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Management of Glyphosate-Resistant Palmer amaranth (*Amaranthus palmeri* S. Watson) in Dicamba/Glyphosate-Resistant Soybean

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Management of Glyphosate-Resistant Palmer amaranth (*Amaranth palmeri* S. Watson) in Dicamba/Glyphosate-Resistant Soybean

by

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While not a historically problematic weed in Nebraska, Palmer amaranth has become increasingly problematic in many agronomic cropping systems. Throughout the state, several cohorts of Palmer amaranth have been found resistant to several different sites of action. Of major concern is a population found resistant to glyphosate the most common post-emergence herbicide in Nebraska. As chemical control methods are the most common forms of weed control throughout the state methods alternatives or enhancements are highly desired. Two field experiments were conducted in 2018 and 2019 at a grower's field near Carleton, Nebraska with the objectives to evaluate the effects of row spacing and herbicide programs and separately analyze the effect of overlapping residual herbicides on control of glyphosate-resistant (GR) Palmer amaranth, gross profit margin, and benefit-cost ratios of these herbicide programs. Evaluation of the effect on row spacing found no significant effect of narrowing row spacing on control, density, or biomass reduction of GR Palmer amaranth across all herbicide programs. Herbicide program had a higher impact on GR Palmer amaranth control with all PRE fb EPOST except dicamba + chlorimuron/flumioxazin followed by dicamba and all PRE fb EPOST+RH providing greater than 85% control from 14 d after EPOST (DAEPOST) to 36 DAEPOST. Evaluation of overlapping residual

herbicides on management of GR Palmer amaranth found that flumioxazin/pyroxasulfone/metribuzin provided 78% to 82% control from 14 DAEPOST to 70 DAEPOST in 2018 and 94% to 98% in 2019. Addition of dicamba + acetochlor EPOST to flumioxazin/pyroxasulfone/metribuzin provided 83% to 96% from 14 DAEPOST to 70 DAEPOST in 2018 and 99% in 2019.

As the adoption of new application technologies, herbicide-resistant crops, and alternative weed control methods change with the times, surveys provide insight into changes in weed dynamics and crop production over time. Conducting multiple surveys over the course of several years provides a vital framework in developing future research and extension outreach. During the winter of 2019-2020, a survey of Nebraska stakeholders was carried to quantify crop production, weed control, and management practices throughout the state. In order of importance, Palmer amaranth, horseweed, common waterhemp, kochia, and giant ragweed were ranked the most problematic weeds statewide. Based on survey responses, 27% of respondents, cited integrated weed management systems as the primary concern for future research and extension outreach for the state of Nebraska.

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CHAPTER 1:
INTRODUCTION AND OBJECTIVES

INTRODUCTION

Palmer amaranth

Palmer amaranth [*Amaranthus* palmeri (L.) Watson] has rapidly become one of the most concerning weeds affecting agronomic row crops in the United States (WSSA 2017). In Nebraska, a 2015 survey found that stakeholders ranked Palmer amaranth as the sixth most problematic weed (Sarangi and Jhala 2018); more recently a 2019 survey has moved Palmer amaranth to the number one most problematic weed in Nebraska (McDonald et al. 2021). Of concern is the evolution of herbicide resistance in Palmer amaranth biotypes and their widespread occurrence. To date several populations of Palmer amaranth in Nebraska have been found resistant to acetolactate synthase (ALS), hydroxyphenylpyruvate dioxygenase (HHPD), photosystem II (PSII) inhibitors, and glyphosate (Chahal et al. 2017, Jhala et al. 2014, Vieira et al. 2018).

Endemic to the Southwestern United States, Palmer amaranth has spread across the continental United States since the beginning of the 20th century due to seed and equipment transportation and agricultural expansion (Sauer 1957; Ward et al. 2013). Several key factors that have led Palmer amaranth to become such a dominant row crop weed throughout the United States are its prolific seed production (Burkey et al. 2007, Guo and Al-Khatib 2003, Massinga et al. 2001, Keeley et al. 1987, Scott and Smith 2011, and Sellers et al. 2003), season long emergence (Jha et al. 2008, Spaunhorst et al. 2014), and rapid growth rate (Ehleringer and Forseth 1980). In addition to high seed proliferation, Palmer amaranth is a dioecious species, primarily pollinated by wind (Franssen et al. 2001; Ward et al. 2013) that can easily transfer and proliferate herbicide resistance alleles via pollen-mediated gene flow (Jhala et al. 2021).

Dicamba/Glyphosate-Resistant Soybean

First commercialized in 2017, the dicamba/glyphosate-resistant (DGR) soybean system has quickly risen in popularity. Current trends in adoption of DGR soybean have risen from 20% to almost 80% of Nebraska soybean acres (Werle et al. 2018, Jhala et al. 2019). This rapid adoption of DGR soybean consequently has led to an increase in dicamba usage alone or in mixtures for post-emergence control of broadleaf weeds largely due to widespread occurrence of glyphosate-resistant weeds in Nebraska particularly horseweed, waterhemp, and Palmer amaranth.

Cultural Controls: Row Spacing

As chemical control methods have long been the primary means of weed control in agronomic cropping systems, the increased occurrence of herbicide-resistant weeds has driven growers toward alternative solutions. Prior studies have demonstrated the integration of chemical control programs and cultural control methods such as tillage, crop rotation, crop density, row spacing, and cover crops can provide effective control of horseweed (*Conyza canadensis* L.), burclover (*Medicago polymorpha* L.), common lambsquarters (*Chenopodium album* L.), littleseed canarygrass (*Phalaris minor* Retz.), scarlet pimpernel (*Anagallis arvensis* L.), toothed dock (*Rumex dentatus* L.), and GR giant ragweed (*Ambrosia trifida* L.) (Bhullar et al. 2015; Chahal and Jhala 2019; Ganie et al. 2016). By alternating the row width can affect several important factors attributed to plant growth such as light with increased light interception observed with narrower row spacings (Flénet et al. 1996). In soybean, two different row spacings 38 cm and 76 cm are in common usage for soybean cultivation in

Nebraska. Prior studies have recognized the utility of narrowed row spacings to provide enhanced weed control in glyphosate-resistant and glufosinate -resistant soybean as well as sweet potato (Bell et al. 2015, Meyers et al. 2010, Whitaker et al. 2010).

Multiple Sites of Action & Overlapping Residuals Herbicides

With the high cost of herbicide programs and the increased presence of herbicide-resistant weeds, growers have multiple concerns and constraints when it comes to weed management. Cost saving measures such as avoiding the usage of PRE herbicides have been employed by growers to the detriment of crop yield (Hall et al. 1992, Schuster and Smeda 2007). As usage of herbicides with multiple sites of action have higher costs associated with them, managing the multiple herbicide-resistant weeds is a constant challenge. As high costs can be difficult to justify the usage of higher priced chemical control programs to mitigate the evolution of herbicide-resistance, many growers will not adopt these management programs until after the establishment of herbicide-resistant weeds (Edwards et al. 2014, Norsworthy et al. 2012). In conjunction with usage of herbicides with multiple sites of action, implementation of soil-residual herbicides mixed with foliar active herbicides in post-emergence applications have been encouraged for weeds with extended emergence patterns (Neve et al. 2011).

Survey of Stakeholders

Over the past several decades multiple surveys of growers, crop consultants, and other stakeholders in agronomic cropping systems have helped shaped university and extension research in areas of weed dynamics and management (Gibson et al. 2005, Givens et al 2009a,b, Norsworthy 2003, Riar et al. 2013a, b, Sarangi and Jhala 2018). With the commercialization of new herbicide-resistant crops, herbicide chemistries, application technology, and farming practices the need to detect and monitor shifts in the aforementioned weed dynamics such as the rise in issues with weeds like *Amaranthus* spp are key to make informed decision making. As climates vary greatly from east to west in Nebraska so do the cropping systems and weed issues. Data from these stakeholder surveys provide some of the best insights into the issues of Nebraska's stakeholders and provides the basis for further research and extension outreach conducted by the University of Nebraska-Lincoln.

OBJECTIVES

1. Evaluate the effects of soybean row spacing and herbicide programs on control of glyphosate-resistant Palmer amaranth in dicamba/glyphosate-resistant soybean.
2. Economics of overlapping residual herbicide programs for glyphosate-resistant Palmer amaranth management in dicamba/glyphosate-resistant soybean.
3. Survey Nebraska stakeholders to assess cropping systems, problem weeds, and weed management in Nebraska agronomic cropping systems.

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CHAPTER 2:

EFFECT OF ROW SPACING AND HERBICIDE PROGRAMS FOR CONTROL OF GLYPHOSATE-RESISTANT PALMER AMARANTH (AMARANTHUS PALMERI) IN DICAMBA/GLYPHOSATE-RESISTANT SOYBEAN

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ABSTRACT

Glyphosate-resistant (GR) Palmer amaranth is one of the most difficult to control weeds in soybean production fields in Nebraska and the United States. An integrated approach is required for effective management of GR Palmer amaranth. Cultural practices such as narrow row spacing might augment herbicide efficacy for management of GR Palmer amaranth. The objectives of this study were to evaluate the effect of row spacing and herbicide programs for management of GR Palmer amaranth in dicamba/glyphosate-resistant (DGR) soybean. Field experiments were conducted in a grower's field with a uniform population of GR Palmer amaranth near Carleton, Nebraska in 2018 and 2019. Year-by-herbicide program-by-row spacing interactions were significant for all variables; therefore, data were analyzed by year. Herbicides applied pre-emergence (PRE) controlled GR Palmer amaranth ≥ 95% in both years 14 d after PRE (DAPRE). Across soybean row-spacing, most PRE fb early-POST (EPOST) herbicide programs provided 84% to 97% control of Palmer amaranth compared with most EPOST fb late-post (LPOST) programs, excluding dicamba in single and sequential

applications (82% to 95% control). Mixing microencapsulated acetochlor with a POST herbicide in PRE fb EPOST herbicide programs controlled Palmer amaranth ≥ 93% 14 DAEPOST and ≥ 96% 21 DALPOST with no effect on Palmer amaranth density. Interaction of herbicide program-by-row spacing on Palmer amaranth control was not significant; however, biomass reduction was significant at soybean harvest in 2019. The herbicide programs evaluated in this study caused no soybean injury. Due to drought conditions during a majority of the 2018 growing season, soybean yield in 2018 was reduced compared to 2019.

INTRODUCTION

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

Palmer amaranth is a prolific seed producer despite competition with agronomic crops (Burke et al. 2007; Guo and Al-Khatib 2003; Massinga et al. 2001), with female plants producing ≥ 200,000 seeds plant^{-1} (Keeley et al. 1987; Scott and Smith 2011; Sellers et al. 2003).

Palmer amaranth has the potential to produce high numbers of seed. Keeley et al. (1987) reported that Palmer amaranth could produce 200,000 to 600,000 seeds plant^{-1}, while Scott and Smith (2011) reported seed production from 150,000 to 200,000 seeds plant^{-1} when Palmer amaranth was grown under competition with cotton or soybean. However, (Scott and Smith 2011) indicated that seed production of Palmer amaranth grown without competition can exceed 1.5 million seeds plant^{-1}. Like waterhemp (*Amaranthus tuberculatus* Sauer), Palmer amaranth has an extended emergence period from May to September in the southeastern United States (Jha et al. 2008) and from May to August in the midwestern United States (Spaunhorst et al. 2014). In addition, Palmer amaranth is a dioecious species primarily pollinated by wind (Franssen et al. 2001; Ward et al. 2013) that can transfer herbicide resistance alleles via pollen-mediated gene flow (Jhala et al. 2021).

Glyphosate, a broad-spectrum systemic herbicide, is the most widely used agricultural pesticide globally (Benbrook 2016). An estimated 8.6 billion kg of glyphosate was applied worldwide between 1974 and 2014, with the United States accounting for 19%, or 1.6 billion kg, of global usage (Benbrook 2016). Glyphosate use in the United States was estimated at 18 million kg year^{-1} in 1996, increasing to an estimated 125 million kg in 2013 (USGS 2020). The popularity of glyphosate can be attributed in large part to the widespread adoption of GR crops, low cost, broad spectrum of weed control, and flexibility with crop rotation without carryover injury (Woodburn 2000). Glyphosate was ranked as the most commonly used herbicide in GR corn-soybean cropping systems in Nebraska in a survey conducted in 2015 (Sarangi and Jhala 2018).

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

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

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

MATERIALS AND METHODS

Study Site and Experimental Design

Field experiments were conducted during the summer of 2018 and 2019 in a grower's rainfed field in Thayer County, Carleton, NE (40.30ºN, 97.67ºW). The field was naturally infested with Palmer amaranth resistant to glyphosate with 37-40 fold resistance (Chahal et al. 2017).

The soil texture at the research site was Crete silt loam (montmorillonitic, mesic, Pachic Argiustolls) with a pH of 6.0, 19% sand, 63% silt, 18% clay, and 2.6% organic matter content. Palmer amaranth was the primary weed in the field with sporadic presence of horseweed, green foxtail (*Setaria viridis* P. Beauv.), and giant foxtail (*Setaria faberi* Herrm.).

The producer's field had been in a GR corn-soybean rotation with reliance on glyphosate for weed control in a no-till production system for the previous 10 yr. Corn residue from the previous cropping season was retained and the study conducted using no-till practices. Paraquat (Gramoxone® SL, Syngenta Crop Protection, Greensboro, NC 24719) at 840 g ai ha^{-1} plus 2,4-D ester (Weedone® LV6, Nufarm Inc., Burr Ridge, IL 60527) at 386 g ae ha^{-1} plus a nonionic surfactant (Induce®, Helena Chemical, Collierville, TN 38017) at 0.25% v/v was applied two wk before soybean planting with a tractor-mounted sprayer calibrated to deliver 140 L ha^{-1} at 276 kPa for control of winter annual weeds. Dicamba/glyphosate-resistant soybean (Northern King NK S29K3X) was planted on May 10, 2018 and May 15, 2019 at 346,000 seeds ha^{-1} at a depth of 3.0 cm.

Treatments were arranged in a randomized split-block design with four replications (Federer and King 2006). Herbicide programs were assigned as the whole plot factor (Table 2-1) in a randomized complete block whereas row spacing (38 or 76 cm) was assigned as the subplot factor, which resulted in non-standard incomplete "column" blocks, each containing 15 herbicide programs across the four replications. An incomplete blocking factor was added to simplify the field operation of planting soybean in 38 cm and 76 cm row spacing and reduce field traffic to avoid soil compaction. Plots were 3 m wide by 9 m long with four soybean rows spaced 76 cm apart or 6 soybean rows spaced 38 cm apart. In total, 15 herbicide programs were evaluated: two early-POST (EPOST), four EPOST followed by (fb) late-POST (LPOST), four

PRE fb EPOST, four PRE fb EPOST plus a residual herbicide (RH), and a nontreated control (Table 2-1). PRE herbicides were applied on the same day after planting DGR soybean, and EPOST herbicides were applied on June 18, 2018 and June 25, 2019 when soybean was at the V3 to V4 growth stage and Palmer amaranth was 7.5 to 10.5 cm tall. LPOST herbicides were applied on July 6, 2018 and July 2, 2019 when soybean was at the R1 growth stage. The PRE, EPOST, and LPOST herbicides were applied using a handheld CO_2 pressurized backpack sprayer fitted with an AIXR 110015 flat fan or TTI 11005 flat angle nozzles (TeeJet®, Spraying Systems Co., P.O. Box 7900, Wheaton, IL 60139) based on label requirements and calibrated to deliver 140 L ha^{-1} at 276 kPa.

Data Collection

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

65°C for 14 d, with Palmer amaranth aboveground biomass data converted into percent biomass reduction compared with the nontreated control using the following equation (Wortman 2014)**:**

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

where C is equal to the aboveground biomass of the nontreated control plot and *B* is equal to the biomass of an individual treated plot. Soybean yield was taken from the center two or four rows in each plot (for 76 and 38 cm row spacing, respectively) using a plot combine (Gleaner K2, AGCO, 4205 River Green Parkway, Duluth, GA) and adjusted to 13% moisture content.

Statistical Analysis

Statistical analysis was performed in R statistical software v. 4.0.3 (R Core Team 2018) using the "glmmTMB" package (Brooks et al. 2017) and "lme4" package (Bates et al. 2015), with subsequent contrast analysis preformed using the "gmodels" package (Warnes et al. 2018). Year-by-treatment and year-by-treatment-by-row spacing interactions were evaluated, and if significant, data were analyzed separately by year. In the models separated by year, the interaction of herbicide treatment and row spacing were considered fixed effects whereas the interaction of replication by herbicide treatment, column, and column by row spacing were considered random effects.

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

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

RESULTS AND DISCUSSION

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

Temperature and Precipitation

Growing conditions differed between the 2018 and 2019 growing seasons (Figure 2-1). In both years, field experiments were conducted under rainfed conditions. During 2018, cumulative precipitation received was below the 30-yr average (517 mm) for most of the growing season. In contrast, during 2019, cumulative precipitation received during the growing season exceeded the 30-yr average by 221 mm. Average daily temperatures in 2018 exceeded the 30-yr average during the early growing season, whereas they closely resembled the 30-yr average in 2019 (Figure 2-1). Herbicide programs evaluated in this study displayed excellent safety in DGR soybean, with no observable injury across both years (data not shown).

Palmer amaranth Control

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

At 14 DAEPOST, the interaction of herbicide program-by-row spacing and the main effect of row spacing for Palmer amaranth control were not significant for either year. For both years, EPOST and EPOST fb LPOST herbicide programs provided reduced control of Palmer amaranth compared with PRE fb EPOST application of dicamba or dicamba plus acetochlor. Imazethapyr applied EPOST provided 15% and 4% Palmer amaranth control in 2018 and 2019, respectively. Likewise, EPOST or EPOST fb LPOST applications of glyphosate provided 10% to 30% control across both years. Reduced Palmer amaranth control with imazethapyr and glyphosate observed in this study can be attributed primarily to the prevalence of ALS-inhibitor resistant and GR Palmer amaranth biotype present at the study location (Chahal et al. 2017). In EPOST and EPOST fb LPOST herbicide programs where dicamba was applied, Palmer amaranth control from EPOST programs varied from 36% to 68% in 2018 and 85% to 89% in 2019 (Table 2-3). *A priori* contrasts comparing the main effect of herbicides on Palmer amaranth control were significant ($P < 0.05$) 14 DAEPOST for both years, with PRE fb EPOST herbicide programs providing 90% and 99% Palmer amaranth control in 2018 and 2019, respectively. The addition of acetochlor with

EPOST herbicides increased Palmer amaranth control 14 DAEPOST in 2018 and 2019 (88% vs. 93% and 83% vs. 94%, respectively).

At 21 DAEPOST, PRE fb EPOST and PRE fb EPOST + RH (acetochlor) programs controlled Palmer amaranth 84% to 97% in both years, with comparable control also provided by most EPOST or EPOST fb LPOST dicamba applications (Table 2-3). Conversely, glyphosate provided 36% to 43% control in 2018 and 7% to 8% control in 2019. This indicates the level of glyphosate resistance and demonstrates that even two applications of glyphosate could not provide > 45% control. Imazethapyr applied EPOST controlled Palmer amaranth 58% in 2018 and 3% in 2019, whereas mixing fomesafen/*S*-metolachlor with imazethapyr improved control to 75% and 61% 21 DAEPOST in 2018 and 2019, respectively (Table 2-3). *A priori* contrasts comparing the main effects of herbicide programs on Palmer amaranth control were significant ($P < 0.001$) 21 DAEPOST, with PRE fb EPOST and PRE fb EPOST + RH providing the highest Palmer amaranth control. Averaged across PRE herbicides, mixing acetochlor with dicamba applied EPOST increased Palmer amaranth control 21 DAEPOST in 2018 (97%) compared to dicamba alone (92%), but not in 2019 (Table 2-3).

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

A priori contrasts comparing the main effects of herbicide programs on Palmer amaranth control were significant 21 DALPOST with PRE fb EPOST herbicide programs providing ≥ 92% Palmer amaranth control. Tank-mixing acetochlor with POST herbicides increased Palmer amaranth control 21 DALPOST (Table 2-3). In 2018, the interaction of herbicide program by row spacing was significant ($P < 0.001$) for Palmer amaranth control 21 DALPOST, although comparisons of estimated marginal means across row spacing was only significant for EPOST applications of glyphosate, which provided 53% and 26% Palmer amaranth control in 38 and 76 cm row spacing, respectively (Table 2-4). In both years, contrasts comparing the main effects of herbicide programs on Palmer amaranth control were significant 21 DALPOST, with PRE fb EPOST herbicide programs providing 92% and 88% control in 2018 and 2019, respectively. Mixing acetochlor with POST herbicides increased Palmer amaranth control 21 DALPOST (Table 2-3). The increased Palmer amaranth control via the inclusion of acetochlor as an overlapping residual herbicide is similar to results reported by Sarangi and Jhala (2019) in which overlapping residual herbicides increased Palmer amaranth control and biomass reductions in conventional soybean 28 DAPOST in a field study in Nebraska.

Prior to soybean harvest, most PRE fb EPOST and PRE fb EPOST + RH programs controlled GR Palmer amaranth 91% to 99%, with the exception of dicamba fb dicamba in 2018, which provided 76% control (Table 2-5). These results are similar to those reported by Bell et al. (2015) in a two-year study in which herbicide programs receiving PRE herbicides controlled Palmer amaranth ≥ 95% regardless of row spacing when evaluated prior to harvest. The EPOST and EPOST fb LPOST applications of dicamba provided similar control to PRE fb EPOST herbicide programs, with the exception of dicamba applied EPOST in 2018 (72%). As observed at 21 DALPOST, imazethapyr fb dicamba and imazethapyr mixed with fomesafen/*S*-metolachlor fb dicamba provided 60% to 78% Palmer amaranth control. *A priori* contrasts comparing the main effects of herbicide programs on Palmer amaranth control were significant for pre-harvest Palmer amaranth control with PRE fb EPOST herbicide programs providing 92% to 99% Palmer amaranth control. Mixing acetochlor with EPOST herbicide increased Palmer amaranth control at pre-harvest in 2018, but not in 2019 (Table 2-5). While the effect of acetochlor applied POST in soybean is well documented (Bell et al. 2015; Manuchehri et al. 2017; Sarangi and Jhala 2018), the effect of including acetochlor with dicamba in DGR soybean applied POST for Palmer amaranth control is limited. The inconsistency of pre-harvest Palmer amaranth control with acetochlor has been reported elsewhere. For example, Spaunhorst et al. (2014) reported that the inclusion of acetochlor applied EPOST or LPOST did not provide additional control of waterhemp compared to programs without acetochlor in DGR soybean in Missouri. Likewise, including acetochlor in an overlapping residual herbicide program did not increase Palmer amaranth control compared to programs lacking acetochlor in cotton (Manuchehri et al. 2017). In contrast, research conducted in Nebraska with multiple HR Palmer amaranth in corn has indicated that acetochlor applied POST in a PRE fb POST herbicide program was an effective management strategy (Chahal et al. 2018). An important distinction to note is that the inclusion of acetochlor with POST herbicides did not result in reduced Palmer amaranth control (via antagonistic effects) compared to corresponding programs that did not include acetochlor.

Palmer amaranth Biomass Reduction

The main effect of row spacing and the interaction of herbicide-by-row spacing were not significant 14 DAEPOST in 2018 (Table 2-6). The PRE fb EPOST and PRE fb EPOST plus RH programs provided the highest reduction of Palmer amaranth biomass (91% to 100%) compared to EPOST (23% to 78%) and EPOST fb LPOST (22% to 68%) 14 DAEPOST (Table 2-6). *A priori* contrasts in 2018 comparing the main effect of herbicide programs on Palmer amaranth biomass reduction were significant, with PRE fb EPOST programs providing the greatest reduction of Palmer amaranth biomass. The addition of acetochlor as a RH was not significant 14 DAEPOST in 2018 (Table 2-6).

A priori contrasts in 2019 comparing the main effect of herbicide program on Palmer amaranth biomass reduction were significant 14 DAEPOST and 14 DALPOST, with PRE fb EPOST programs providing 97% and 90% biomass reductions, respectively. The addition of acetochlor as a RH was significant 14 DAEPOST in 2019 (99% vs. 94% biomass reduction), but not 14 DALPOST ($P < 0.05$) (Table 2-6). Acetochlor has been previously shown to provide > 80% control of Palmer amaranth up to 50 d after application (Cahoon et al. 2015), while mixing acetochlor with glufosinate has been shown to provide ≥ 93% biomass reduction of GR common ragweed (*Ambrosia artemisiifolia* L.) in glufosinate-resistant soybean (Barnes et al. 2017) and ≥ 84% control applied alone or tank-mixed with fluometuron, diuron, fomesafen, or diuron/fomesafen (Cahoon et al. 2015).

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

Palmer amaranth Density

Palmer amaranth density was higher in EPOST and EPOST fb LPOST herbicide programs compared to programs containing PRE herbicides 14 DAEPOST in both years (Table 2-7). However, the interaction of herbicide by row spacing was significant 14 DAEPOST (P = 0.028 and P = 0.04, respectively), although after adjusting for multiple comparisons, estimated marginal mean groupings were similar for herbicide programs and row spacing (Table 2-8). This is likely attributed to the large variance in Palmer amaranth densities across herbicide programs and row spacings, or the conservative nature of Post-hoc Tukey P-value adjustments and Sidak method confidence-level adjustments utilized during estimated marginal mean separation. For the analysis of main effects, *A priori* contrasts comparing Palmer amaranth density 14 DAEPOST for both years were significant with reduced Palmer amaranth density in PRE fb EPOST herbicide programs compared to EPOST and EPOST fb LPOST herbicide programs. The addition of acetochlor with a POST herbicide did not reduce Palmer amaranth density in PRE fb EPOST herbicide programs, indicating that a RH at EPOST is not needed in every field and that careful herbicide selection is necessary based on weed density and moisture availability to avoid extra cost (Table 2-7).

At 14 DALPOST in 2019 (e.g., 36 DAEPOST), density of Palmer amaranth was not significant by herbicide or herbicide by-row spacings. Row spacing was significant (P = 0.002), with 1.0 Palmer amaranth plant m^{-2} in 38 cm row spacing compared to 15 Palmer amaranth plants in 76 cm row spacing across the herbicide programs evaluated. Mixing acetochlor did not reduce Palmer amaranth density compared to PRE fb EPOST herbicide programs without acetochlor (Table 2-7). Inclusively, findings from the current study at 14 DALPOST are similar to the results of Spaunhorst et al. (2014), which reported that acetochlor with EPOST or LPOST herbicides did not reduce waterhemp density in DGR soybean in Missouri compared to EPOST and LPOST herbicides that did not include acetochlor.

Soybean Yield

Due to drought conditions during a majority of the growing season in 2018, soybean yield was reduced compared with 2019 (Figure 2-1; Table 2-5). In 2018, the main effect of herbicide program was significant for soybean yield, whereas row spacing and the interaction effect of herbicide-by-row spacing were not significant. Yield was consistently higher in PRE fb EPOST (695 kg ha^{-1}) and PRE fb EPOST plus RH programs (925 kg ha^{-1}) compared to most EPOST and EPOST fb LPOST herbicide programs with the exception of dicamba applied EPOST (655 ± 55 kg ha^{-1}) and dicamba applied EPOST fb LPOST (564 ± 75 kg ha^{-1}). *A priori* contrasts comparing soybean yield in 2018 were significant, with the highest yield occurring in treatments that received PRE fb EPOST herbicides, which is consistent with literature indicating the economic importance of PRE fb POST herbicide programs (Barnes et al. 2017; Rosenbaum et al. 2013) as well as multiple applications to control Palmer amaranth (Cahoon et al. 2015).

The main effects of row spacing and herbicide programs were significant for soybean yield, with 4,607 ± 238 and 3,930 ± 203 kg ha–1 in 38 and 76 cm row spacing, respectively, in 2019 (Table 2-5). Across row spacings, soybean yield was similar for most herbicide programs, excluding glyphosate applied EPOST (3,176 ± 269 kg ha–1). Wax and Pendleton (1968) reported soybean yield increase of 10%, 18%, and 20% in 76, 50, and 25-cm row spacing compared with the 101 cm row spacing in field experiments conducted in Illinois. A priori contrasts comparing soybean yield in 2019 were significant with the highest yield in PRE fb EPOST or EPOST fb LPOST herbicide programs, indicating the importance of utilizing PRE herbicide programs in DGR soybean; however, mixing acetochlor with POST herbicides did not result in increased soybean yield (Table 2-5). While soybean grain yield reduction of up to 79% due to Palmer amaranth interference has previously been reported (Bensch et al. 2003; Klingaman and Oliver 1994; Monks and Oliver 1988), the control of Palmer amaranth provided by most of the herbicide programs in this research was substantial enough to avoid the yield reductions that occurred to the nontreated control (2,284 kg ± 199 kg ha–1).

Conclusion

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

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

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Table 2-1. Herbicides and application timings, rates, and products used for control of glyphosate-resistant Palmer amaranth in dicamba/glyphosate-resistant soybean in field experiments conducted near Carleton, NE in 2018 and 2019.

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

[a] Abbreviations: ai, active ingredient; ae, acid equivalent; AMS, ammonium sulfate (N-Pak AMS Liquid, Winfield United, LLC., St. Paul, MN 55164); DRA, drift reducing agent (Intact, Precision Laboratories, Waukegan, IL 60085); EPOST, early POST-emergence; fb, followed by; LPOST, late POST-emergence; NIS, non-ionic surfactant (Induce, Helena Chemical, Collierville, TN 38017); RH, residual herbicide; WC, water conditioner (Class Act Ridion, Winfield United, Arden Hills, MN, 55126).

[b] Bayer CropScience, Research Triangle Park, NC; BASF Corporation, Research Triangle Park, NC; Syngenta Crop Protection, LLC., Greensboro, NC; Valent USA Corporation, Walnut Creek, CA.

[c] AMS at 3% v/v, DRA at 0.5% v/v, NIS at 0.25% and WC at 1% v/v were mixed with herbicide treatments based on label recommendations.

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

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

[a] Abbreviations: ai, active ingredient; ae, acid equivalent; DAPRE, days after pre-emergence herbicide; PRE, pre-emergence herbicide; RH, residual herbicide.

[b] PRE fb EPOST and PRE fb EPOST + RH treatments were combined (n = 8) for analysis of 14 and 28 DAPRE control.

[c] Data for each year were logit transformed before analysis; however back-transformed values are presented based on interpretations of transformed data.

[d] Means presented within the same column with no common letters are significantly different according to estimated marginal means with Sidak confidence-level adjustments and Tukey *P*-value adjustments.

Table 2-3. Control of glyphosate-resistant Palmer amaranth at 14 and 21 DAEPOST and 21 DALPOST in dryland field experiments conducted near Carleton, NE to determine the effect of row spacing and herbicide programs in dicamba/glyphosate-resistant soybean in 2018 and 2019.

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

[a] Abbreviations: DAEPOST, days after early-POST emergence; DALPOST, days after late-POST emergence; DAPRE, days after pre-emergence; EPOST, early-POST emergence; fb, followed by; LPOST, late-POST emergence; RH, residual herbicide.

[b] Data for each year were logit transformed before analysis; however back-transformed values are presented based on interpretations of transformed data.

[c] Means presented within the same column with no common letters are significantly different according to estimated marginal means with Sidak confidence-level adjustments and Tukey *P*-value adjustments.

[d] *a priori* contrasts; * = significant ($P < 0.05$); **= significant ($P < 0.01$); ***= significant ($P < 0.001$); NS, non-significant ($P \geq 0.05$)

Table 2-4. Interaction of herbicide programs and row spacing (38 cm or 76 cm) for control of glyphosate-resistant Palmer amaranth at 21 DAEPOST and 21 DALPOST and biomass reduction at pre-harvest in rainfed field experiments conducted near Carleton, NE in dicamba/glyphosate-resistant soybean in 2018 and 2019.

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

[a] Abbreviations: GR, glyphosate-resistant; DGR, dicamba/glyphosate-resistant; DAEPOST, days after early-POST emergence herbicide; DALPOST, days after late-POST emergence herbicide; DAPRE, days after pre-emergence herbicide; EPOST, early-POST emergence herbicide; fb, followed by; LPOST, late-POST emergence herbicide; PRE, pre-emergence herbicide; RH, residual herbicide.

[b] Data for each year were logit transformed before analysis; however back-transformed values are presented based on interpretations of transformed data.

[c] Means presented within the same column with no common letters are significantly different according to estimated marginal means with Sidak confidence-level adjustments and Tukey *P*-value adjustments.

Table 2-5. Pre-harvest control of glyphosate-resistant Palmer amaranth and soybean yield in rainfed field experiments conducted near Carleton, NE to determine the effect of row spacing and herbicide program in dicamba/glyphosate-resistant soybean in 2018 and 2019.

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

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

Table 2-6. Effect of row spacing and herbicide programs on glyphosate-resistant Palmer amaranth biomass reduction at 14 DAEPOST, 14 DALPOST, and pre-harvest in rainfed field experiments conducted near Carleton, NE in dicamba/glyphosate-resistant soybean in 2018 and 2019.

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

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

Table 2-7. Effect of row spacing and herbicide programs on glyphosate-resistant Palmer amaranth density at 14 DAEPOST and 14 DALPOST in rainfed field experiments conducted near Carleton, NE in dicamba/glyphosate-resistant soybean in 2018 and 2019.

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

[a] Abbreviations: DAEPOST, days after early-POST emergence; DALPOST, days after late-POST emergence; EPOST, early-POST emergence; fb, followed by; LPOST, late-POST emergence; RH, residual herbicide.

[b] Data for each year were square root or log transformed before analysis; however back-transformed values are presented based on interpretations of transformed data.

[c] Means presented within the same column with no common letters are significantly different according to estimated marginal means with Sidak confidence-level adjustments and Tukey *P*-value adjustments.

[d] *a priori* contrasts; * = significant ($P < 0.05$); **= significant ($P < 0.01$); ***= significant ($P < 0.001$); NS, non-significant ($P \geq 0.05$).

Table 2-8. Interaction of herbicide programs and row spacing for glyphosate-resistant Palmer amaranth density at 14 DAEPOST in rainfed field experiments conducted near Carleton, NE in dicamba/glyphosate-resistant soybean in 2018 and 2019.

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

[a] Abbreviations: DAEPOST, days after early-POST emergence; DALPOST, days after late-POST emergence; EPOST, early-POST emergence; fb, followed by; LPOST, late-POST emergence; RH, residual herbicide.

[b] Data for each year were logit transformed before analysis; however back-transformed values are presented based on interpretations of transformed data.

[c] Means presented within the same column with no common letters are significantly different according to estimated marginal means with Sidak confidence-level adjustments and Tukey *P*-value adjustments.

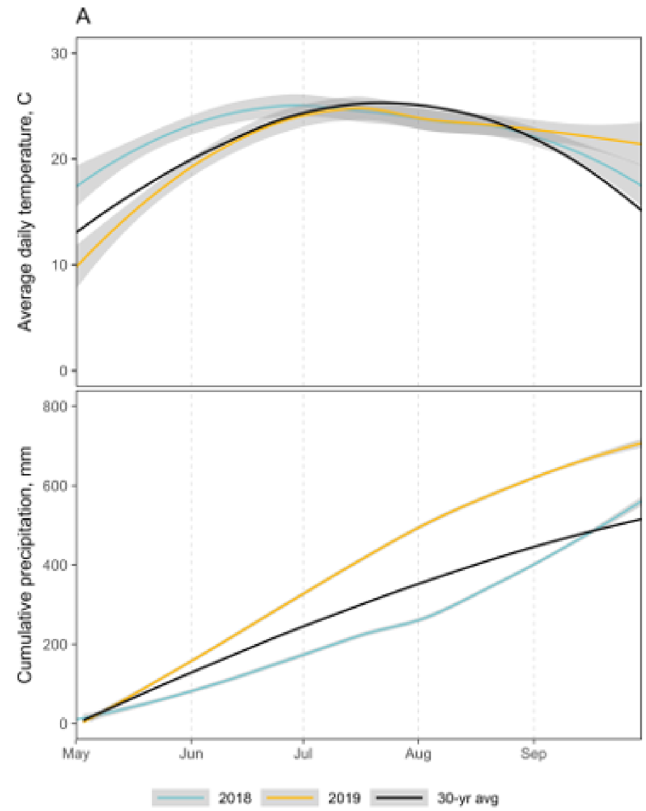

Figure 2-1. Average daily air temperature (°C) and total cumulative precipitation (mm) received during the 2018 and 2019 growing seasons compared to the 30-year average for dryland field experiments conducted to determine the effect of row spacing and herbicide programs for control of glyphosate-resistant Palmer amaranth in dicamba/glyphosate-resistant soybean near Carleton, Nebraska, in 2018 and 2019.

CHAPTER 3:
ECONOMICS OF OVERLAPPING RESIDUAL HERBICIDE PROGRAMS FOR GLYPHOSATE-RESISTANT PALMER AMARANTH MANAGEMENT IN SOYBEAN

ABSTRACT

The rapid growth and extended germination window of Palmer amaranth along with the wide-spread evolution of herbicide-resistant biotypes have complicated management programs of this problem weed. Field experiments were conducted in 2018 and 2019 in a grower's field near Carleton, NE to evaluate the effect of pre-emergence (PRE) followed by (fb) a tank-mixture of foliar active and residual post-emergence (POST) herbicide programs for control of glyphosate/ALS-inhibitor-resistant Palmer amaranth in dicamba/glyphosate-resistant soybean. PRE herbicides evaluated in this study provided 94%- 100% reductions in weed biomass 14 d after PRE (DAPRE) in 2019. At 28 DAPRE, PRE herbicides provided 80% to 92% control of Palmer amaranth during both years. Likewise, in 2019, PRE-only, PRE fb POST, and PRE fb POST + RH (residual herbicide) programs provided 98% to 100% reductions in Palmer amaranth biomass 28 DALPOST. All herbicide programs provided similar control 21 DAEPOST in 2018. Herbicides applied PRE provided 94% control of Palmer amaranth compared to 99% control with PRE fb POST and PRE fb POST + RH 21DAEPOST in 2019. While soybean yields did not differ across herbicide programs in 2018, PRE fb POST + RH programs produced higher yields (4,860 kg ha^{-1}) than PRE-only (4,487 kg ha^{-1}), PRE fb POST (4,569 kg ha^{-1}), and POST fb LPOST (4,537 kg ha^{-1}) programs in 2019. While programs with chlorimuron/flumioxazin/pyroxasulfone fb dicamba + acetochlor & flumioxazin/pyroxasulfone/metribuzin fb dicamba + acetochlor produced negative gross

profit margins in 2018 consequentially produced the highest overall gross profit margins $1,603 ha^{-1} and $1,658 ha^{-1} in 2019, respectively.

INTRODUCTION

Weed infestation in agronomic crop production systems has been recognized as one of the major threats to global food security and it continue to be an issue in modern agriculture (Blackman and Templeman 1938; Weber and Staniforth 1957). Competition for nutrients, water, space, and sunlight between crops and weeds lead to losses in crop yield (Tillman 1990). Metanalysis conducted by Soltani et al. (2016) and (2017) reported that weed infestation resulted in US $48 billion in yield losses in corn and soybean in Canada and US combined. To mitigate economic losses to weed interference, farmers are required to consider a multitude of factors, including the type of crop and any associated herbicide-resistance traits, weed control spectrum, selectivity, cost of herbicides, environment, and fit with conservation agriculture (Buhler 1999; Swanton and Weise 1991). Increasing in prevalence with the movement of sustainable crop production, conservation agriculture consists of three main points: minimal soil disturbance, permanent soil cover with crop residue and or cover crops, and crop rotations (FAO 2017). Conservation agriculture has seen rapid growth globally with a 12.5% increase from an estimated 106 million ha in 2008/2009 to 180 million ha in 2015/2016 (Kassam et al. 2019). As of the 2017 United States Department of Agriculture (USDA) Ag Census, US growers reported 42,270,399 ha of crop lands under no-till practices (USDA 2017). While there are number of benefits of no-till crop production system, the major limitation is weed control is primarily depends on herbicides.

Development and commercialization of herbicide-resistant crops, primarily glyphosate-resistant (GR) crops, in the 1990s have provided simplified, flexible, and cost-effective weed control option and promoted conservation agriculture by reducing deep tillage and maintaining crop residues on the soil surface (Carpenter and Gianessi 1999; Dill et al. 2008; Triplett and Dick 2008). However, given the steady reliance on glyphosate, several reports have expressed concerns regarding the evolution of GR weed biotypes (Chahal and Jhala 2017, Norswothty et al 2008, Kohrt et al. 2017). As of 2020, a total of 53 weed species have been reported as GR globally, of those 17 have been reported in the United States (Heap 2021), with 6 being reported in Nebraska (Jhala 2018). Given the widespread occurrence of GR weeds in the United States, application of residual herbicides at planting or certain labeled herbicides mixed with POST herbicides have been shown to aide in management of GR weeds (Norsworthy et al. 2012; Sarangi et al. 2017; Whitaker et al. 2010). Sarangi and Jhala 2018 reported 60% of NE producers use residual herbicides, similar trends were also observed nationally (70%) (Beckie 2018).

An increasing evolution of GR weeds in the USA due to the widespread use of glyphosate led growers to look for alternative herbicides. Soybean resistant to dicamba and glyphosate was commercialized in 2017 providing growers an option to apply dicamba for POST weed control. A synthetic auxin herbicide (WSSA: Group 4), dicamba is a popular foliar-applied herbicide in Nebraska corn (*Zea mays* L.), sorghum (*Sorghum bicolor* L.), and wheat (*Triticum aestivum* L.) production (Sarangi and Jhala 2018). Since it’s commercialization in 2017, dicamba/glyphosate-resistant (DGR) soybean has rapidly grown in popularity as seen with the adoption rate increasing from 20% in 2017 to 80% in 2019 for the state of Nebraska (Chahal and Jhala 2019; Werle et al. 2018). Usage of the dicamba-resistance trait is likely to remain steady in commercial soybean production with the recent release of glyphosate/dicamba/glufosinate-resistant soybean (Jhala 2019).

Palmer amaranth (*Amaranthus palmeri*) has been recognized as a major problem weed in agronomic crops in the United States (WSSA 2017). A survey conducted in 2015 found that stakeholders ranked Palmer amaranth as the sixth most problematic weed in Nebraska (Sarangi and Jhala 2018); however, a recent survey in Nebraska reported Palmer amaranth as the most common problem weed (McDonald et al. 2021). As of 2021, Palmer amaranth biotypes resistant to acetolactate synthase (ALS), hydroxyphenylpyruvate dioxygenase (HPPD), photosystem II (PSII) inhibitors, and glyphosate was confirmed in Nebraska (Chahal et al. 2017; Jhala et al. 2014; Vieira et al. 2018). In addition, a population of dicamba-resistant Palmer amaranth has been confirmed in Tennessee (Steckel 2020) and glufosinate-resistant Palmer amaranth has been confirmed in Arkansas (Barber et al 2021).

In prior studies of season-long interference, Palmer amaranth at a density of 3.33 and 10 plants per m of soybean row reduced grain yield by 64% and 68%, respectively (Klingaman and Oliver 1994). Similarly, Bensch et al. (2003) reported that Palmer amaranth interference at a density of 8 plants m^{-1} of soybean row resulted in 79% yield loss in Kansas. With wide emergence window of Palmer amaranth from May to September in the Southeastern United States (Jha et al. 2008) and May to August in the Midwestern United States (Spaunhorst et al. 2018), effective season-long control of Palmer amaranth is necessary to reduce the impact on crop yield. For example, Sarangi and Jhala (2018) reported 7% to 40% higher soybean yield in conventional non-GMO soybeans which received a PRE fb POST + residual herbicides compared to PRE fb POST herbicide programs. However, due to the recent commercialization of DGR soybean, scientific literature examining the utility of soil-applied residual herbicides used in combination with PRE and POST herbicides programs is not available for GR Palmer amaranth management.

As the number of HR weeds increases consequentially the cost of herbicides to manage them is significant. Multiple sites of action residual PRE herbicides as well as POST herbicides are usually higher in cost than that of commonly used herbicides that involve single site of action POST herbicides. Due to high-cost constraints, growers do not adopt HR weed management recommendations until they notice the presence of HR weeds in their fields (Edwards et al. 2014; Norsworthy et al. 2012). Several growers avoid using PRE herbicide and are dependent on POST herbicides as a cost saving measure. A consequence of avoiding PRE herbicide however is the establishment of early-season crop-weed competition, which often results in a yield penalty (Hall et al. 1992; Schuster and Smeda 2007). Therefore, it is crucial to evaluate the economic benefits of implementing herbicide programs with multiple sites of action for herbicide-resistant Palmer amaranth management.

The objectives of this study were to (1) compare PRE-only, PRE followed by (fb) POST, PRE fb POST with residual herbicide (POST-RH), and EPOST fb late POST (LPOST) programs for control, density reduction, and biomass reduction of Palmer amaranth in DGR soybean; and (2) evaluate the soybean injury, yield, gross profit margin, and benefit–cost ratio in response to different herbicide programs.

MATERIALS AND METHODS

Study Site and Experimental Design

Field experiments were conducted on a grower’s field near Carleton, NE following a GR corn-soybean rotation with reliance on glyphosate for weed control in a no-till production system in 2018 and 2019. Corn residue from previous cropping season was retained and the study conducted using no-till practices. Paraquat (Gramoxone® SL, Syngenta Crop

Protection, Greensboro, NC 24719; at 840 g ai ha^{-1}) plus 2,4-D ester (Weedone® LV6, Nufarm Inc., Burr Ridge, IL 60527; at 386 g ae ha^{-1}) plus a nonionic surfactant (Induce®, Helena Chemical, Collierville, TN 38017; at 0.25% v/v) were applied two weeks before soybean planting with a tractor-mounted sprayer calibrated to deliver 140 L ha^{-1} at 276 kPa for control of winter annual weeds. Dicamba/glyphosate-resistant soybean (Northern King NK S29K3X) was planted on May 10, 2018 and May 10, 2019 at 346,000 seeds ha^{-1} at a depth of 3.0 cm. Treatments were arranged in a randomized complete block design containing 14 herbicide treatments including a weed free and a non-treated control with four replications. An individual plot was 3 m wide by 9 m long with four soybean rows spaced 76 cm apart. Herbicide programs evaluated included: PRE-only, PRE followed by (fb) POST, PRE fb POST plus a residual herbicide (RH), EPOST fb late POST (LPOST), a weed free control, and a nontreated control (Table 3-1). PRE herbicides were applied on the same day after planting DGR soybean and POST herbicides were applied on June 9, 2018 and June 10, 2019 when soybean was at the V3 to V4 growth stage and Palmer amaranth was 7.5 to 10.5 cm tall. LPOST herbicides were applied on July 6, 2018 and July 2, 2019 when soybean was at the R1 growth stage and Palmer amaranth was 8 to 15 cm tall depending on treatment. Herbicides were applied using handheld CO_2 pressurized backpack sprayer fitted with AIXR 110015 flat fan for non-dicamba herbicides and TTI 11005 flat angle nozzles for dicamba applications (TeeJet®, Spraying Systems Co., P.O. Box 7900, Wheaton, IL 60139) based on label requirements and calibrated to deliver 140 L ha^{-1} at 276 kPa.

Data Collection

Palmer amaranth control was visually assessed using a scale of 0% to 100%, with 0% representing no control and 100% representing complete control. Palmer amaranth control was assessed at 14 and 28 d after PRE (DAPRE), 14, 21, 28, 42, and 70 d after POST (DAEPOST). Palmer amaranth density was recorded at 14 DAPRE and 14 DAPOST by counting Palmer amaranth plants in two 0.5 m^2 quadrats placed randomly between the two center soybean rows in each plot and was converted to plants per m^2. Soybean injury was visually assessed at 14 DAPRE, 14 DAEPOST, and 14 DALPOST on a scale of 0% to 100%, with 0% representing no control and 100% representing complete control. Aboveground biomass of Palmer amaranth was collected at 14 DAPRE and 14 DAEPOST. Biomass samples were oven-dried at 65°C for 14 d, with Palmer amaranth aboveground biomass data converted into percent biomass reduction compared with the nontreated control using the following equation (Wortman 2014)**.**

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

where C is aboveground biomass of the nontreated control plot and B is biomass of an individual treated plot. Soybean yield was taken from the center two rows in each plot using a plot combine (Gleaner K2, AGCO, 4205 River Green Parkway, Duluth, GA 30096) and adjusted to 13% moisture content.

Economic Analysis

To assess the profitability for each weed management program, gross profit margins and benefit/cost ratio were calculated. Gross profit margin was calculated for each weed management program using the following equation:

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

R is the gross revenue calculated by multiplying soybean yield for each treatment by the average price received for dicamba/glyphosate-resistant soybean (US$0.30 kg^{-1}) and W is the total weed management program cost which includes the average cost of custom application of herbicides and spray adjuvants for each treatment (PRE, \$17.30 ha^{-1}; non-dicamba POST \$18.94 ha^{-1}; dicamba-containing POST \$31.71 ha^{-1}) with the weighted average seed cost for the soybean cultivar/trait planted. Average market price for soybean was derived from Nebraska cash prices reported by the USDA National Agricultural Statistics Service Information from September to December in 2018 and 2019 (USDANASS, 2019).

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 non-dicamba 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 dicamba/glyphosate-resistant soybean used in this study, which were adjusted based on planting density. The benefit/cost ratios were calculated for each herbicide program using the following equation:

$$\text{Benefit/Cost ratio for a program (US\$/US\$)} = (R\text{T} - R\text{C})/W$$

RT is the overall gross revenue of each weed management program, RC 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.

Statistical Analysis

Palmer amaranth control, density reduction, aboveground biomass reduction, and yield data were subjected to ANOVA using R statistical software v. 4.0.3 (R Core Team, 2018). Prior to conducting ANOVA, variance assumptions were tested by using Levene's tests (Wang et al., 2017) with the levene Test function at $\alpha = .05$. Variables that failed variance assumptions were transformed, fit to 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). Visual estimates of weed control and biomass reduction data were arc-sine square-root transformed before analysis as these data failed to follow normality assumptions; however, back-transformed data are presented with the means separated using Fisher's protected LSD test, where $\alpha = 0.05$. In the model, treatments and years were considered fixed effects, whereas blocks were considered random effects. To determine the relative efficacy of the herbicide programs (PRE-only vs. PRE fb EPOST; PRE vs PRE fb EPOST + RH, PRE vs EPOST fb LPOST, PRE fb EPOST vs. PRE fb EPOST + RH, PRE fb EPOST vs. EPOST fb LPOST, and PRE fb EPOST + RH vs. EPOST fb LPOST) for Palmer amaranth control, density, and aboveground biomass reduction, along with yield, a priori orthogonal contrasts (single degree of freedom contrasts) were performed.

RESULTS AND DISCUSSION

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

Average Daily Temperature and Precipitation

Growing conditions differed widely between the 2018 and 2019 growing seasons (Figure 3-1). In 2018, cumulative precipitation received was below 30-year average (517 mm) for the duration of the growing season. In contrast, cumulative precipitation in 2019 exceeded the 30-year average by 221 mm. Likewise, average daily temperatures for the 2018 exceeded the 30-year average for the duration of the growing season, whereas the 2019 closely resembled the 30-year average (Figure 3-1). In both site-years, field experiments were conducted under dry-land conditions without access to irrigation, resulting in drought-like conditions in which soybean growth and development was limited in 2018 compared with the 2019 growing season.

Palmer amaranth Control, Density, and Biomass Reduction

PRE herbicides controlled Palmer amaranth 85% to 99% 14 DAPRE and was reduced to 63% to 84% 28 DAPRE in 2018. In 2019, efficacy of PRE herbicides was higher, with all PRE herbicides providing ≥ 98% Palmer amaranth control 14 and 28 DAPRE (Table 3-2). Similarly, field studies in Kansas and Nebraska have shown greater than 97% control of Palmer amaranth 14 and 28DAPRE with chlorimuron-ethyl/flumioxazin/metribuzin, saflufenacil/imazethapyr + dimethenamid-P, flumioxazin/pyroxasulfone, and sulfentrazone/metribuzin (Hay 2017, Sarangi and Jhala 2018). In common waterhemp, a closely related species to Palmer amaranth, Sarangi et al. (2017) found similar levels (>92%) of control using saflufenacil/imazethapyr + dimethenamid-P, flumioxazin/chlorimuron-ethyl, and flumioxazin/pyroxasulfone. It is emphasized that PRE-applied residual herbicides provide a critical base for early-season weed control in soybean for Palmer amaranth (Ward et al. 2013) Improved efficacy in 2019 compared to 2018 can be partially attributed to adequate precipitation in 2019. PRE herbicides reduced Palmer amaranth density to ≤ 6 plants m^{-2} which was similar to the nontreated control (13 plants m^{-2}) at 14 DAPRE in 2018 (Table 3-2). In 2019 PRE herbicides reduced the density of Palmer amaranth to 0 plants m^{-2}. The significant reduction in Palmer amaranth density with PRE herbicide programs resulted in a 100% reduction of Palmer amaranth biomass (Table 3-2).

Through 14 DAEPOST to 21 DAEPOST control of Palmer amaranth was maintained at 94% to 99% in PRE, PRE fb POST, and PRE fb POST + RH (Table 3-3). PRE fb POST and PRE fb POST + RH treatments retained >90% control through the duration of the growing season up to 70 DAEPOST. Two studies point to improved Palmer amaranth control with PRE fb POST herbicide programs in soybean (Butts et al. 2016, Whitaker et al. 2010), though it is expected that the extended emergence period of Palmer amaranth will allow later-emerging cohorts to escape in-crop POST treatments. Addition of very-long-chain fatty acid (VLCFA)-inhibiting herbicides in POST herbicide programs has long been cited as effective means of extended season long control of small-seed broadleaf weeds, like Palmer amaranth (Geier et al. 2006, Grey et al. 2014, Hay 2017, Sarangi et al 2015b, 2017, 2018, Neve et al. 2011) At 14 DAEPOST (28 DAPRE), all PRE, PRE fb EPOST, and PRE fb EPOST + RH programs reduced Palmer amaranth density compared to the nontreated control in 2018 (317 plants m^{-2}) and 2019 (408 plants m^{-2}) (Table 3-4). Weed density at POST application timings plays a key role in determining the efficacy of herbicides and weed survival (Dieleman et al 1999). Across PRE fb EPOST herbicide programs, density ranged from 3 to 64 plants m^{-2} in 2018, whereas in 2019 density ranged from 0 to 9 plants m^{-2} (Table 3-4). Contrast analysis examining the inclusion of acetochlor at EPOST as a RH were significant vs PRE fb EPOST in 2018 and significant vs EPOST fb LPOST in 2019. However, the use of PRE herbicides significantly reduced Palmer amaranth density compared to glyphosate applied EPOST fb LPOST (281 and 390 plants m^{-2}) or dicamba (207 and 119 plants m^{-2}) in 2018 and 2019, illustrating the utility of PRE herbicides (Table 3-4). Reductions to Palmer amaranth density in 2019 correlated to 96 to 100% reductions in Palmer amaranth biomass for all PRE and PRE fb EPOST programs in 2019 (Table 3-4). In contrast, EPOST fb LPOST programs of glyphosate (9% biomass reduction) or dicamba (66% biomass reduction) had less biomass reduction compared to programs which included the use of PRE herbicides.

Yield and Gross Revenue

The adverse weather conditions in 2018 resulted in drought-like conditions for a majority of the growing season and yield and gross revenue in 2018 was reduced compared to 2019 (Table 3-5). In 2018, soybean grain yield ranged from 641 kg ha^{-1} for flumioxazin/pyroxasulfone to 215 kg ha^{-1} in plots which received glyphosate fb glyphosate which yielded 215 50 kg ha^{-1}. Reduced yield potential in 2018 resulted in gross revenue of ≤ \$225 ha^{-1} across herbicide programs. In 2019, yields (2,128 kg ha^{-1} to 4,951 kg ha^{-1}) were statistically similar for PRE, PRE fb EPOST, PRE fb EPOST + RH, and EPOST fb LPOST programs. Contrast analysis comparing yield in PRE fb EPOST and PRE fb EPOST + RH programs were significant ($P < 0.001$), with higher yield (4,860 kg ha^{-1}) obtained when acetochlor was included as a RH in comparison to PRE fb EPOST programs (4,569 kg ha^{-1}) (Table 3-5). Due to higher yield potential observed in 2019, gross revenue exceeded \$1,375 ha^{-1} for all programs, with the highest gross revenue observed in PRE fb EPOST + RH programs (\$1,526 to \$1,856 ha^{-1}). A similar study indicated higher net returns with PRE fb POST herbicide programs containing multiple sites of action despite them having significantly higher program costs (Chahal et al. 2018).

Weed Management Program Costs, Gross Profit Margin and Benefit-Cost Ratio

Average cost of herbicide programs were \$69.5 ha^{-1} for PRE-only, \$148 ha^{-1} for PRE fb EPOST, \$188 ha^{-1} for PRE fb EPOST+RH, and \$120 ha^{-1} for EPOST fb LPOST. PRE-only programs (2018, 75 – 153 \$ ha^{-1}; 2019, 1,305 – 1,414 \$ ha^{-1}) consistently provided higher gross profit margins (GPM) compared to PRE fb EPOST (2018, 12 – 61 \$ ha^{-1}; 2019, 1,282 – 1,341 \$ ha^{-1}) programs in 2018 and 2019. In 2019, two PRE fb POST+RH programs (chlorimuron/flumioxazin/pyroxasulfone fb dicamba + acetochlor and flumioxazin/pyroxasulfone/metribuzin fb dicamba + acetochlor, 1,603 and 1,657 \$ ha^{-1} respectively) had higher gross profit margins (GPM) than all PRE-only and PRE fb EPOST programs despite higher program costs. In contrast, chlorimuron/flumioxazin/pyroxasulfone fb dicamba + acetochlor; and flumioxazin/pyroxasulfone/metribuzin fb dicamba + acetochlor had negative GPMs (-14 and -47 \$ ha^{-1} respectively) in 2018. In 2018, all programs except PRE-only provided positive benefit cost ratios (0.16 – 1.28) compared to PRE fb EPOST (-0.39 - -0.03), PRE fb EPOST + RH (-0.57 - -0.17), and EPOST fb LPOST (-0.67 - -0.91). In 2019, PRE-only maintained the highest overall benefit/cost ratios (2.06 - 4.17). While poor performing in 2018, chlorimuron/flumioxazin/pyroxasulfone fb dicamba + acetochlor and flumioxazin/pyroxasulfone/metribuzin fb dicamba + acetochlor had higher performances in 2019 with benefit/cost ratios of 2.32 and 2.51, respectively compared to all PRE fb EPOST programs.

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Table 3-1. Herbicides and application timings, rates, and products used for control of glyphosate-resistant Palmer amaranth in dicamba/glyphosate-resistant soybean in dryland field experiments conducted near Carleton, NE in 2018 and 2019.[a,b]

Herbicide Programs		Timing	Rate	Trade Name	Manufacturer		Adjuvants[c]
PRE	POST		(g ai/ae ha^{-1})		PRE	POST	
Nontreated Control	--	--	--	---	---		--
Chlorimuron/flumioxazin/pyroxasulfone + metribuzin	Acetochlor + dicamba + glyphosate	PRE fb EPOST + RH	197 + 450 fb 1,260 + 56 + 1,260	Fierce XLT + Tricor fb Warrant + Roundup + Xtendimax	Valent, UPL	Bayer	DRA + WC
Chlorimuron/flumioxazin	--	PRE	128	Valor XLT	Valent	--	--
Flumioxazin/pyroxasulfone	--	PRE	160	Fierce	Valent	--	--
Chlorimuron/flumioxazin/pyroxasulfone	--	PRE	197	Fierce XLT	Valent	--	--
Flumioxazin/pyroxasulfone/metribuzin	--	PRE	370	Fierce MTZ	Valent	--	--
Chlorimuron/flumioxazin	Dicamba	PRE fb EPOST	128 fb 560	Valor XLT fb Xtendimax	Valent	Bayer	DRA + WC
Flumioxazin/pyroxasulfone	Dicamba	PRE fb EPOST	150 fb 560	Fierce fb Xtendimax	Valent	Bayer	DRA + WC
Chlorimuron/flumioxazin/pyroxasulfone	Dicamba	PRE fb EPOST	197 fb 560	Fierce XLT fb Xtendimax	Valent	Bayer	DRA + WC
Flumioxazin/pyroxasulfone/metribuzin	Dicamba	PRE fb EPOST	370 fb 560	Fierce MTZ fb Xtendimax	Valent	Bayer	DRA + WC
Chlorimuron/flumioxazin	Acetochlor + dicamba	PRE fb EPOST + RH	128 fb 1,260 + 560	Valor XLT fb Warrant + Xtendimax	Valent	Bayer	DRA + WC
Flumioxazin/pyroxasulfone	Acetochlor + dicamba	PRE fb EPOST + RH	160 fb 1,260 + 560	Fierce fb Warrant + Xtendimax	Valent	Bayer	DRA + WC
Chlorimuron/flumioxazin/pyroxasulfone	Acetochlor + dicamba	PRE fb EPOST + RH	197 fb 1,260 + 560	Fierce XLT fb Warrant + Xtendimax	Valent	Bayer	DRA + WC
Flumioxazin/pyroxasulfone/metribuzin	Acetochlor + dicamba	PRE fb EPOST + RH	370 fb 1,260 + 560	Fierce MTZ fb Warrant + Xtendimax	Valent	Bayer	DRA + WC
--	Glyphosate fb glyphosate	EPOST + LPOST	1,260	Roundup PowerMAX	Bayer	Bayer	AMS + NIS
--	Dicamba fb dicamba	EPOST + LPOST	560	Xtendimax	Bayer	Bayer	DRA + WC

[a] Abbreviations: ai, active ingredient; ae, acid equivalent; AMS, ammonium sulfate (N-Pak AMS Liquid, Winfield United, LLC., St. Paul, MN 55164; DRA, drift reducing agent (Intact, Precision Laboratories, Waukegan, IL 60085); POST, post-emergence herbicide; fb, followed by; NIS, non-ionic surfactant (Induce, Helena Chemical, Collierville, TN 38017); PRE, pre-emergence herbicide; EPOST, early post-emergence, LPOST, late post-emergence; RH, residual herbicide; WC, non-AMS water conditioner (Class Act Ridion, Winfield United, Arden Hills, MN, 55126).

[b] Bayer Crop Science, Research Triangle Park, NC 27709; UPL, King of Prussia, PA 19406, 1540; Valent U.S.A. Corporation, Walnut Creek, CA 94596

[c] AMS at 3% v/v, DRA at 0.5% v/v, NIS at 0.25% and WC at 1% v/v were mixed with POST herbicide treatments based on label recommendations.

Table 3-2. Effect of herbicide programs on glyphosate-resistant Palmer amaranth control, density, and biomass reduction in dicamba/glyphosate-resistant soybean in dryland field experiments conducted near Carleton, NE in 2018 and 2019.[a,b,c,d]

Herbicide Program(s)[c]	Palmer amaranth Control				Palmer amaranth Density		Biomass Reduction
	14 DAPRE		28 DAPRE		14 DAPRE		14 DAPRE
PRE	2018	2019	2018	2019	2018	2019	2019
	%				no. plants m^{-2}		%
Nontreated Control	--	--	--	--	13	5 a	--
Chlorimuron/flumioxazin	85 ab	99	63	98	6	0 b	100
Flumioxazin/pyroxasulfone	99 a	99	75	99	5	0 b	100
Chlorimuron/flumioxazin/pyroxasulfone	90 ab	99	66	98	4	0 b	100
Flumioxazin/pyroxasulfone/metribuzin	90 ab	99	84	99	5	0 b	100
Treatment *P*-value(s)	**0.003**	**0.543**	**0.529**	**0.421**	**0.434**	**<0.001**	**0.103**

[a] Abbreviations: DAPRE, days after pre-emergence herbicide; PRE, pre-emergence herbicide

[b] Means presented within the same column with no common letters are not significantly different according to estimated marginal means with Sidak confidence-level adjustments and Tukey *P*-value adjustments.

[c] PRE herbicide programs were combined across POST herbicide programs n=12 for individual site-years and combined site years (n=24)

[f] Data presented in this table were separated by year (2018 vs 2019).

Table 3-3. Effect of herbicide programs on Palmer amaranth control as affect by herbicide programs in dicamba/glyphosate-resistant soybean in dryland field experiments conducted near Carleton, NE in 2019 and 2019.[a,b,c]

Herbicide Program(s)		Palmer amaranth control[d]									
		14 DAEPOST		21 DAEPOST		28 DAEPOST (7 DALPOST)		42 DAEPOST (21 DALPOST)		70 DAEPOST (49 DALPOST)	
PRE	EPOST & LPOST	2018	2019	2018	2019	2018	2019	2018	2019	2018	2019
		%									
Nontreated Control	--	--	--	--	--	--	--	--	--	--	--
Chlorimuron/flumioxazin	--	82 abc	94 a	84 abc	89 bc	86 a	92 b	83 ab	92 b	83 a	90 b
Flumioxazin/pyroxasulfone	--	85 abc	98 a	76 abc	97 ab	77 a	98 a	70 abc	99 a	62 bc	99 a
Chlorimuron/flumioxazin/pyroxasulfone	--	73 bc	95 a	68 c	95 ab	67 ab	98 a	60 bcd	97 ab	75 ab	96 ab
Flumioxazin/pyroxasulfone/metribuzin	--	78 abc	98 a	82 abc	97 ab	75 a	97 ab	78 abc	94 ab	78 ab	94 ab
Chlorimuron/flumioxazin	Dicamba	80 abc	99 a	73 bc	99 a	77 a	99 a	72 abc	99 a	72 ab	98 a
Flumioxazin/pyroxasulfone	Dicamba	70 c	99 a	83 abc	99 a	77 a	99 a	83 ab	99 a	90 a	99 a
Chlorimuron/flumioxazin/pyroxasulfone	Dicamba	87 abc	99 a	73 bc	99 a	70 a	98 a	75 abc	99 a	75 ab	99 a
Flumioxazin/pyroxasulfone/metribuzin	Dicamba	87 abc	99 a	80 abc	99 a	70 a	99 a	83 ab	99 a	78 ab	99 a
Chlorimuron/flumioxazin	Dicamba + acetochlor	73 bc	99 a	87 ab	99 a	82 a	99 a	85 ab	99 a	85 a	97 ab
Flumioxazin/pyroxasulfone	Dicamba + acetochlor	90 abc	99 a	77 abc	99 a	81 a	99 a	70 abc	99 a	73 ab	98 a
Chlorimuron/flumioxazin/pyroxasulfone	Dicamba + acetochlor	93 ab	99 a	85 abc	99 a	87 a	99 a	82 ab	99 a	88 a	99 a
Flumioxazin/pyroxasulfone/metribuzin	Dicamba + acetochlor	96 a	99 a	90 a	99 a	83 a	99 a	90 a	99 a	92 a	99 a
--	Glyphosate fb glyphosate	22 d	5 c	47 d	5 d	33 b	0 d	37 d	0 d	40 d	0 d
--	Dicamba fb dicamba	77 abc	85 b	72 abc	85 c	84 a	80 c	53 cd	65 c	45 cd	53 c
Treatment *P*-value(s)		**0.917**	**<0.001**	**0.3117**	**0.059**	**0.504**	**<0.001**	**0.712**	**<0.001**	**0.967**	**<0.001**
Contrasts[d]											
PRE vs. PRE fb EPOST		NS	95 vs 99 **	NS	94 vs 99 ***	NS	96 vs 98 *	NS	96 vs 98 *	79 vs 75 NS	NS
PRE vs. PRE fb EPOST + RH		NS	95 vs 99 ***	NS	94 vs 99 ***	NS	96 vs 99 **	NS	96 vs 99 **	79 vs 85 NS	95 vs 98 *
PRE vs. EPOST fb LPOST		NS	95 vs 85 ***	NS	94 vs 85 ***	NS	96 vs 80 ***	79 vs 53 **	96 vs 65 ***	79 vs 45 ***	95 vs 53 ***
PRE fb EPOST vs. PRE fb EPOST + RH		80 vs 88 *	NS	NS	99 vs 99 NS	NS	98 vs 99 NS	NS	NS	75 vs 85 **	NS
PRE fb EPOST vs. EPOST fb LPOST		NS	99 vs 85 ***	NS	99 vs 85 ***	NS	98 vs 80 ***	75 vs 53 **	98 vs 65 ***	75 vs 45 ***	98 vs 53 ***
PRE fb EPOST + RH vs. EPOST fb LPOST		NS	99 vs 85 ***	NS	99 vs 85 ***	NS	99 vs 80 ***	80 vs 53 ***	99 vs 65 ***	85 vs 45 ***	98 vs 53 ***

[a] Abbreviations: fb, followed by; PRE, pre-emergence; EPOST, early post-emergence; LPOST, late post-emergence; RH, residual herbicide.
[b] Means presented within the same column with no common letters are not significantly different according to estimated marginal means with Sidak confidence-level adjustments and Tukey *P*-value adjustments.
[c] Data presented in these columns were separated by year (2018 vs 2019).
[d] *a priori* orthogonal contrasts; * = significant ($P < 0.05$); **= significant ($P < 0.01$); ***= significant ($P < 0.001$); NS, non-significant ($P \geq 0.05$).

Table 3-4. Effect of herbicide programs on Palmer amaranth density and biomass reduction in no-till dicamba/glyphosate-resistant soybean in dryland field experiments conducted near Carleton, NE in 2019 and 2019.[a,b,c]

Herbicide Program(s)		Palmer amaranth Density[d]		Biomass Reduction[d]
PRE	EPOST & LPOST	2018	2019	2019
		no. plants m^{-2}		%
Nontreated Control	--	317 b	408 c	--
Chlorimuron/flumioxazin	--	16 a	11 a	94 a
Flumioxazin/pyroxasulfone	--	13 a	3 a	99 a
Chlorimuron/flumioxazin/pyroxasulfone	--	4 a	3 a	100 a
Flumioxazin/pyroxasulfone/metribuzin	--	15 a	9 a	96 a
Chlorimuron/flumioxazin	Dicamba	64 a	0 a	100 a
Flumioxazin/pyroxasulfone	Dicamba	53 a	0 a	100 a
Chlorimuron/flumioxazin/pyroxasulfone	Dicamba	4 a	0 a	100 a
Flumioxazin/pyroxasulfone/metribuzin	Dicamba	11 a	0 a	100 a
Chlorimuron/flumioxazin	Dicamba + acetochlor	8 a	0 a	100 a
Flumioxazin/pyroxasulfone	Dicamba + acetochlor	3 a	0 a	100 a
Chlorimuron/flumioxazin/pyroxasulfone	Dicamba + acetochlor	8 a	0 a	100 a
Flumioxazin/pyroxasulfone/metribuzin	Dicamba + acetochlor	5 a	0 a	100 a
--	Glyphosate fb glyphosate	281 b	390 c	9 c
--	Dicamba fb dicamba	207 b	119 b	66 b
Treatment *P*-value(s)		**<0.001**	**<0.001**	**<0.001**
Contrasts[d]				
PRE vs. PRE fb EPOST		NS	NS	NS
PRE vs. PRE fb EPOST + RH		NS	NS	98 vs 100 **
PRE vs. EPOST fb LPOST		11 vs 207 ***	6 vs 119 ***	98 vs 66 ***
PRE fb EPOST vs. PRE fb EPOST + RH		NS	NS	NS
PRE fb EPOST vs. EPOST fb LPOST		29 vs 207 ***	2 vs 119 ***	99 vs 66 ***
PRE fb EPOST + RH vs. EPOST fb LPOST		6 vs 207 ***	0 vs 119 ***	100 vs 66 ***

[a] Abbreviations: fb, followed by; PRE, pre-emergence; EPOST, early post-emergence; LPOST, late post-emergence; RH, residual herbicide:
[b] Means presented within the same column with no common letters are not significantly different according to estimated marginal means with Sidak confidence-level adjustments and Tukey *P*-value adjustments.
[c] Data presented in this table were separated by year (2018 vs 2019).
[d] *a priori* orthogonal contrasts; * = significant ($P < 0.05$); **= significant ($P < 0.01$); ***= significant ($P < 0.001$); NS, non-significant ($P \geq 0.05$).

Table 3-5. Palmer amaranth yield and gross revenue as affected by POST herbicide programs in no-till dicamba/glyphosate-resistant soybean in Nebraska in field experiments conducted in 2018 and 2019 near Carleton, NE.[a,b,c]

Herbicide Program(s)		Yield (±SEM)		Gross Revenue[e]	
PRE	POST & LPOST	2018	2019	2018	2019
		kg ha^{-1}		\$ ha^{-1}	
Nontreated Control	--	182 ± 43 b	2,182 ± 71 b	65	1,163
Weed Free Control	--	591 ± 137 ab	4,731 ± 154 a	195	1,515
Chlorimuron/flumioxazin	--	401 ± 93 ab	4,603 ± 150 a	135	1,474
Flumioxazin/pyroxasulfone	--	641 ± 149 a	4,294 ± 140 a	222	1,374
Chlorimuron/flumioxazin/pyroxasulfone	--	458 ± 107 ab	4,561 ± 149 a	153	1,460
Flumioxazin/pyroxasulfone/metribuzin	--	509 ± 118 ab	4,609 ± 150 a	170	1,476
Chlorimuron/flumioxazin	Dicamba	438 ± 102 ab	4,531 ± 148 a	150	1,451
Flumioxazin/pyroxasulfone	Dicamba	527 ± 123 ab	4,648 ± 152 a	181	1,488
Chlorimuron/flumioxazin/pyroxasulfone	Dicamba	615 ± 143 a	4,474 ± 146 a	210	1,432
Flumioxazin/pyroxasulfone/metribuzin	Dicamba	611 ± 142 a	4,570 ± 149 a	202	1,464
Chlorimuron/flumioxazin	Dicamba + acetochlor	613 ± 143 a	4,769 ± 156 a	213	1,526
Flumioxazin/pyroxasulfone	Dicamba + acetochlor	566 ± 132 ab	4,803 ± 157 a	206	1,537
Chlorimuron/flumioxazin/pyroxasulfone	Dicamba + acetochlor	471 ± 110 ab	4,951 ± 162 a	176	1,793
Flumioxazin/pyroxasulfone/metribuzin	Dicamba + acetochlor	376 ± 88 ab	4,949 ± 161 a	150	1,856
--	Glyphosate fb glyphosate	215 ± 50 ab	4,276 ± 139 a	73	1,457
--	Dicamba fb dicamba	331 ± 77 ab	4,693 ± 153 a	116	1,446
Treatment *P*-value(s)		**<0.001**	**<0.001**	--	--
Contrasts[d]					
PRE vs .PRE fb POST		NS	NS	--	--
PRE vs. PRE fb POST + RH		NS	4,487 vs 4,860 ***	--	--
PRE vs. POST fb LPOST		NS	NS	--	--
PRE fb POST vs. PRE fb POST + RH		NS	4,569 vs 4,860 ***	--	--
PRE fb POST vs. POST fb LPOST		NS	NS	--	--
PRE fb POST + RH vs. POST fb LPOST		NS	4,860 vs 4,537 ***	--	--

[a] Abbreviations: PRE, pre-emergence herbicide; EPOST, early post-emergence herbicide; LPOST, late post-emergence herbicide; RH, residual herbicide: fb, followed by; SEM, standard error of the mean

[b] Means presented within the same column with no common letters are not significantly different according to estimated marginal means with Sidak confidence-level adjustments and Tukey *P*-value adjustments.

[c] Data presented in these columns were separated by year (2018 vs 2019).

[d] *α priori* orthogonal contrasts; * = significant ($P < 0.05$); **= significant ($P < 0.01$); ***= significant ($P < 0.001$); NS, non-significant ($P \geq 0.05$).

[e] Data presented is based on an averaged commodity pricing in 2018 and 2019 in Nebraska (0.33 and 0.32 \$USD kg^{-1}, respectively)

Table 3-6. Herbicide program costs, and effect of herbicide program on gross profit margin and benefit-cost ratios in dicamba/glyphosate-resistant soybean in Nebraska.[a]

Herbicide Program(s)		Weed Management Program Cost[b]					Gross Profit Margin[c]		Benefit/Cost Ratio[d]	
		PRE	EPOST	LPOST	CAC	Total	2018	2019	2018	2019
PRE	POST & LPOST	$ ha^{-1}								
Nontreated Control	--	--	--	--	--	--	65	1,164	--	--
Weed Free Control	--	69	100	--	49	186	9	1,328	- 0.30	0.89
Chlorimuron/flumioxazin	--	43	--	--	17	60	75	1,414	0.16	4.17
Flumioxazin/pyroxasulfone	--	52	--	--	17	67	153	1,305	1.28	2.06
Chlorimuron/flumioxazin/pyroxasulfone	--	54	--	--	17	72	81	1,388	0.22	3.13
Flumioxazin/pyroxasulfone/metribuzin	--	62	--	--	17	79	90	1,397	0.32	2.95
Chlorimuron/flumioxazin	Dicamba	43	46	--	49	138	12	1,314	- 0.39	1.09
Flumioxazin/pyroxasulfone	Dicamba	52	46	--	49	147	35	1,341	- 0.21	1.21
Chlorimuron/flumioxazin/pyroxasulfone	Dicamba	54	46	--	49	150	61	1,282	- 0.03	0.79
Flumioxazin/pyroxasulfone/metribuzin	Dicamba	62	46	--	49	157	45	1,307	- 0.13	0.91
Chlorimuron/flumioxazin	Dicamba + acetochlor	43	86	--	49	178	35	1,349	- 0.17	1.04
Flumioxazin/pyroxasulfone	Dicamba + acetochlor	52	86	--	49	187	19	1,350	- 0.25	1.00
Chlorimuron/flumioxazin/pyroxasulfone	Dicamba + acetochlor	54	86	--	49	190	-14	1,603	- 0.42	2.32
Flumioxazin/pyroxasulfone/metribuzin	Dicamba + acetochlor	62	86	--	49	197	-47	1,657	- 0.57	2.51
--	Glyphosate fb glyphosate	--	23	23	38	84	-10	1,374	- 0.91	2.51
--	Dicamba fb dicamba	--	46	46	63	156	-40	1,291	- 0.67	0.82

[a] Abbreviations: CAC, custom application cost; EPOST, early post-emergence; LPOST, late post-emergence; PRE, pre-emergence herbicide.

[b] 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}).

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

[d] Benefit/Cost ratio were calculated as gross revenue minus gross revenue in the nontreated control, divided by weed management program cost.

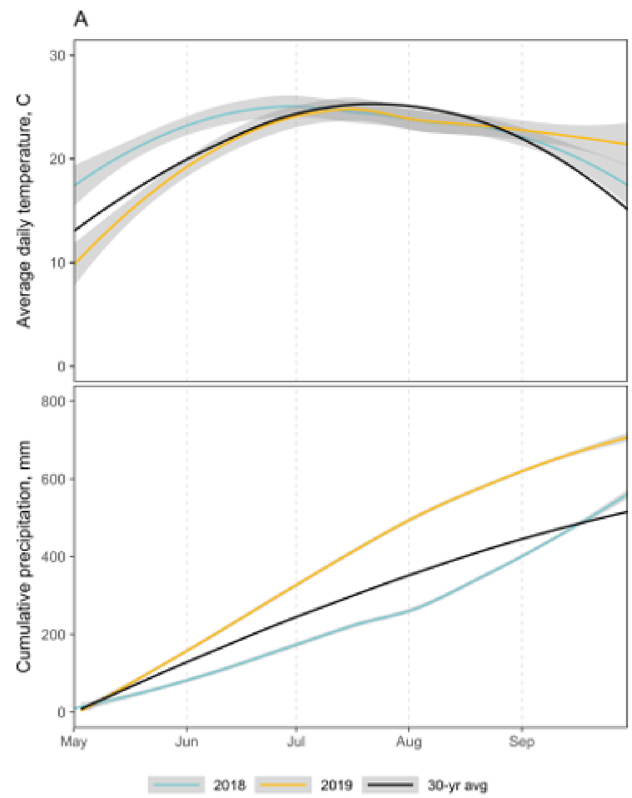

Figure 3-1. Average daily air temperature (°C) and total cumulative precipitation (mm) received during the 2018 and 2019 growing seasons compared to the 30-year average for dryland field experiments conducted to determine effect on management of glyphosate-resistant Palmer amaranth and economic impact of herbicide programs in dicamba/glyphosate-resistant soybean near Carleton, NE, in 2018 and 2019.

CHAPTER 4:
A 2019 SURVEY OF STAKEHOLDERS IN NEBRASKA TO ASSESS PROBLEM WEEDS AND MANAGEMENT PRACTICES IN AGRONOMIC CROPPING SYSTEMS

ABSTRACT

Stakeholders from across the state of Nebraska were surveyed in 2019 to assess problem weeds and their management practices in agronomic crops. A total of 416 complete responses were obtained across four Nebraska extension districts (Northeast, Panhandle, Southeast, and West Central). Accumulated across the state, 65.5% of farmed or scouted crop ground in Nebraska were under no-till production, with major crops corn and soybean representing 39.3% and 30.7% of Nebraska crop production area, respectively. Palmer amaranth, horseweed, waterhemp, kochia, and giant ragweed were ranked the most problematic weeds statewide. The most commonly used preplant herbicides were 2,4-D, glyphosate, and dicamba. A majority of growers (69%) reported the usage of a PRE herbicide for early season weed control. Atrazine applied alone or in a mixture with acetochlor, bicyclopyrone, clopyralid, mesotrione, or *S*-metolachlor were the most commonly applied PRE herbicides in corn, whereas the most commonly used PRE herbicides in soybean were metribuzin/sulfentrazone, flumioxazin/pyroxasulfone, and sulfentrazone/chloransulam-methyl. Glyphosate was the most frequent choice of the survey respondents as a POST herbicide in glyphosate-resistant corn and soybean; 2,4-D was the most commonly used POST herbicide in grain sorghum and wheat. Majority of the respondents (77%) were aware of the new multiple herbicide–resistant crops, and 86% of them listed physical drift and volatility of the auxinic herbicides as their primary concern. Twenty-three percent of survey respondents identified integrated pest management as a primary research and extension priority for profitable crop production.

INTRODUCTION

The rapid adoption of glyphosate-resistant (GR) crops since their introduction in 1996 has greatly impacted the herbicide use pattern in modern agriculture (Benbrook 2016). From 1974 to 2014, an estimated 8.6 billion kg of glyphosate has been applied worldwide, with the United States accounting for 19% of the global usage or 1.6 billion kg (Benbrook 2016). Usage of glyphosate in the United States was estimated at a total of 18 million kg year^{-1} in 1996, increasing to an estimated 125 million kg in 2013 (USGS 2020). In large part, the popularity of glyphosate can be attributed to the widespread adoption of GR crops given its low application cost and broad-spectrum of weed control (Woodburn 2000). As of 2021, six weeds have been confirmed resistant to glyphosate in Nebraska (Jhala 2021). Despite the increasing number of GR weeds and their widespread occurrence in the United States, growers continue to use glyphosate.

As multiple herbicide-resistant crops came to market in recent years, the options for selecting herbicide for POST weed control has increased. Since commercialization in 2017, dicamba/glyphosate-resistant soybean has rapidly grown in popularity as seen with the adoption rate increasing from 20% of soybean planting in 2017 to 80% in 2019 in Nebraska (Chahal and Jhala 2019; Werle et al. 2018). As the adoption of GR crops increased in popularity there has been a shift towards reduced usage of tillage for weed control (Sarangi and Jhala 2018).

The adoption of conservation tillage and changes in weed management practices significantly altered weed population dynamics (Nichols et al. 2015), with a major shift towards smaller seeded broadleaf weeds such as Amaranthaceae family (Kruger et al. 2009). Surveys have been conducted over the past two decades to determine the perceptions of stakeholders in areas of agronomics and weed management, as well as look at the dynamics of weed issues since the adoption of GR crops in the United States (Gibson et al. 2005, Givens et al. 2009a, Norsworthy 2003, Riar et al. 2013a, b, Sarangi and Jhala 2018). Sarangi and Jhala (2018) completed a statewide survey and provided a base looking at the distinct differences in problem weeds in Nebraska, weed dynamics, and management practices adopted by growers in the diverse climates of Nebraska.

The Nebraska Extension, comprising 83 county offices and four extension centers serving 93 counties throughout the state, has an enormous impact on the state's youth, families, farms and ranches, communities, and economy. A survey was developed for participants (growers, certified crop advisors, crop consultants, certified pesticide applicators, cooperative managers, and industry representatives) attending the Nebraska Extension's winter annual meetings and extension portal cropwatch.unl.edu. The objectives of this survey were to identify stakeholders' perceptions about problematic weeds and assess their attitudes and perceptions about agronomic and weed management practices in agronomic crops in Nebraska and monitor any differences that may have arisen since the previous Nebraska stakeholder survey in 2015.

MATERIALS AND METHODS

The survey was distributed online (www.cropwatch.unl.edu) as well as in person at several locations during summer and winter extension meetings organized by the Nebraska Extension in 2019. Survey responses were separated by county representing four major extension districts defined by the Nebraska Extension based on their agroclimatic characteristics, soil texture, and cropping systems (Figure 4-1). Paper questionnaires were distributed to in-person participants while online participants received a web-based format; questions were mostly short answer, but some closed questions were also included. Prior to release, the questionnaire was reviewed by 10 people, including weed scientists, agronomy undergraduate and graduate students, to assess its acceptability and readability. The final questionnaire (Table 4-1) was divided into four sections:

1. Crop Production and Problem Weeds

2. Herbicide Use

3. Herbicide Resistant Weed Management

4. Weed Management Research and Extension Priorities

Respondents were asked to state their primary occupation, county, and state of residence. Respondents that were not directly in farm management/operations or agribusiness decision making were disqualified along with individuals that did not reside in state. In Section 1, respondents were asked about the total of acres they farmed or scouted (Question 1.1 in Table 4-1); responses were later converted into hectares. In the same section, respondents were directed to rank the five most problematic weeds according to their personal experience (Question 1.3). In Section 2, respondents were directed to list the top three commonly used preplant, pre-emergence (PRE), and post-emergence (POST) herbicides used in fields they manage or advise (Questions 2.1 to 2.3). Section 3 included questions regarding different methods of managing herbicide-resistant (HR) weeds and delaying the evolution of HR weeds. This section consisted of several Yes/ No questions, as well as a ranked slider-scale question (Question 3.8) about management approaches for managing the evolution of HR weeds at the field level. In Section 4, respondents were asked to identify extension or research priorities for improved future weed management practices in Nebraska (Table 4-1). In total, 416 valid responses were collected and processed from the statewide survey. Respondents were categorized based on their occupation into three groups: growers, crop consultants, and others. Growers were separated from those that owned or directly participate in farm operations and or decision making. Respondents that reported an occupation of agronomist certified crop advisor, or crop consultant were categorized as crop consultants. Those that did not fit in the grower or crop consultant category such as pesticide applicators, cooperative managers, or industry representatives were assigned as “others”. Out of 416 respondents, 48%, 32%, and 20% were listed as growers, crop consultants, and others, respectively (Table 4-2). Total number of responses were tabulated from each of the extension districts with the Southeast district (n= 209), followed by the Northeast (n= 106), West Central (n= 76), and Panhandle (n= 25) districts. Data were imported to R (R Core Team 2020) and the results interpreted based on the frequency distribution for most of the questions, with a mean (average) and median calculated wherever possible. To rank the most problematic weeds and most used herbicides in Nebraska, a relative problematic/importance points system was used. For example, five, four, three, two, and one problematic point was assigned to rank #1, #2, #3, #4, and #5 problem weeds, respectively (Question 1.3 in Table 4-1), and the relative problematic point (RP) was calculated for each weed species using the equation:

Equation 1: $RP = \sum_{r=1}^{5} \frac{FX}{n}$

where F is the number of respondents choosing a rank (r) for a certain weed species, X is the problematic points associated with that rank, and *n* is the total number of responses for that rank, including all the weed species. The top five most problematic weeds were reported at the state and district levels in Nebraska, and similarly for the most common use preplant burndown, PRE, and POST herbicides (Questions 2.1 to 2.3 in Table 4-1) were ranked based on their level of importance, where three, two, and one importance points were assigned to rank #1, #2, and #3 of the most common use herbicides, respectively. The relative importance point for an herbicide were calculated using Equation 1, with an r value ranging from 1 to 3.

RESULTS AND DISCUSSION

Crop Production and Problem Weeds

Average farmed areas reported by the growers for the 2019-2020 season were 760, 780, 850, and 920 ha in the Northeast, Panhandle, Southeast, and West Central districts, respectively, and the state average was 798 ha (Table 4-3). It is evident that some of the larger values for per capita farm areas led to a relatively higher average value. In 2012 the Census of Agriculture conducted by the United States Department of Agriculture (USDA) found that the average Nebraska farm was 367 ha; however, the USDA census data included farm areas under row crops and other commodity production systems such as livestock operations (USDA-NASS 2014), in contrast to our survey where respondents were mostly row crop producers. Crop consultants participating in this survey scouted average areas ranging between 3,267 and 6,154 ha in different districts, with a state average of 4,828 ha (Table 4-3). The maximum area in no-till production was reported from the Southeast district (74.6%), followed by the Northeast (67.2%), West Central (56.1%), and Panhandle (48.8%) districts, and the state average for no-till production area was 65.5%. Under the 2012 Census of Agriculture each Nebraska farm consisted of an average of 57% no-till production (USDA-NASS 2014).

Areas Under Different Crops

The survey results showed that corn and soybean were the major crops in Nebraska, with 39.3% and 3.07% of the total farmed or scouted area reported, respectively (Table 4-3). The USDA data from the 2014 growing season reported up to 75% of Nebraska cropland was under corn and soybean production (USDA-NASS 2015). Survey results indicated that the maximum corn growing regions were the Southeast district (48.2% of total farmed or scouted areas), followed by the Northeast (46.5%), West Central (26%), and Panhandle (26%) districts. Maximum soybean growing regions are ranked as the Northeast (41%), Southeast (39.3%), West Central (33%), and Panhandle (18%) districts. The Panhandle district was the only district to get responses for dry edible bean *(Phaseolus vulgaris* L.) and sugarbeet (*Beta vulgaris* L.) production consisting of 5% and 12%, respectively (Table 4-3). Results also indicated that the areas in Nebraska under grain sorghum (*Sorghum bicolor*), wheat (*Triticum aestivum* L.), and alfalfa (*Meticago satvia*) production were 2.7%, 4.9%, 4.1%, respectively. Other crops including hay, cereal rye (*Secale cereal* L.), and oat (*Avena satvia* L.) accounted for 3.6% of the agronomic crop production in Nebraska.

Problem Weeds

The top five most difficult to control weeds across Nebraska were Palmer amaranth, horseweed, waterhemp, kochia, and giant ragweed (Table 4-4). Higher relative problematic points (ranging between 3.1 and 3.6 out of a maximum possible 5.0 points) for Palmer amaranth, horseweed, and waterhemp showed that majority of respondents listed them as the most problematic weeds. A 2016 survey by the Weed Science Society of America (WSSA) ranked Palmer amaranth as the most troublesome weed in the United States (Van Wychen 2016a). Of the top five most problematic weed species, Palmer amaranth, horseweed, waterhemp, kochia, and giant ragweed have confirmed glyphosate-resistant population in Nebraska (Chahal et al. 2017; Rana and Jhala 2016; Sandell et al. 2011; Sarangi et al. 2015; Sarangi and Jhala 2017), which likely has led to the outcome of them being the most challenging weeds to manage. In a multistate growers' survey conducted in 2005–2006, Kruger et al. (2009) reported that waterhemp, velvetleaf, and foxtails were the three most problematic weeds in GR corn and soybean rotation in Nebraska; however, due to the evolution of resistance to glyphosate and multiple herbicides in recent years, horseweed, kochia, and waterhemp top the list. In the Southeast district, Palmer amaranth, horseweed, and waterhemp were identified as extremely concerning to manage, whereas respondents from the Panhandle district listed kochia and Palmer amaranth as the most problematic weeds. In parity with the Southeast district, Palmer amaranth was listed as the most problematic weed both the Northeast and West Central districts.

Glyphosate-Resistant Weeds

A majority of stakeholders suspected the presence of glyphosate-resistant weeds in their agronomic crop fields in Nebraska. Only a small number of responses (n=25) were recorded from the Panhandle district, so results were not reported (Table 4-5). In the Northeast district, 71%, 65%, 25%, and 12% of respondents suspected the presence of GR waterhemp, horseweed, Palmer amaranth, and giant ragweed, respectively (Table 4-5). Reports of suspected glyphosate-resistance correlates with some of the most problematic weeds in this region (Table 4-4). Several respondents reported presence of the suspected waterhemp biotype with stacked resistance to 4-hydroxyphenylpyruvate dioxygenase (HPPD) inhibitors and ALS inhibitors as well as indications of resistance to synthetic auxin-based herbicides in Palmer amaranth, waterhemp, and horseweed in the Northeast, Southeast, and West Central districts (data not shown). Prior field sampling of waterhemp biotypes from the Northeast district (Platte County) have confirmed resistant to HPPD-inhibiting herbicides (Oliveira et al. 2017b). Most of the survey respondents in the Southeast and West Central districts listed glyphosate-resistant weeds as the primary herbicide-resistance concern. In the Southeast district, 61%, 49%, 44%, and 4% of respondents reported the presence of suspected GR Palmer amaranth, horseweed, waterhemp, and giant ragweed, respectively (Table 4-5). A Palmer amaranth biotype from Southeast Nebraska (Thayer County) was confirmed to be 40-fold resistant to glyphosate as well as resistant to ALS-inhibiting herbicides and atrazine (Chahal et al. 2017). While the 2015 survey reported Palmer amaranth as the sixth most troublesome weed in Nebraska as of this survey Palmer amaranth has rapidly became the most troublesome weed in Nebraska as of 2020. In the West Central district, 63%, 48%, 37%, and 24% of respondents reported suspected GR Palmer amaranth, kochia, horseweed, and waterhemp, respectively (Table 4-5).

Herbicide Usage

Preplant Herbicide Usage

The 2012 Census of Agriculture found that 82% of Nebraska cropland was treated with at least one herbicide (USDA-NASS 2014a). Effective weed management has long recommended the control of standing vegetation before planting in no-till crop production systems (Stougaard et al. 1984; VanGessel et al. 2001). Across the state, 70% of respondents reported the usage of at least one preplant herbicide prior to planting (data not shown). Participant responses across all occupational classes (growers, crop consultants, and others) were compiled together to rank the most commonly used preplant herbicides in Nebraska, with the results showing that 2,4-D, glyphosate, and dicamba were the top three common use preplant burndown herbicides in Nebraska (Table 4-6), followed by saflufenacil (data not shown). Several multistate surveys that included Nebraska also reported that glyphosate and 2,4-D were the most popular choices among growers for preplant herbicides (Givens et al. 2009a, b; Prince et al. 2012a). Additionally, Prince et al. (2012a) reported that synthetic auxins (e.g., 2,4-D) and PPO inhibitors were mostly used to control GR weeds.

PRE Herbicide Usage

Over half (69%) of growers reported the usage of a PRE herbicide for early season weed control (data not shown). Sufficient responses for PRE herbicide usage were not obtained from the

Panhandle district; therefore, survey results indicating PRE herbicide usage were not included (Table 4-7). In Nebraska, the three most commonly used PRE herbicides in corn were atrazine/bicyclopyrone/mesotrione/*S*-metolachlor (Acuron), acetochlor/clopyralid/mesotrione (Resicore), and isoxaflutole/thiencarbazone-methyl (Corvus) (Table 4-7). Other major corn herbicides were atrazine plus *S*-metolachlor, and atrazine (data not shown). Results of the top five most commonly used PRE herbicides in corn clearly show the dominance of atrazine-based herbicides and premixes for early season weed control. Results from a 2016 multistate survey of corn-producing states including Nebraska reported atrazine as the most commonly used corn herbicide, applied in more than half (60%) of corn production fields (USDA- NASS 2017). The most commonly used PRE herbicides in soybean were metribuzin/sulfentrazone, flumioxazin/pyroxasulfone, and sulfentrazone/chloransulam-methyl (Table 4-7). In sorghum, atrazine-based herbicides dominated the top three spots with atrazine/*S*-metolachlor/mesotrione, atrazine, and atrazine/*S*-metolachlor (Table 4-7). Results suggest that soybean growers are highly reliant on PRE herbicides containing ALS inhibitors, very long chain fatty acid (VLCFA) inhibitors, and PPO inhibitors, in contrast to the more diverse PRE usage in corn.

POST Herbicide Usage

Most of the growers (73%) reported applying a POST herbicide(s) for weed control in row crops (data not shown), with glyphosate being the most commonly used POST herbicide for weed control in GR corn and soybean (Table 4-7). A multistate survey also noted that more than 95% of the GR crop growers in 22 corn-, soybean-, and cotton-growing states including Nebraska applied glyphosate as their primary POST herbicide (Prince et al. 2012). In corn, the most commonly used POST herbicides after glyphosate were dicamba/diflufenzopyr (Status), and mesotrione (Callisto) (Table 4-7). While glyphosate remains the most commonly used POST herbicide in soybean, with the release of dicamba/glyphosate-resistant soybean, dicamba has rapidly become a popular POST herbicide for weed management in dicamba-resistant soybean. Glyphosate was applied to over 85% of soybean-producing ground as reported from the Agricultural Chemical Use Survey in 2015 (USDA-NASS 2016). The most commonly used POST soybean herbicides after glyphosate and dicamba were glufosinate (Liberty), *S*-metolachlor (Dual II Magnuam), and fomesafen (Flexstar) (relative importance points ranging between 0.3 and 1.2; data not shown). Inadequate responses for sorghum and wheat POST herbicides were reported in the Northeast district, therefore, results were not included. In the West Central district, 2,4-D, dicamba, and bromoxynil plus pyrasulfotole (Huskie) were the three most commonly used POST herbicides in sorghum; while 2,4-D, atrazine, and dicamba were the highest ranked for the Southeast district, respectively (Table 4-7). Respondents ranked 2,4-D, chlorsulfuron/metsulfuron-methyl, and halauxifen-methyl/florasulam as the top three commonly used POST herbicides in wheat (Table 4-6).

Cost of Weed Management in GR Crops

With the growing concern of GR weeds in Nebraska, usage of PRE herbicides and the usage of more diverse POST-applied tank mixes has increased in popularity, which consequentially has led to the increased cost of weed management programs (Sarangi and Jhala 2018). Along with the increased diversification of chemical control programs usage of tillage and manual weed removal can have been used in conjunction with chemical control. Averaged across districts, the cost of weed management in GR corn and soybean were \$101 and \$115 ha^{-1}, respectively (Table 4-8).

Herbicide-Resistant Weed Management

The Problem of Herbicide-Resistant Weeds

Results indicated that 80% of growers in Nebraska suspected the presence of at least one HR weed species on their farms. Respondents were asked to rate the problem of HR weeds on a scale of 0 to 10, with 0 meaning not at all a problem and 10 meaning highly problematic (Question 3.1 in Table 4-1). Averaged across districts, respondents indicated that there was high concern (average score of 8.1 with a median 8.3) about the problem of GR weeds in Nebraska (Figure 4-2). In the West Central district, respondents rated GR weeds as their biggest problem (average score of 8.9 with a median 9.2) compared to other districts, possibly explainable by the results showing that weeds like GR Palmer amaranth was the highest ranked in the West Central district (Table 4-5). Palmer amaranth is well documented as being a major challenge in row crop agriculture in recent time. Several studies have shown the extended emergence pattern of Palmer amaranth can create major hurdles in management (de Sanctis 2021). It has been recommended that mixing residual herbicide such as acetochlor or pyrozasulfone with POST herbicide can aid in management by providing overlapping residual activity (Hartzler et al. 2004; Jha and Norsworthy 2009), particularly in non-GMO conventional soybean (Sarangi and Jhala 2019).

Non-GR Crop Production Systems

Overall, 32% of growers in Nebraska responded positively toward rotating GR crops with non-GR crops (Table 4-8). Unique from all other districts, respondents in the Panhandle district showed that growers are more likely (68%) to rotate GR crops with non-GR crops compared to a range of 28% to 33% in other districts. Survey results indicated that the highest crop diversity (56.6% of total farmed or scouted areas under crops other than corn, sugarbeet) was reported in the Panhandle district (Table 4-3), which was believed to have led to the highest percentage of non-GR crops being planted in the Panhandle district.

Field Scouting and Late-Season Weed Control

Scouting for weeds both prior to and after herbicide application is a key tenant of an integrated weed management program, reducing the risks of herbicide-resistance evolution in weed species (Norsworthy et al. 2012; Young 2017). Averaged across districts, 95% of respondents reported they either have scouted or advised scouting farms before and after herbicide application (Table 4-9). Of concern is the relatively low response to controlling weed escapes late in season specifically in the Panhandle district with slightly over half (51%) of respondents controlling weed escapes. In contrast to the Panhandle district, 71% to 77% of growers reported practicing late-season weed management in other three districts (Table 4-9). Late-season weed escapes can be often disregarded by growers, take more labor, and rarely affect crop yields; however, long-term biological, ecological, and economic benefits of late-season weed management are benefits that cannot be overlooked. Several weed species, such as waterhemp and Palmer amaranth, exhibit prolonged emergence pattern (Hartzler et al. 2004; Jha and Norsworthy 2009), delayed emergence can lead to late season weed escapes, as most POST herbicides in row crops are made early in the season and have residuals that last only part way through the growing season. Mechanical and/or manual removal weed management was practiced by 17% of the respondents for late season weed control (data not shown).

Use of Herbicides with Multiple Sites of Action

This statewide survey showed a high degree of familiarity (93%) with herbicide sites of action (SOA), with 93% using at least two SOAs in their herbicide programs (Table 4-9). High prevalence of ALS inhibitor–resistant and GR weeds in Nebraska was likely a major contributor towards growers using herbicides with multiple SOAs. In crops like corn, a major contributor to diversifying herbicide SOAs, can be attributed to the more commonly used PRE and POST herbicides being premixes of different SOAs (Table 4-7.)

Weed Management Practices to Delay the Evolution of Herbicide Resistance

Seven management practices that are believed to slow the rate of herbicide resistance weed evolution were listed in Question 3.6 in Table 4-1. Survey participants were directed to indicate their perception of the effectiveness of those management practices on a scale of 1 to 10 (with 1 meaning not at all effective and 10 meaning highly effective). Respondents' perception of the effectiveness of herbicide applications following the label instructions (correct label rates and weed types and growth stages) was among the highest rated (average rating of 9 with the median 9.2) (Figure 4-2). Similarly reported in perceived effectiveness was PRE herbicides containing a residual herbicide followed by (fb) POST application of glyphosate mixed with other herbicide (average rating of 9 with the median 8.8). Several studies reported that PRE fb a POST herbicide program using mixtures of two or more herbicides was considered the most effective measure to control GR weeds in GR crops (Ganie et al. 2016, Sarangi et al. 2017a). Among the weed management practices listed, cover crops were considered the least effective (average rating of 6.5 with the median 5.8) option for GR weed management (Figure 4-2).

Adoption of New Multiple Herbicide–Resistant Crops

Survey results showed that 77% of respondents were aware of new stacked herbicide-resistant crops that came to the marker recently or set to be released in the near future (Table 4-9). Along with awareness of new herbicide-resistant crop lines is the willingness to adopting these new technologies. Of respondents, 67% noted a willingness to adopt new crop technologies a year or two after product release (data not shown). A majority of respondents had a high degree of willingness to adopt new crop technologies with 94% stating willingness to adopt within two years of product release (data not shown). Since the commercial release of dicamba/glyphosate-resistant soybean in 2017, off-target injury issues have become a significant concern for stakeholders with 86% of respondents reporting physical drift/volatility concerns (Figure 4-3). Off target movement of synthetic auxins has been of increasing concern as a survey from the southern United States in 2011 reporting 77% of crop consultants were concerned with off-target movement of synthetic auxins with the adoption of synthetic auxin resistant crops (Riar et al. 2013). A major portion of respondents (38%) indicated a growing concern with legal issues specifically regarding synthetic auxin herbicides such as dicamba. Given the relative proximity of sensitive crops to mid-season applications of synthetic auxins, a growing concern of disputes between neighbors has been noted by survey respondents. As shown by survey responses, movement of synthetic auxins is of major interest and concern to stakeholders with 45% looking for education about proper applications and identifying the signs of temperature inversions (Figure 4-3). Along with a major concern of related issues with synthetic auxin herbicides, 22% of survey respondents had concerns that new technologies may lead to reliance a small handful of herbicides used in POST applications, leading to an evolution of herbicide-resistant weeds (Figure 4-3). A wide variety of other concerns were reported, with 27% of respondents expressing concerns such as application technologies associated with new herbicide-resistant crops, market issues, extension/research concerns, among others.

Weed Management Research and Extension Priorities

Survey participants were directed to list several research and extension priorities to improve future weed management in Nebraska (Question 4.1 in Table 4-1). Of the 130 responses, the largest portion (23%) indicated the need for integrated pest management research conjoining popular chemical control options with other biological and mechanical management methods (Figure 4-3). Few survey participants (17%) noted that additional herbicide SOAs are needed to control increasing number of weeds resistant to multiple herbicides in row crops along with testing new formulations. No corn/soybean herbicide belonging to a new SOA has come to the marketplace in the last three decades (Duke 2012), and there is little possibility of commercialization of a new SOA herbicide in the near future. Other areas highlighted by respondents cited interest in research areas of application technology, cover crops, and drift management as their top priorities (Figure 4-3).

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Table 4-1. A condensed version of the survey questionnaire used in 2019 survey of stakeholders in Nebraska to access problem weeds and their management practices in agronomic crops.

General Information:

Please best describe your primary occupation. Which county and state are you from?

Section 1. Crop Production and Problem Weeds

1.1 How many acres did you farm/scout last year (2019)? How many of these acres were under tillage and no-till production?

1.2 How many acres (farmed/scouted) were under different crops (corn, dry edible beans, grain sorghum, soybean, sugarbeet, wheat, and others)?

1.3 What are the five most difficult-to-control weed in your opinion? Please write them in order, where #1 is the weed most difficult to control.

1. _________; 2. _________; 3. _________; 4. _________; 5. _________

1.4 Which herbicide-resistant weeds do you suspect on your farm/scouted areas, or are you concerned about them in the future? What are the resistances you suspect? Do you have any glyphosate-resistant weeds on your farm/scouted areas? Please list them.

Suspected herbicide-resistant weeds: ________; Resistant to (herbicide name): ________

1.5 How many acres of each crop trait did you farm/scout last year (2019)?

Conventional Corn: ________
Convention Soybean: ________
LibertyLink Corn: ________
Enlist Soybean: ________

Section 2: Herbicide Usage

2.1 Do you use preplant burndown herbicides? Please list the three most common preplant burndown herbicides in order, where #1 is the most used herbicide.

1._________; 2._________; 3._________

2.2 Do you use preemergence (soil residual) herbicides? Please list the five most common preemergence herbicides in order, where #1 is the most used herbicide.

Corn: 1._________; 2._________; 3._________
Soybean: 1._________; 2._________; 3._________
Wheat: 1._________; 2._________; 3._________
Others (_____): 1._________; 2._________; 3._________

2.3 Do you use postemergence herbicides? Please list the five most common postemergence herbicides in order, where #1 is the most used herbicide.

Corn: 1._________; 2._________; 3._________
Soybean: 1._________; 2._________; 3._________
Wheat: 1._________; 2._________; 3._________
Others (_____): 1._________; 2._________; 3._________

2.4 What is your average cost per acre of weed control in Roundup Ready (glyphosate-resistant) traited crops?

Table 4-1 Cont.

Section 3: Glyphosate-resistant weed management
3.1 How serious is the weed resistance to glyphosate? Answer using a scale of 1 to 10 where 1 is "not at all serious" and 10 is "very serious".
3.2 Do you rotate between Roundup Ready and non-Roundup Ready Crops?
3.3 Do you scout field before and after herbicide applications?
3.4 Do you control weed escapes or prevent seed set later in the season? Yes: ______ No: ______ If Yes, with which methods (chemical, mechanical, or manual control methods): ________
3.5 How familiar are you with herbicide sites of action (1-10, 1 is "not well known" and 10 is "well known")?
3.6 As a way of managing potential herbicide-resistant weeds, how effective are the following practices in your opinion? When answering use a scale of 1-10, 1 is "not at all effective" and 10 is "very effective": a. Rotating herbicide-resistant crops from year to year b. Tillage c. Using correct labeled rates and apply herbicides at a proper timing for size and type of weed present d. Cover crops
3.7 Are you aware of new multiple herbicide-resistant crops such as Alite 27/Balance soybean (glufosinate-, glyphosate-, and isoxaflutole-resistance) and Xtendiflex soybean (dicamba-, glufosinate-, and glyphosate-resistance)? Yes: ________ No: ________
3.8 Do you have any concerns such as volatility or drift hazards, etc., with the adoption of newly released herbicide resistant crops? Please list them. 1. ________; 2. ________; 3. ________
Section 4: Weed Management Research and Extension Priorities
4.1 What are your future research and extension needs/expectations from the University of Nebraska-Lincoln's Weed Scientist and experts? 1. ________; 2. ________; 3. ________

Table 4-2. The number of survey respondents categorized based on occupation

	Districts				
Occupation	Northeast	Panhandle	Southeast	West Central	Nebraska
	--- No. of Respondents ---				
Growers	67	20	131	48	262
Crop Consultants[a]	28	8	54	20	110
Others[b]	12	4	20	8	44
Total Respondents	106	25	209	76	416

[a]Survey respondents with the primary occupation of certified crop advisors, agronomist, and farm manager were considered as "crop consultants"

[b]Survey respondents not categorized as growers or crop consultants were considered "others", which included pesticide applicators, farm workers, farm managers, and industry sales representatives

Table 4-3. Information on average farm size, areas in no-till production, and primary crops in 2019 survey of stakeholders in Nebraska to access problem weeds and their management practices in agronomic crops.

Crop Production Systems	Districts				Nebraska
	Northeast[d]	Panhandle	Southeast[d]	West Central[d]	
Farming areas (ha) by growers[a]	760 (132)	780 (352)	850 (96)	920 (201)	798 (83)
Scouted areas (ha) reported by crop consultants[a]	4385 (1244)	3267 (1453)	6154 (1395)	3421 (1102)	4828 (762)
Area in no-till production (% of total area farmed or scouted)[b]	67.2	48.8	74.6	56.1	64.5
Area under primary crops (% of total area farmed or scouted)[b]					
Corn	46.5	26	48.2	26	39.3
Soybean	41	18	39.3	33	30.7
Grain Sorghum	1.2	9	7	14	2.7
Wheat	6	16	4	15	4.9
Alfalfa	5	7.5	6	5	4.1
Dry Edible Bean[e]	NA	5	NA	NA	-
Sugarbeet[e]	-NA	12	NA	NA	-
Others	0.8	24	1.1	4.2	3.6

[a]Values in parentheses represent the standard error of the mean (SEM)
[b]Responses of growers and the crop consultants were considered for this question
[c]Abbreviation: NA, not available; respondents did not report the required information
[d]No information on soybean was listed from the Panhandle district
[e]Crop was reported only from Panhandle district of Nebraska; therefore, average state results were not calculated

Table 4-4. Respondents' ranking of weeds most difficult to control in 2019 survey of stakeholders in Nebraska to access problem weeds and their management practices in agronomic crops[a].

Rank	Districts				Nebraska
	Northeast	Panhandle	Southeast	West Central	
--- Name of the Problem Weed ---					
1	Palmer amaranth (3.9)	Kochia (4.4)	Palmer amaranth (4.0)	Palmer amaranth (4.2)	Palmer amaranth (3.6)
2	Common waterhemp (3.6)	Palmer amaranth (3.6)	Horseweed (3.8)	Kochia (2.9)	Horseweed (3.2)
3	Horseweed (3.0)	Field bindweed (1.5)	Common waterhemp (3.7)	Common waterhemp (2.7)	Common waterhemp (3.1)
4	Kochia (1.9)	Horseweed (0.7)	Velvetleaf (1.6)	Horseweed (2.2)	Kochia (1.8)
5	Giant ragweed (1.1)	Velvetleaf (0.6)	Kochia (0.8)	Foxtails (0.9)	Giant ragweed (0.8)

[a]Values in parentheses represent problematic points for a weed, calculated using the equation:

$$RP = \sum_{r=1}^{5} \frac{FX}{n}$$

where F is the number of respondents choosing a particular rank (r) for a weed species, X is the problem points (5 for r#1, 4 for r#2, 3 for r#3, 2 for r#4, 1 for r#5) for that rank, and n is the total number of responses recorded in favor of that rank. The maximum relative problematic points for a weed species are 5.0.

Table 4-5. Weeds listed by the respondents for suspected glyphosate-resistance in 2019 survey of stakeholders in Nebraska to access problem weeds and their management practices in agronomic crops[a,b,c].

	Districts		
Responses	Northeast	Southeast	West Central
Suspected glyphosate-resistance	Common waterhemp (71)	Palmer amaranth (61)	Palmer amaranth (63)
	Horseweed (65)	Horseweed (49)	Kochia (48)
	Palmer amaranth (25)	Common waterhemp (44)	Horseweed (37)
	Giant ragweed (12)	Giant ragweed (4)	Common waterhemp (24)

[a]Responses of the growers and crop consultants were considered for this question
[b]Values in parentheses represent the percentage of the respondents who reported a certain weed species
[c]Sufficient responses were not recorded from the Panhandle district; therefore, data from Panhandle district were not included in this table.

Table 4-6. Respondents' ranking of the most commonly used preplant herbicides in 2019 survey of stakeholders in Nebraska to access problem weeds and their management practices in agronomic crops.

	Districts				
Rank	Northeast	Panhandle	Southeast	West Central	Nebraska
			--- Herbicides ---		
1	2,4-D (2.7)	Glyphosate (1.9)	2,4-D (2.5)	2,4-D (2.2)	2,4-D (2.7)
2	Dicamba (1.3)	Saflufenacil (1.1)	Glyphosate (1.9)	Dicamba (1.3)	Glyphosate (1.4)
3	Glyphosate (1.3)	2,4-D (0.8)	Dicamba (1.0)	Glyphosate (1.0)	Dicamba (1.3)

[a]Values in parentheses represent the relative importance points, calculated using the equation:

$$RP = \sum_{r=1}^{3} \frac{FX}{n}$$

where F is the number of respondents choosing a particular rank (r) for an herbicide, X is the problem points (3 for r#1, 2 for r#2, 1 for r#3) for that rank, and n is the total number of responses recorded in favor of that rank. The maximum relative importance points are 3.0.

Table 4-7. Respondents' ranking of the most common use PRE and POST herbicides in major agronomic crops in 2019 survey of stakeholders in Nebraska to access problem weeds and their management practices in agronomic crops[a].

	Districts[b]			
Rank	Northeast	Southeast	West Central	Nebraska[c]
	--- **PRE Herbicides** ---			
Corn				
1	Acetochlor + clopyralid + mesotrione (2.5)	Atrazine + bicyclopyrone + mesotrione + *S*-metolachlor (1.7)	Atrazine + bicyclopyrone + mesotrione + *S*-metolachlor (2.5)	Atrazine + bicyclopyrone + mesotrione + *S*-metolachlor (1.9)
2	*S*-metolachlor (1.1	Atrazine (1.1)	*S*-metolachlor (1.8)	Acetochlor + clopyralid + mesotrione (1.8)
3	Isoxaflutole + thiencarbazone-methyl (1.0)	Atrazine + *S*-metolachlor + mesotrione (1.0)	Atrazine (1.6)	Isoxaflutole + thiencarbazone-methyl (1.7)
Soybean				
1	Flumioxazin + pyroxasulfone (1.8)	Metribuzin + sulfentrazone (1.6)	Flumioxazin + pyroxasulfone (1.9)	Metribuzin + sulfentrazone (1.3)
2	Sulfentrazone + chloransulam-methyl (1.5)	Chlorimuron-ethyl + flumioxazin + pyroxasulfone (1.1)	Saflufenacil + imazethapyr + pyroxasulfone (1.2)	Flumioxazin + pyroxasulfone (1.3)
3	Chlorimuron-ethyl + flumioxazin + thifensulfuron (0.8)	Sulfentrazone + chlorimuron-ethyl (0.8)	Metribuzin + sulfentrazone (0.9)	Sulfentrazone + chloransulam-methyl (1.2)
Sorghum				
1	Atrazine + *S*-metolachlor + mesotrione (1.9)	Atrazine + *S*-metolachlor + mesotrione (2.7)	Atrazine + *S*-metolachlor + mesotrione (2.4)	Atrazine + *S*-metolachlor + mesotrione (2.3)
2	Atrazine (1.4)	Atrazine (1.3)	Atrazine + *S*-metolachlor (1.2)	Atrazine (1.3)
3	Atrazine + *S*-metolachlor (1.0)	Atrazine + *S*-metolachlor (1.1)	Atrazine (1.1)	Atrazine + *S*-metolachlor (1.0)

Table 4-7 Cont.

Rank	Districts[b]			
	Northeast	**Southeast**	**West Central**	**Nebraska**
		--- POST Herbicides ---		
Corn				
1	Glyphosate (1.8)	Glyphosate (2.5)	Glyphosate (1.7)	Glyphosate (2.7)
2	Mesotrione (1.1)	Dicamba + diflufenzopyr (1.5)	Dicamba + diflufenzopyr (1.6)	Dicamba + diflufenzopyr (1.3)
3	Dicamba + diflufenzopyr (0.8)	Mesotrione (1.0)	Acetochlor + clopyralid + mesotrione (0.7)	Mesotrione (1.0)
Soybean				
1	Glyphosate (2.1)	Glyphosate (2.3)	Dicamba (2.2)	Glyphosate (2.3)
2	Dicamba (1.8)	Dicamba (1.9)	Glyphosate (1.9)	Dicamba (2.0)
3	Fomesafen (1.0)	Glufosinate (1.2)	*S*-metolachlor (0.7)	Glufosinate (1.2)
Sorghum				
1	NA[d]	2,4-D (2.1)	2,4-D (1.8)	2,4-D (1.9)
2	NA	Atrazine (1.1)	Dicamba (1.0)	Dicamba (1.1)
3	NA	Dicamba (0.9)	Bromoxynil + pyrasulfotole (0.6)	Atrazine (0.7)
Wheat				
1	NA	2,4-D (1.8)	2,4-D (1.9)	2,4-D (1.7)
2	NA	Chlorsulfuron + metsulfuron-methyl (1.2)	Chlorsulfuron + metsulfuron-methyl (1.1)	Chlorsulfuron + metsulfuron-methyl (1.1)
3	NA	Dicamba (0.9)	Halauxifen-methyl + florasulam (1.0)	Halauxifen-methyl + florasulam (0.8)

[a]Values in parentheses represent the relative importance points, calculated using the equation:

$$RP = \sum_{r=1}^{3} \frac{FX}{n}$$

where F is the number of respondents choosing a particular rank (r) for an herbicide, X is the problem points (3 for r#1, 2 for r#2, 1 for r#3) for that rank, and n is the total number of responses recorded in favor of that rank. The maximum relative importance points are 3.0.

[b]Sufficient responses were not recorded from the Panhandle district; therefore, data from the Panhandle district were not included in this table

[c]Collective responses from three districts (Northeast, Southeast, and West Central) were listed under Nebraska

[d]Abbreviation; NA, not available, respondents did not report the required information

Table 4-8. Average cost of weed management in glyphosate-resistant crops as reported by the stakeholders in 2019 survey of stakeholders in Nebraska to access problem weeds and their management practices in agronomic crops[a,b].

Crops	Districts				
	Northeast	Panhandle	Southeast	West Central	State
			--- $ ha^{-1} ---		
Corn	96 (16-198)	93 (42-178)	99 (30-185)	141 (30-198)	101 (16-198)
Soybean	115 (30-247)	NA	113 (30-296)	154 (30-257)	115 (30-296)
Alfalfa	33 (17-74)	NA	44 (12-74)	40 (15-68)	41 (12-74)

[a]Responses of growers and crop consultants were both considered
[b]Values in parentheses indicate the min to max range of the cost
[c]Abbreviation: NA, not available; respondents did not report the required information

Table 4-9. Respondents' knowledge and perception about the management strategies to control herbicide-resistant weeds in 2019 survey of stakeholders in Nebraska to access problem weeds and their management practices in agronomic crops.

Glyphosate-resistant weed management questions	Districts				Nebraska
	Northeast	Panhandle	Southeast	West Central	
Average problem ratings for the weeds resistant to glyphosate (on a scale of 1 to 10)[a]	7.5 (0.2)	7.3 (0.7)	8.3 (0.4)	8.9 (0.4)	8.1 (0.2)
Glyphosate-resistant crops rotated with crops not resistant to glyphosate (% of total growers)	30	68	33	28	32
Percentage of respondents that suspect herbicide-resistant weeds	84	94	90	98	88
Percentage of respondents scouted/advised to scout farms before and after herbicide applications[b,c]	98	90	93	97	95
Percentage of growers controlled weed escapes or prevented seed set later in the season	75	51	71	77	72
Percentage of respondents familiar with the herbicide SOA[c]	92	84	94	96	93
Percentage of growers using multiple SOAs in their herbicide programs	94	90	93	94	93
Percentage of respondents aware of new crops resistant to multiple herbicides	87	64	79	77	77
Percentage of respondents concerned with drift issues arising from new herbicide resistant crops	55	58	71	62	63

[a]Values in parentheses represent the standard error of the mean (SEM)
[b]Respondents for this question include only growers and crop consultants
[c]Abbreviation: SOA, site of action

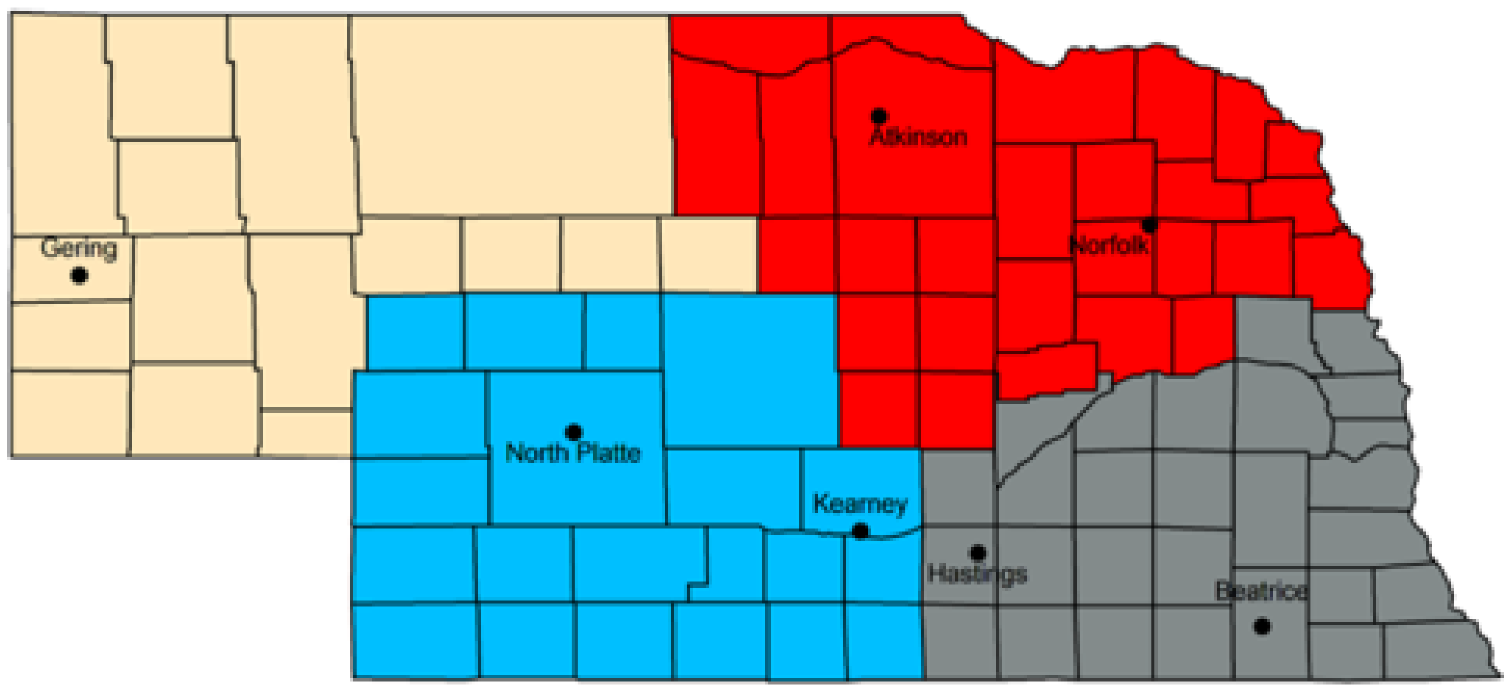

Figure 4-1. County map of Nebraska divide into four extension districts by Nebraska Extension.

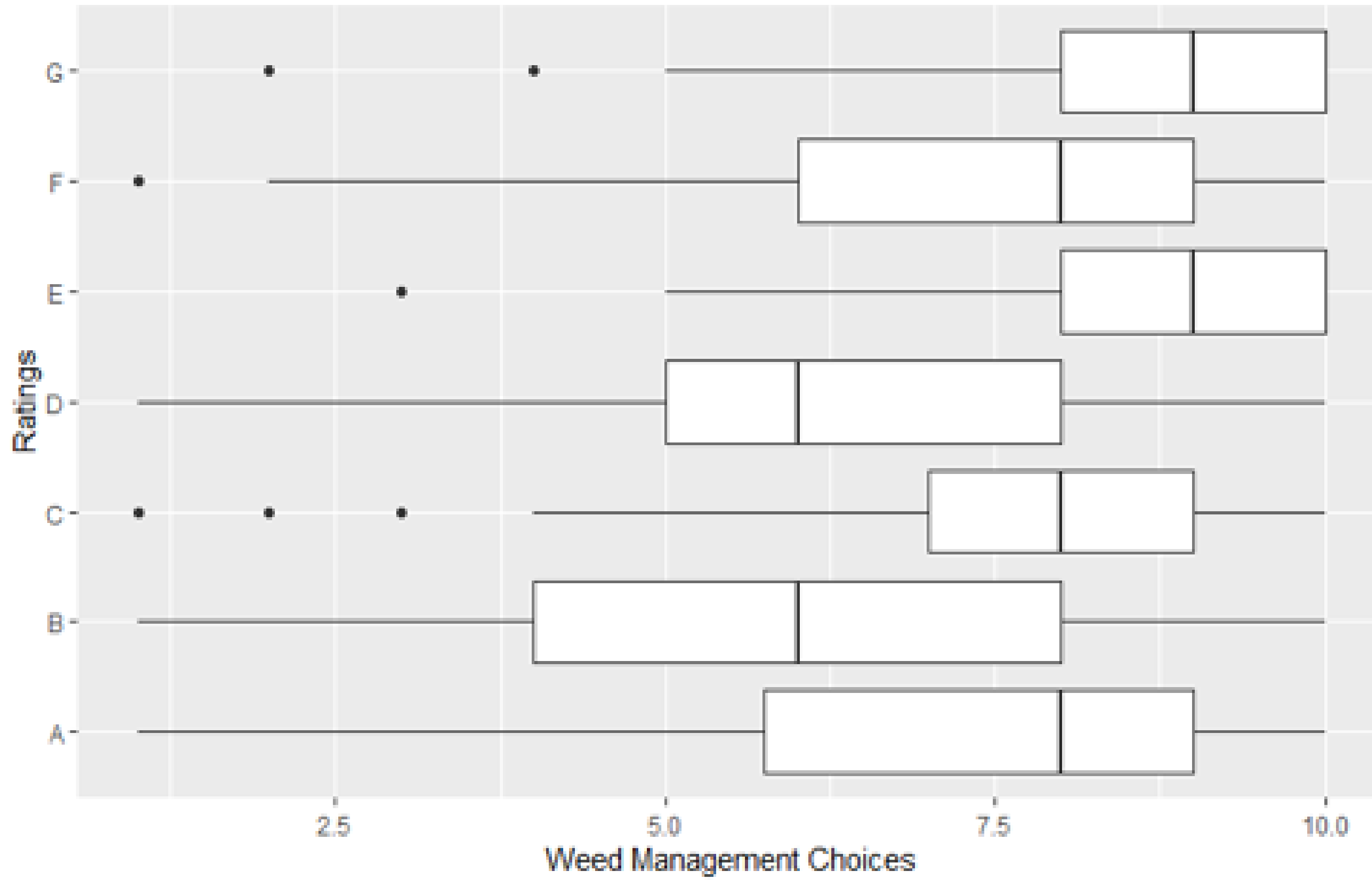

Figure 4-2. Boxplot presenting the respondents' perception of the effectiveness of weed management choices for controlling glyphosate-resistant weeds in Nebraska. The line at the center of each boxplot shows the median value of the ratings. Respondents rated the effectiveness of a weed management choice on a scale of 1 to 10, where 1 means not at all effective and 10 means very effective. Details about weed management choices are listed in Table 1.

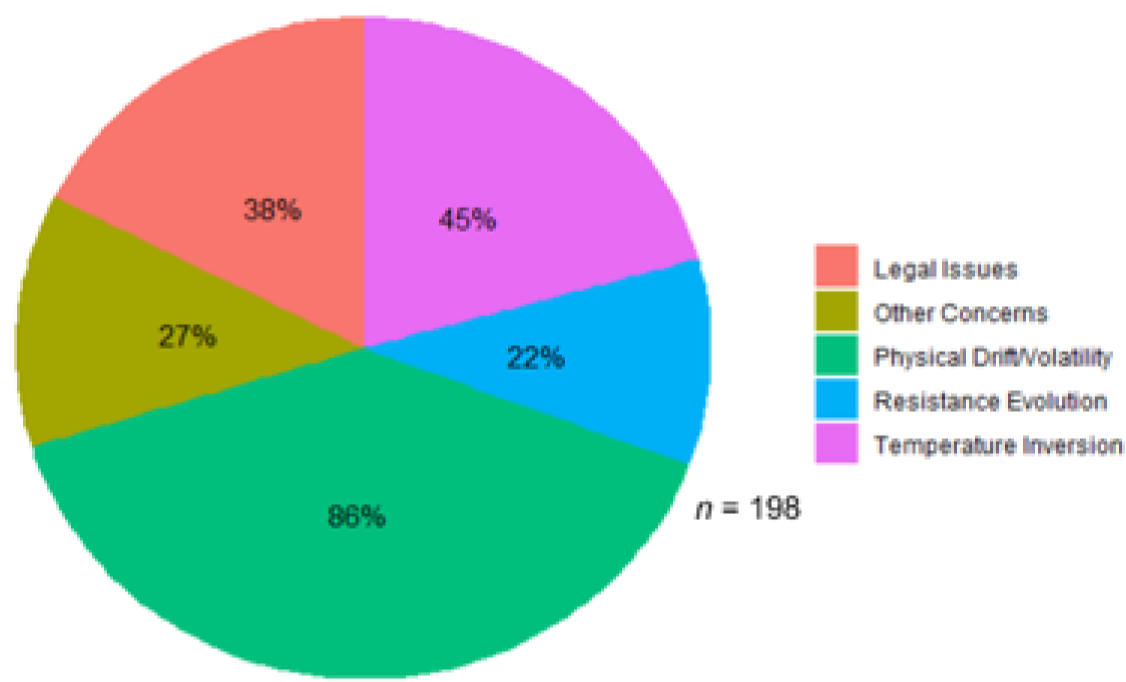

Figure 4-3. The relative importance of concerns by the survey respondents about the adoption of new crops resistant to multiple herbicides

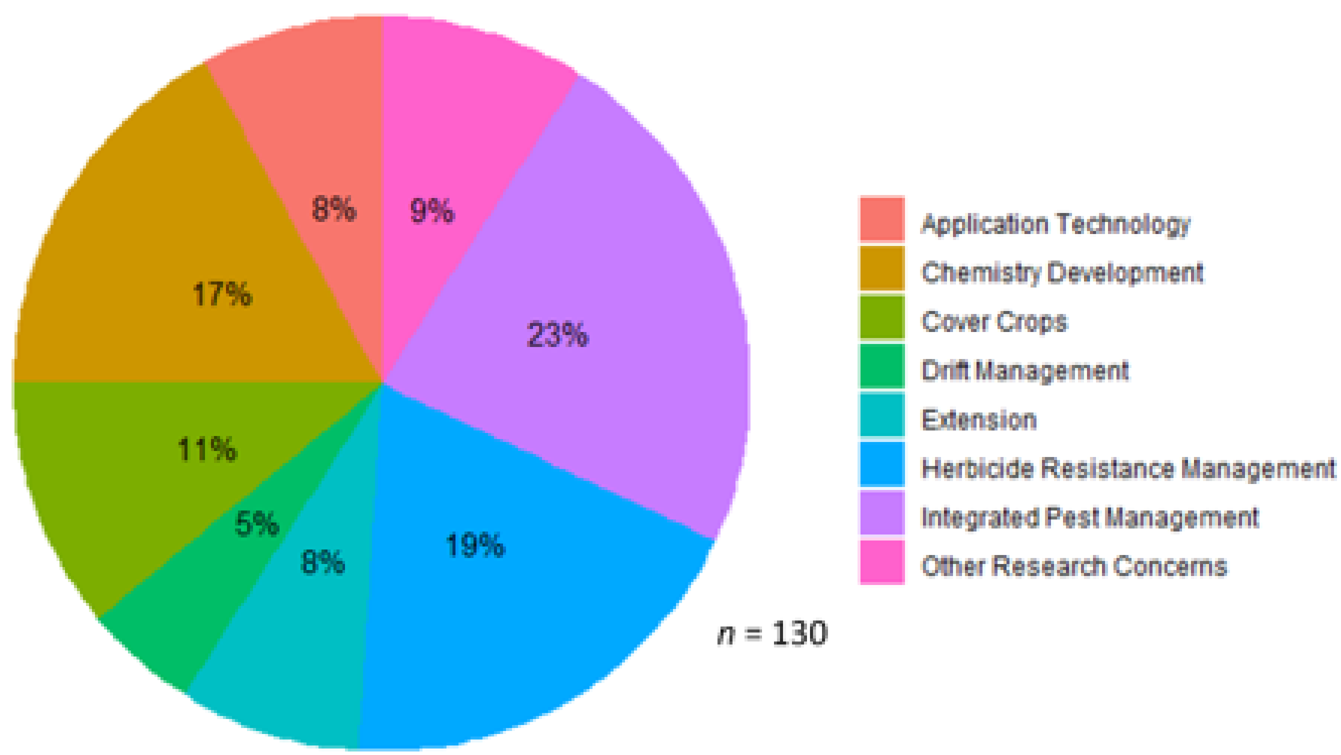

Figure 4-4. Future weed science research and extension priorities reported by the survey respondents