass reduction

At 14 and 28 DAPOST, most POST herbicide programs provided $\geq 87\%$ control of Palmer amaranth, common lambsquarters, velvetleaf, and grass weed species (Table 5). Aboveground biomass reduction at 28 DAPOST was significant ($P < .001$), with dicamba plus glyphosate, glyphosate, and glufosinate resulting in $\geq 97\%$ reduction of total weed biomass relative to the nontreated control ($1,178 \text{ g m}^{-2}$). Weed biomass reduction was 89% for acetochlor plus clethodim plus lactofen (Table 5).

Density rates of Palmer amaranth, common lambsquarters, and grass weed species were similar ($P > .05$) across POST herbicide programs 28 DAPOST with 0–1 plants m^{-2} , whereas density of velvetleaf at 14 and 28 DAPOST and common lambsquarters at 14 DAPOST was significant ($P < .001$), although only equal to 1 plant m^{-2} for acetochlor plus clethodim plus lactofen. Density of grassweed species at 14 DAPOST was not different (Table 6), and POST herbicide program was not significant for total weed density reduction at 28 DAPOST ($P = .832$), with POST herbicide programs reducing total weed density 86–94% from densities present in the nontreated control (85 plants m^{-2}).

Table 3 Weed control at 14 and 28 days after pre-emergence herbicide application (DAPRE) in field experiments conducted across five locations in Nebraska to determine economics of herbicide programs in conventional, glufosinate, and dicamba/ glyphosate-resistant soybean in 2018 and 2019.

Herbicide program ^a	Palmer amaranth		Common lambsquarters		Velvetleaf		Grass species		Total biomass reduction ^b	
	14	28	14	28	14	28	14	28	28–45	
	DAPRE	DAPRE	DAPRE	DAPRE	DAPRE	DAPRE	DAPRE	DAPRE	DAPRE	
					%					
Nontreated control	0	0	0	0	0	0	0	0	0	
Weed-free control	99	99	99	99	99	99	99	99	100ac	
Sulfentrazone/S-metolachlor + metribuzin	98a	99a	96a	99a	92ab	92abc	97a	97a	96ab	
Chlorimuron/flumioxazin/ thifensulfuron-methyl	94ab	93b	72bc	90b	86ab	88bc	84ab	81c	72d	
Flumioxazin/pyroxasulfone + metribuzin	98a	98a	93ab	95ab	96a	87c	92a	83c	88b	
Chlorimuron/ flumioxazin/ metribuzin	98a	96ab	85ab	96ab	94a	92ab	93a	84c	83c	
Imazethapyr/ pyroxasulfone/saflufenacil	82b	96ab	59bc	92b	70b	94a	73b	88b	77d	
<i>p</i> -value	<.001	<.001	<.001	<.001	.041	.009	<.001	.001	<.001	
Site-years (<i>n</i>)	6 (672)	7 (784)	5 (560)	5 (560)	4 (448)	6 (672)	4 (448)	7 (784)	6 (672)	

Note. Weed control data at 14 and 28 DAPRE were combined for all study locations in 2018 and 2019. Data were log(x + 1) or square root transformed before analysis; however back transformed values are presented based on interpretations of transformed data. Mean separation for weed control at 14 and 28 DAPRE excluded comparisons to the nontreated control and weed-free control, whereas biomass reduction at 28–45 DAPRE included the comparison of PRE herbicide programs to the nontreated control and weed-free control.

a. PRE, pre-emergence.

b. Total weed biomass in the nontreated control at 28–45 DAPRE was 258 g m⁻².

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 4 Weed density at 14 and 28 days after pre-emergence herbicide application (DAPRE) in field experiments conducted across five locations in Nebraska to determine economics of herbicide programs in conventional, glufosinate, and dicamba/glyphosate-resistant soybean in 2018 and 2019.

Herbicide program ^a	Palmer <i>amaranth</i>		Common <i>lambsquarters</i>		Velvetleaf		Grass species		Total density reduction ^b
	14	28	14	28	14	28	14	28	28–45
	DAPRE	DAPRE	DAPRE	DAPRE	DAPRE	DAPRE	DAPRE	DAPRE	DAPRE
	no. plants m ⁻²								%
Nontreated control	5c	30c	21d	44c	5b	8c	16b	18c	0e
Weed-free control	0a	0a	0a	0a	0a	0a	0a	0a	100a
Sulfentrazone/ S-metolachlor + metribuzin	0a	1ab	0a	1a	1a	2b	1a	0a	79b
Chlorimuron/ flumioxazin/ thifensulfuronmethyl	0a	2b	4c	13b	0a	1ab	4a	3b	61d
Flumioxazin/ pyroxasulfone+ metribuzin	0a	1ab	0a	6ab	0a	1ab	2a	1ab	73bc
Chlorimuron/ flumioxazin/ metribuzin	0a	1ab	1ab	8b	0a	1ab	0a	1ab	71bc
Imazethapyr/ pyroxasulfone/ saflufenacil	1a	1ab	3bc	11b	1a	0a	2a	0a	68cd
<i>P</i> -value	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001
Site-years (<i>n</i>)	5 (560)	7 (784)	5 (560)	6 (672)	4 (448)	6 (672)	5 (560)	7 (784)	8 (896)

Note. Weed density data at 14 and 28 DAPRE were combined for all study locations in 2018 and 2019. Data were log($x + 1$) or square-root transformed before analysis; however, back-transformed values are presented based on interpretations of transformed data. Mean separation for weed density at 14 and 28 DAPRE and total density reduction at 28 DAPRE included comparisons of PRE herbicide programs to the nontreated control and weed-free control.

a. PRE, pre-emergence.

b. Total weed density in the nontreated control at 28-45 DAPRE was 160 plants m⁻².

c. Means 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 Weed control at 14 and 28 days after post-emergence herbicide application (DAPOST) in field experiments conducted across five locations in Nebraska to determine economics of herbicide programs in conventional, glufosinate, and dicamba/ glyphosate-resistant soybean in 2018 and 2019

Herbicide program ^a	Palmer <i>amaranth</i>		Common <i>lambsquarters</i>		Velvetleaf		Grass species		Total biomass reduction ^b
	14	28	14	28	14	28	14	28	28–45
	DAPRE	DAPRE	DAPRE	DAPRE	DAPRE	DAPRE	DAPRE	DAPRE	DAPRE
%									
Nontreated control	0	0	0	0	0	0	0	0	0
Weed-free control	99	99	99	99	99	99	99	99	100
Dicamba + glyphosate	97	95	98a	98a	98a	98a	97	98	98a
Glyphosate	94	93	98a	98a	98a	98a	98	97	97a
Glufosinate	96	94	98a	97a	98a	97a	97	97	97a
Acetochlor + clethodim + lactofen	95	94	90b	87b	90b	89b	94	95	89b
POST <i>P</i> -value	.631	.216	.008	.024	.001	<.001	.128	.501	<.001
PRE <i>P</i> -value	.999	.150	.999	.957	.999	.999	.986	.994	.896
Site-years (<i>n</i>)	7 (784)	7 (784)	5 (560)	5 (560)	4 (448)	4 (448)	7 (784)	7 (784)	7 (784)

Note. Weed control data at 14 and 28 DAPOST were combined for all study locations in 2018 and 2019. Data were $\log(x + 1)$ or square root transformed before analysis; however, back-transformed values are presented based on interpretations of transformed data. Mean separation for weed control at 14 and 28 DAPOST and weed biomass reduction at 28 DAPOST excluded comparisons to the nontreated control and weed-free control.

a. PRE, pre-emergence; POST, postemergence.

b. Total weed biomass for the nontreated control at 28 DAPOST was 1,178 g m⁻².

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 6 Weed density at 14 and 28 days after POST herbicide application (DAPOST) in field experiments conducted across five locations in Nebraska to determine economics of herbicide programs in conventional, glufosinate, and dicamba/glyphosate-resistant soybean in 2018 and 2019.

Herbicide program ^a	Palmer amaranth		Common lambsquarters		Velvetleaf		Grass species		Total density reduction ^b
	14	28	14	28	14	28	14	28	28–45
	DAPRE	DAPRE	DAPRE	DAPRE	DAPRE	DAPRE	DAPRE	DAPRE	DAPRE
	no. plants m ²								%
Nontreated control	9	11	24	18	4	7	13	34	0
Weed-free control	0	0	0	0	0	0	0	0	100
Dicamba + glyphosate	0	1	0ac	0	0a	0a	0a	0	94
Glyphosate	1	1	0a	0	0a	0a	0a	0	94
Glufosinate	1	1	0a	0	0a	0a	0a	1	92
Acetochlor + clethodim + lactofen	0	1	1b	2	1b	1b	1b	2	86
POST <i>P</i> -value	.369	.633	.016	.999	<.001	<.001	.007	.999	.832
PRE <i>P</i> -value	.930	.651	.973	.999	.998	.997	.543	.999	.949
Site-years (<i>n</i>)	6 (672)	7 (784)	5 (560)	7 (784)	4 (448)	4 (448)	6 (672)	7 (784)	7 (784)

Note. Weed density data at 14 and 28 DAPOST were combined for all study locations in 2018 and 2019. Data were $\log(x + 1)$ or square root transformed before analysis; however, back-transformed values are presented based on interpretations of transformed data. Mean separation for weed density at 14 and 28 DAPOST and total density reduction excluded comparisons to the nontreated control and weed-free control.

a. PRE, pre-emergence; POST, post-emergence.

b. Total weed density in the nontreated control at 28 DAPOST was 85 plants m⁻².

c. Means 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.

3.5 Soybean injury

Pre-emergence herbicide programs evaluated in this study displayed a high margin of crop safety, with $\leq 4\%$ soybean injury at 14 or 28 DAPRE across site-years (Supplemental Table 1). No crop injury was observed in DGR soybean at 14 or 28 DAPOST, whereas off-target movement of dicamba in GLU-R and conventional soybean resulted in phytotoxic deformities of 12–13% at 14 DAPOST and 11–12% at 28 DAPOST (Supplemental Table 2). Across all site-years, crop injury from dicamba in dicamba-sensitive cultivars did not exceed the threshold of 30% injury required to cause greater than 5% soybean yield loss, as reported in a meta-analysis conducted by Kniss (2018). Lactofen applied POST in conventional soybean resulted in 12 and 9% phytotoxic necrosis at 14 and 28 DAPOST, with lactofen injury fading as the growing season progressed. It has been previously reported that crop injury from lactofen does not usually result in yield loss (Sarangi et al., 2015; Wichert & Talbert, 1993).

3.6 Soybean yield

For individual site-years presented in this study, the main effect of PRE herbicide program was significant for six of six site-years, whereas the main effect of POST herbicide program was significant for four of six site-years (data not shown). Due to a significant site-year effect ($P = .002$), locations were analyzed by site-years. The interaction of PRE by POST herbicide program was significant at all study locations (Table 7), excluding North Platte in 2019 ($P = .132$); therefore, analyses of soybean yield and economics were conducted on PRE fb POST herbicide programs. Across site-years, soybean yield for PRE fb POST herbicide programs in DGR, GLU-R, and conventional soybean was similar to the weed-free control for the respective system for nearly all PRE fb POST programs. At Clay Center, conventional soybean receiving chlorimuron/flumioxazin/thifensulfuron or imazethapyr/pyroxasulfone/saflufenacil produced 2,000–2,360 kg ha⁻¹ less than the weed-free control (3,771 kg ha⁻¹) in 2019 (Table 7). Conventional soybean yield was similar to HR cultivars for all PRE fb POST herbicide programs at Lincoln in 2018 and Concord in 2019. In contrast, conventional soybean yield was significantly lower than HR cultivars at Clay Center,

Table 7 Soybean yield affected by herbicide programs in field experiments conducted across five locations in Nebraska to determine economics of herbicide programs in conventional, glufosinate, and dicamba/glyphosate-resistant soybean in 2018 and 2019

HR trait ^a	Herbicide program ^b		Program cost ^c	Soybean yield ^d					
	PRE	POST		Clay Center, 2018	Concord, 2018	Lincoln, 2018	Scottsbluff 2018	Concord, 2019	North Platte, 2019
\$ ha ⁻¹ / kg ha ⁻¹									
DGR	Nontreated control	–	132.96	640ghe	1,850e	620d	410gh	2,180c	2,480
	Weed-free control	fb dicamba + glyphosate	342.31	4,350abc	3,660ab	4,800ab	4,730abc	4,530a	3,510
	Sulfentrazone/ <i>S</i> -metolachlor + metribuzin		358.52	4,280abc	3,850ab	4,810ab	4,990ab	4,670a	3,700
	Chlorimuron/flumioxazin/thifensulfuron		282.57	3,930abc	3,740ab	4,690ab	4,530abc	4,690a	3,300
	Flumioxazin/pyroxasulfone + metribuzin		307.93	4,670a	3,770ab	4,730a	4,780abc	4,880a	3,850
DGR	Chlorimuron/flumioxazin/metribuzin		297.75	4,340ab	3,830ab	4,770ab	3,550abcde	4,590a	3,330
	Imazethapyr/pyroxasulfone/saflufenacil		302.19	4,150abc	3,550ab	4,590ab	4,770abc	4,600a	3,220
	Nontreated control	–	132.96	780fgh	1,890e	670d	270h	2,020c	2,010
	Weed-free control	fb glyphosate	284.46	4,450ab	3,800ab	5,140a	5,120ab	4,720a	2,830
	Sulfentrazone/ <i>S</i> -metolachlor + metribuzin		300.67	3,930abc	3,910ab	4,680ab	4,440abc	4,674a	3,470
DGR	Chlorimuron/flumioxazin/thifensulfuron		224.72	4,070abc	3,740ab	4,550ab	4,900a	4,540a	3,180
	Flumioxazin/pyroxasulfone + metribuzin		250.08	4,360a	3,840a	4,690a	5,080a	4,860a	3,270
	Chlorimuron/flumioxazin/metribuzin		239.9	3,960ab	3,840ab	4,720ab	4,730abc	4,770a	3,130
	Imazethapyr/pyroxasulfone/saflufenacil		244.34	3,920abc	3,580ab	4,290ab	5,280a	4,650a	3,010

(continued)

Table 7 (Continued)

HR trait ^a	Herbicide program ^b		Program cost ^c	Soybean yield ^d					
	PRE	POST		Clay Center, 2018	Concord, 2018	Lincoln, 2018	Scottsbluff, 2018	Concord, 2019	North Platte, 2019
CON	Nontreated control	–	108.58	360h	1,750e	1,280c	110h	2,550	2,420
	Weed-free control	fb acetochlor + clethodim + lactofen	375.36	3,770abc	3,020cd	4,790ab	2,450ef	4,630a	2,620
	Sulfentrazone/S-metolachlor + metribuzin		391.57	2,940abcd	2,950d	4,530ab	3,170cdef	4,780a	3,780
	Chlorimuron/flumioxazin/thifensulfuron		315.62	1,670def	2,740d	4,480ab	2,090ef	4,730a	2,850
	Flumioxazin/pyroxasulfone + metribuzin		340.98	2,740bcde	2,900cd	3,930b	2,700def	4,680a	3,700
	Chlorimuron/flumioxazin/metribuzin		330.8	2,470cde	2,970cd	4,430ab	1,890fg	4,940a	3,290
	Imazethapyr/pyroxasulfone/saflufenacil		335.24	1,410efg	2,990cd	4,100ab	2,340ef	4,720a	2,900
PRE fb POST	P-value			<.001	.009	<.001	.002	.014	.132

a. CON, conventional; DGR, dicamba/glyphosate-resistant; fb, followed by; GLU-R, glufosinate resistant.

b. PRE, pre-emergence; POST, post-emergence.

c. Weed management program cost was averaged from three independent sources in Nebraska and include custom application cost: PRE (US\$17.30 ha⁻¹ application 1), non-dicamba-containing POST (US\$18.94 ha⁻¹ application 1), dicamba containing POST (US\$31.71 ha⁻¹ application 1), and seed costs: DGR (US\$132.96 ha⁻¹), GLU-R (US\$109.33 ha⁻¹), CON (US\$108.58 ha⁻¹).

d. Yield data for each site-year were log(1 + x) or square root transformed before analysis; however back-transformed values are presented based on interpretations of transformed data.

e. Means 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.

Concord, and Scottsbluff in 2018 (Table 7), although poor field emergence of conventional soybean cultivar U11-917032 (95,000 plants ha⁻¹) at Scottsbluff in 2018 likely contributed to the reduced yield potential for that specific site-year. Soybean yield in GLU-R soybean was similar to DGR soybean for all site-years (Table 7).

3.7 Economic analysis

Pre-emergence herbicide program plus cost of custom application ranged from US\$58.30 to US\$135.25 ha⁻¹, whereas POST herbicide programs plus cost of custom application ranged from US\$33.46 to US\$148.74 ha⁻¹ (Table 2). Herbicide program costs were added to the cost of conventional and HR cultivar seed, with the weighted average of US\$132.96 ha⁻¹ for DGR soybean, US\$109.33 ha⁻¹ for GLU-R soybean, and US\$108.58 ha⁻¹ for commercially available conventional soybean cultivars across all locations (**Table 8**). Low local demand at most locations for conventional soybean seed resulted in higher-than expected conventional seed costs.

Gross profit margins for most weed management programs in DGR cultivars were similar within most site-years, with a study-wide average gross profit margin of US\$976.56 and US\$1023.56 ha⁻¹ for dicamba/glyphosate and glyphosate, respectively (Table 8). In GLU-R cultivars, gross profit margin was comparable to DGR cultivars with a study-wide average of US\$928.24 ha⁻¹ (Table 8), whereas in conventional weed management programs, gross profit margins were lower than in HR cultivars, with a study-wide average of US\$722.02 ha⁻¹ for grain marketed without price premiums (data not shown). However, the lower gross profit margins in conventional soybean could be partially compensated by including a price premium for non-GM soybean, with a study-wide average of US\$814.12 ha⁻¹ for grain marketed with a \$0.05 kg⁻¹ price premium (Table 8). At Lincoln and Scottsbluff in 2018 and 2019, gross profit margins for conventional soybean marketed with a price premium were similar or exceeded the gross profit margin for many HR soybean programs.

Benefit/cost ratios in this study varied by both site-year and soybean cultivar. In HR and conventional soybean, PRE fb POST herbicide provided similar or greater benefit/cost ratios to the weed-free control for most site-years (**Table 9**). Across all site-years excluding North Platte

Table 8 Gross profit margin in field experiments conducted across five locations in Nebraska to determine economics of herbicide programs in conventional, glufosinate, and dicamba/glyphosate-resistant soybean in 2018 and 2019.

HR trait ^a	Herbicide program ^b		Gross profit margin ^c						
	PRE	POST	Clay Center, 2018	Concord, 2018	Lincoln, 2018	Scottsbluff, 2018	Concord, 2019	North Platte, 2019	
			— US\$ ha ⁻¹ —						
DGR	Nontreated control	-	59	429	126	21	526	617	
	Weed-free control	fb dicamba + glyphosate	974	767	1,113	1,087	1,028	719	
	Sulfentrazone/ <i>s</i> -metolachlor + metribuzin		939	808	1,099	1,169	1,056	762	
	Chlorimuron/flumioxazin/thifensulfuron		906	850	1,138	1,110	1,137	718	
	Flumioxazin/pyroxasulfone + metribuzin		1,106	833	1,125	1,148	1,170	858	
	Chlorimuron/flumioxazin/metribuzin		1,018	863	1,146	823	1,092	711	
	Imazethapyr/pyroxasulfone/saflufenacil		956	774	1,089	1,130	1,091	672	
	Nontreated control	-	103	439	102	2.81	479	477	
	Weed-free control	fb glyphosate	1,063	868	1,273	1,255	1,145	572	
	Sulfentrazone/ <i>s</i> -metolachlor + metribuzin		888	883	1,117	1,085	1,115	750	
DGR	Chlorimuron/flumioxazin/thifensulfuron		1,007	907	1,155	1,297	1,150	738	
	Flumioxazin/pyroxasulfone + metribuzin		1,071	913	1,169	1,290	1,221	741	
	Chlorimuron/flumioxazin/metribuzin		959	922	1,189	1,209	1,204	709	
	Imazethapyr/pyroxasulfone/saflufenacil		943	840	1,055	1,351	1,163	667	

(continued)

Table 8 Continued

HR trait ^a	Herbicide program ^b		Gross profit margin ^c						
	PRE	POST	Clay Center, 2018	Concord, 2018	Lincoln, 2018	Scottsbluff, 2018	Concord, 2019	North Platte, 2019	
US\$ ha ⁻¹									
GLU-R	Nontreated control	-	61	562	91	27	572	527	
	Weed-free control	fb glufosinate	1,084	875	1,235	831	1,001	701	
	Sulfentrazone/ <i>s</i> -metolachlor + metribuzin		841	814	1,181	927	1,038	725	
	Chlorimuron/flumioxazin/thifensulfuron		828	820	1,054	1,070	1,119	622	
	Flumioxazin/pyroxasulfone + metribuzin		912	844	1,131	944	1,128	875	
	Chlorimuron/flumioxazin/metribuzin		955	867	1,049	861	1,079	665	
	Imazethapyr/pyroxasulfone/saflufenacil		886	830	1,010	911	1,110	753	
	CON	Nontreated control	-	16	506	340	26	786	739
		Weed-free control	fb acetochlor + clethodim + lactofen	946	683	1,303	476	1,248	544
		Sulfentrazone/ <i>s</i> -metolachlor + metribuzin		638	642	1,196	740	1,285	933
Chlorimuron/flumioxazin/thifensulfuron			271	646	1,253	437	1,341	685	
Flumioxazin/pyroxasulfone + metribuzin			620	675	686	610	1,300	956	
Chlorimuron/flumioxazin/metribuzin			536	707	1,222	349	1,401	824	
Imazethapyr/pyroxasulfone/saflufenacil			159	712	1,099	496	1,319	681	

a. CON, conventional; DGR, dicamba/glyphosate-resistant; fb, followed by; GLU-R, glufosinate-resistant.

b. PRE, pre-emergence; POST, post-emergence.

c. Gross profit margins were calculated as gross revenue from soybean yield based on the average price received in Nebraska from September to December in 2018 and 2019 for genetically modified soybean and non-genetically modified soybean minus weed management program cost (Table 7). Conventional cultivars include gross profit margins with price premiums equivalent of US\$0.05 kg⁻¹.

Table 9 Benefit/cost ratio in field experiments conducted across five locations in Nebraska to determine economics of herbicide programs in conventional, glufosinate, and dicamba/glyphosate-resistant soybean in 2018 and 2019.

HR trait ^a	Herbicide program ^b		Benefit/cost ratio ^c						
	PRE	POST	Clay Center, 2018	Concord, 2018	Lincoln, 2018	Scottsbluff, 2018	Concord, 2019	North Platte, 2019	
DGR			US\$ ha ⁻¹						
	Nontreated control	-							
	Weed-free control	fb dicamba + glyphosate	3.28	1.60	4.23	3.73	2.08	0.91	
	Sulfentrazone/smetolachlor + metribuzin		3.08	1.69	4.05	3.83	2.11	1.03	
	Chlorimuron/flumioxazin/thifensulfuron		3.53	2.02	5.00	4.38	2.69	0.89	
	Flumioxazin/pyroxasulfone + metribuzin		3.97	1.88	4.63	4.23	2.66	1.35	
	Chlorimuron/flumioxazin/metribuzin		3.77	2.01	4.83	3.25	2.45	0.87	
	Imazethapyr/pyroxasulfone/saflufenacil		3.53	1.70	4.58	4.23	2.43	0.74	
DGR									
	Nontreated control	-							
	Weed-free control	fb glyphosate	3.91	2.04	5.37	4.96	2.87	0.87	
	Sulfentrazone/smetolachlor + metribuzin		3.17	2.03	4.61	4.17	2.67	1.47	
	Chlorimuron/flumioxazin/thifensulfuron		4.43	2.49	6.00	6.19	3.39	1.57	
	Flumioxazin/pyroxasulfone + metribuzin		4.34	2.36	5.55	5.64	3.44	1.52	
	Chlorimuron/flumioxazin/metribuzin		4.01	2.46	5.83	5.50	3.47	1.41	
	Imazethapyr/pyroxasulfone/saflufenacil		3.89	2.10	5.19	6.00	3.26	1.23	

(continued)

Table 9 Continued

HR trait ^a	Herbicide program ^b		Benefit/cost ratio ^c					
	PRE	POST	Clay Center, 2018	Concord, 2018	Lincoln, 2018	Scottsbluff, 2018	Concord, 2019	North Platte, 2019
<i>US\$ ha⁻¹</i>								
GLU-R	Nontreated control	-						
	Weed-free control	fb glufosinate	4.29	1.73	4.73	3.50	2.15	1.23
	Sulfentrazone/smetolachlor + metribuzin		3.28	1.48	4.34	3.69	2.21	1.30
	Chlorimuron/flumioxazin/thifensulfuron		4.02	1.68	4.91	5.28	3.01	0.93
	Flumioxazin/pyroxasulfone + metribuzin		4.05	1.71	4.83	4.32	2.84	1.98
	Chlorimuron/flumioxazin/metribuzin		4.37	1.84	4.64	4.11	2.71	1.12
	Imazethapyr/pyroxasulfone/saflufenacil		4.01	1.67	4.41	4.26	2.80	1.49
CON	Nontreated control	-						
	Weed-free control	fb acetochlor + clethodim + lactofen	3.19	1.18	3.28	2.05	1.94	0.19
	Sulfentrazone/smetolachlor + metribuzin		2.31	1.07	2.91	2.68	2.00	1.22
	Chlorimuron/flumioxazin/thifensulfuron		1.46	1.10	3.55	2.12	2.42	0.48
	Flumioxazin/pyroxasulfone + metribuzin		2.45	1.18	1.70	2.55	2.19	1.32
	Chlorimuron/flumioxazin/metribuzin		2.24	1.29	3.34	1.81	2.53	0.93
	Imazethapyr/pyroxasulfone/saflufenacil		1.10	1.29	2.94	2.23	2.27	0.50

a. CON, conventional; DGR, dicamba/glyphosate resistant; fb, followed by; GLU-R, glufosinate resistant.

b. PRE, pre-emergence; POST, post-emergence.

c. Benefit/cost ratio calculated as gross revenue from soybean yield based on the average price received in Nebraska from September to December in 2018 and 2019 for genetically modified soybean and non-genetically modified soybean minus gross revenue in the nontreated control divided by weed management program cost. Conventional cultivars include gross profit margins with price premiums equivalent of US\$0.05 kg⁻¹.

in 2019, study-wide averages for DGR soybean receiving dicamba plus glyphosate or glyphosate was 3.64 and 4.42, respectively. In GLU-R soybean, the average benefit/cost ratio was 3.91, whereas in conventional soybean the average benefit/cost ratio was 2.25. The benefit/cost ratio for PRE fb POST herbicide programs was reduced to <2.0 at North Platte in 2019, primarily due to late-season competition with kochia (data not shown).

4 Discussion

Results of this study support the recommendation of using PRE herbicide with multiple effective SOA in DGR, GLU-R, and conventional soybean and are consistent with the scientific literature for control of broadleaf and grass weed species evaluated. It has been reported that sulfentrazone/metribuzin provided 92–99% control of common lambsquarters, waterhemp, and velvetleaf 15 DAPRE and 98% control of Palmer amaranth 28 DAPRE in Nebraska (Aulakh & Jhala, 2015; Sarangi & Jhala, 2019). Similarly, Belfry, Cowbrough, Tardif, and Sikkema (2016) reported that *S*-metolachlor plus metribuzin provided 92–100% control of common ragweed, green foxtail, and common lambsquarters 14 DAPRE. Sarangi et al. (2017) reported chlorimuron/flumioxazin/thifensulfuron provided 88% control of GR waterhemp 21 DAPRE in GR soybean in Nebraska. Likewise, Soltani, Nurse, and Sikkema (2014) and Hedges, Hooker, Robinson, & Sikkema (2019) reported that flumioxazin/pyroxasulfone provided 97–99% control of velvetleaf, common ragweed, common lambsquarters, waterhemp, and green foxtail 28 DAPRE. Hay, Shoup, and Peterson (2019) reported that flumioxazin/pyroxasulfone and chlorimuron/ flumioxazin/metribuzin tank-mixed with paraquat provided 90 and 93% control of Palmer amaranth 56 DAPRE, respectively, in field experiments conducted in Kansas. Similarly, Sarangi and Jhala (2019) reported that chlorimuron/flumioxazin/metribuzin provided 96% control of velvetleaf 28 DAPRE in field experiments conducted in Nebraska. The efficacy of various soybean herbicide pre-mixes tank-mixed with glyphosate have been studied in four 2-yr studies in Ontario, Canada, where imazethapyr/saflufenacil plus glyphosate provided 60–83% control of common ragweed 56 d after application, with 79–82% biomass reduction (Wely et al., 2014). Likewise, pyroxasulfone

applied alone at 150 g ai ha⁻¹ provided 94% control of GR waterhemp at 28 DAPRE (Hedges, Soltani, Hooker, Robinson, & Sikkema, 2019) and 95% control of GR waterhemp at 21 DAPRE applied at 208 g ai ha⁻¹ (Sarangi et al., 2017).

From a weed management standpoint, POST herbicide programs in HR soybean provided 94–99% control of Palmer amaranth, common lambsquarters, velvetleaf, and grass weed species. Competition from GR weeds in glyphosate applied POST programs was expected due to their prevalence in Nebraska (Sarangi & Jhala, 2018); however, due to the relatively low frequency of GR weed species at study locations in 2018 and 2019, this was not observed in current study. Multiple herbicide-resistant soybeans, such as isoxaflutole/glufosinate/glyphosate-resistant soybean (LibertyLink/GT27) and dicamba/glufosinate/glyphosate-resistant soybean (XtendFlex), will be available commercially in the near future (Beckie et al., 2019). Therefore, glufosinate remains a viable POST herbicide option for control of GR weeds (Barnes et al., 2017; Jhala et al., 2017). In conventional soybean, a POST program of clethodim plus lactofen including an overlapping residual of acetochlor provided 87–95% control of broadleaf and grass weeds. Producers interested in conventional soybean should take special care to select fields with a weed spectrum that can be managed effectively with PRE fb POST herbicide applications of acetolactate synthase and PPO-inhibiting herbicides along with residual activity of long chain fatty acid inhibitors, such as acetochlor/*S*-metolachlor/ pyroxasulfone, because POST herbicides such as 2,4-D, dicamba, glyphosate, or glufosinate cannot be used as a “rescue treatment.” The total cost of PRE herbicide programs examined in this study was within \$10 ha⁻¹, excluding chlorimuron/ flumioxazin/thifensulfuron, which was US\$15 to US\$20 ha⁻¹ less expensive, and sulfentrazone/*S*-metolachlor plus metribuzin (US\$134.25 ha⁻¹), which was substantially more expensive due to the application of metribuzin at a full-labeled rate for medium-textured soils with 2–4% organic matter (700 g ai ha⁻¹). Previous research with metribuzin tank-mixed with other herbicides has shown that this rate could have been reduced without compromising weed control efficacy and soybean yield potential (Hedges et al., 2019; Kaur, Sandell, Lindquist, & Jhala, 2014; Sarangi & Jhala, 2019; Underwood et al., 2016; Wely et al., 2014; Whitaker, York, Jordan, & Culpepper, 2010).

Total cost of POST herbicide programs varied by soybean system. The least expensive POST herbicide programs were glyphosate or glufosinate. The conventional POST herbicide program was the most expensive (US\$148.74 ha⁻¹) primarily because it included lactofen for waterhemp and Palmer amaranth control and acetochlor to provide an overlapping residual activity to address concerns with late-season weed emergence and weed control issues as reported in the literature (Rosenbaum et al., 2013; Sarangi & Jhala, 2019). Sarangi and Jhala (2019) reported that the use of overlapping residual herbicides was effective for providing season-long control of Palmer amaranth and velvetleaf in conventional soybean in Nebraska. In the same study, it was reported that lactofen applied POST at 210 g ai ha⁻¹ alone or tank-mixed with other herbicides provided 91% control of GR waterhemp 28 DAPOST.

Reduced grain production rates by conventional soybean observed in the current study at three locations agree with results of a five-location, 2-yr study reported by Owen et al. (2010) in which conventional soybean cultivars produced 265 and 315 kg ha⁻¹ less yield than GR and GLUR cultivars, respectively. Likewise, Werle, Glewen, et al. (2018) reported that conventional soybean produced 202 kg ha⁻¹ less than GR and DGR soybean despite receiving the same conventional PRE fb POST herbicide program. However, although conventional soybean produced lower grain yields than HR soybean at three locations, grain yield was similar at Lincoln in 2018 and at Concord in 2019. These results are similar to a 3-yr, single-location study conducted in Tennessee that reported similar crop yields for GR and conventional soybean (Gaban, 2013). Similar yield potential and weed control in conventional, GR, and GLU-R soybean cultivars were also reported by Culpepper, York, Batts, and Jennings (2000) in a 3-yr, six-location study in North Carolina. With variable results in the literature, yield potential of conventional cultivars compared with HR cultivars is inconclusive, as is the underlying cause for these reported yield differences or lack thereof. Differences in genetic yield potential, herbicide injury, and increased competition with weeds are all plausible factors that could result in reduced soybean grain yield in conventional cultivars. Results from the current study support conventional soybean can produce similar yield to HR soybean in some locations, which is likely due in part to differences in location-specific weed spectrum and weed pressure. Results from this study also indicated that soybean yield in GLU-R soybean was similar to DGR soybean.

The higher gross profit margin observed with HR soybean cultivars was due primarily to increased herbicide costs in conventional soybean and reduced yield in certain site-years. In this study, POST herbicide program in conventional soybean included acetochlor as an overlapping residual herbicide, which was not present in POST herbicide programs in HR soybean systems. This additional input added to the cost of the conventional soybean system. However, in site-years where conventional soybean produced similar crop yield to HR soybean, gross profit margins were similar or slightly higher when a \$0.05 kg⁻¹ price premium for non-GM soybean was included. These results indicate that price premiums for non-GM soybean can either partially or fully compensate for additional herbicide costs in conventional programs; however, after including price premium, study-wide gross profit margins were on average US\$114 to US\$209 ha⁻¹ lower in conventional soybean compared with DGR and GLU-R soybean. Results of the current study also indicate that GLU-R soybean can provide similar economic return as DGR soybean.

Potential price savings for PRE fb POST herbicide programs evaluated in this study are possible, with herbicide rebate programs, generic formulations of specific active ingredients or pre-mixture product, and alternative products being commercially available to soybean producers. Special care should be taken when selecting herbicides for weed management in conventional or HR soybean to ensure the products provide multiple effective SOA for control of HR weeds and adequately address the weed spectrum for the specific location.



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Supporting information Additional supporting information follows.



Supplementary Information

Manuscript: Economics of Herbicide Programs for Weed Control in Conventional, Glufosinate-, and Dicamba/Glyphosate-Resistant Soybean Across Nebraska

Supplemental Table 1. Soybean injury ratings at 14 and 28 days after pre-emergence (DAPRE) herbicide application in field experiments conducted across five locations in Nebraska to determine economics of herbicide programs in conventional, glufosinate, and dicamba/glyphosate-resistant soybean in 2018 and 2019.^{a,b,c,d}

Herbicide Program	14 DAPRE	28 DAPRE
PRE	%	
Nontreated control	0.0	0.0
Weed-free control	1.4	4.0
Sulfentrazone/ <i>S</i> -metolachlor + metribuzin	2.4	2.7
Chlorimuron/flumioxazin/thifensulfuron-methyl	1.2	3.1
Flumioxazin/pyroxasulfone + metribuzin	1.0	3.1
Chlorimuron/flumioxazin/metribuzin	1.0	3.2
Imazethapyr/pyroxasulfone/saflufenacil	1.7	3.8
<i>P</i>-value	0.915	0.711
Site-years (n)	6 (672)	6 (672)

^a Abbreviations: DAPRE, day after PRE herbicide application.

^b Crop injury data at 14 and 28 DAPRE were combined for all study locations in 2018 and 2019. Data 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 Mean separation for crop injury at 14 and 28 DAPRE included comparisons to the weed-free control.

Supplemental Table 2. Soybean injury ratings at 14 and 28 days after post-emergence (DAPOST) herbicide application in field experiments conducted across five locations in Nebraska to determine economics of herbicide programs in conventional, glufosinate, and dicamba/glyphosate-resistant soybean in 2018 and 2019.^{a,b,c,d}

Herbicide Program	Cultivar HR-Traits	14 DAPOST		28 DAPOST	
		PHYDEF	PHYNEC	PHYDEF	PHYNEC
POST		%			
Dicamba + glyphosate	DR	0.0 a	0.0 a	0.0 a	0.0 a
Glyphosate	DR	0.0 a	0.0 a	0.0 a	0.0 a
Glufosinate	GLU-R	13.2 b	0.0 a	11.5 b	0.0 a
Acetochlor + clethodim + lactofen	CON	12.7 b	11.7 b	11.9 b	8.5 b
	P-value	<0.001	<0.001	<0.001	0.031
	Site-years (n)	6 (672)	6 (672)	6 (672)	6 (672)

^a Abbreviations: DAPOST, day after POST herbicide application; CON, conventional; GLU-R, glufosinate-resistant; DGR, dicamba/glyphosate-resistant; HR, Herbicide-resistant; PHYDEF, phytotoxic deformities; PHYNEC, phytotoxic necrosis.

^b Crop injury data at 14 and 28 DAPOST were combined for all study locations in 2018 and 2019. Data 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 Mean separation for crop injury at 14 and 28 DAPOST excluded comparisons to the nontreated control and weed-free control.