Palmer amaranth (*Amaranthus palmeri*) control in double-crop dicamba/glyphosate resistant soybean (*Glycine max*) and dicamba and 2,4-D efficacy on Palmer amaranth and common waterhemp (*Amaranthus rudis*)

by

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Abstract

Auxin herbicides have been widely used for broadleaf weed control since the mid-1940's. With new auxinic herbicide-resistant traits in corn, soybean, and cotton, use of these herbicides is likely to increase. Glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) and common waterhemp (*Amaranthus rudis*) are two primary problematic weed species that will be targeted with dicamba and 2,4-D in the new systems.

No-till double-crop soybean after winter wheat harvest is a popular cropping system in central and eastern Kansas, however, management of glyphosate resistant Palmer amaranth has become a serious issue. Field experiments were established near Manhattan and Hutchinson, KS, in 2016 and 2017, to compare seventeen herbicide treatments for control of Palmer amaranth and large crabgrass (*Digitaria sanguinalis*) in dicamba/glyphosate resistant no-till double-crop soybean after winter wheat.

Herbicide programs that included a residual preemergence (PRE) treatment followed by a postemergence (POST) treatment offered greater Palmer amaranth control 8 weeks after planting when compared to PRE-only, POST-only and burndown-only treatments. All treatments that contained glyphosate POST provided complete control of large crabgrass compared to less than 43% control with PRE-only treatments. Soybean grain yield was greater in programs that included PRE followed by POST treatments, compared to PRE-only and burndown-only treatments.

A second set of field experiments were established in 2017 near Manhattan and Ottawa, KS to evaluate dicamba and 2,4-D POST efficacy on Palmer amaranth and common waterhemp. Five rates of dicamba (140, 280, 560, 1121, and 2242 g ae ha^{-1}) and 2,4-D (140, 280, 560, 1121,

and 2242 g ae ha-^{1}) were used to evaluate control of the Amaranthus spp. Each experiment was conducted twice at each location.

Dicamba provided better Palmer amaranth and common waterhemp control than 2,4-D across the rates evaluated. Control of Palmer amaranth was 94% and 99% with dicamba rates of 1121 and 2242 g ae ha^{-1}, respectively, but 2,4-D never provided more than 80% control at any rate. The highest rates of both dicamba and 2,4-D provided greater than 91% common waterhemp control, but control was less than 78% with all other rates of both herbicides. Palmer amaranth and common waterhemp control did not exceed 73% with the highest labelled POST rates of either dicamba or 2,4-D. Auxinic herbicide-resistant traits in corn, soybean, and cotton offer new options for controlling glyphosate-resistant Palmer amaranth and common waterhemp, however proper stewardship is vital to maintain their effectiveness.

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Chapter 1 - Palmer Amaranth (*Amaranthus Palmeri*) Control in Double-Crop Glyphosate/Dicamba Resistant Soybean

ABSTRACT

No-till double-crop soybean after wheat harvest is a popular cropping system in central and eastern Kansas, however, management of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) has become a serious problem. Genetically modified soybean resistant to both dicamba and glyphosate (Roundup Ready 2 Xtend) is a new technology that could help manage glyphosate-resistant Palmer amaranth in double-crop soybean. Field experiments were established near Manhattan and Hutchinson, KS, in 2016 and 2017, to compare seventeen herbicide treatments for control of Palmer amaranth and large crabgrass (*Digitaria sanguinalis*) in dicamba/glyphosate resistant no-till double-crop soybean after winter wheat.

Natural populations of Palmer amaranth (mixture of glyphosate susceptible and resistant) were present at both Manhattan and Hutchinson locations with densities of 23 plants m^{-2} or greater. Preemergence (PRE) treatments were applied five days following wheat harvest to allow for regrowth of Palmer amaranth that was injured during winter wheat harvest. Preemergence treatments consisted of dicamba + glyphosate + residual, glyphosate + residual, glufosinate + residual, and paraquat + residual. Postemergence (POST) treatments consisted of combinations of dicamba + glyphosate, dicamba + glyphosate + acetochlor, or glyphosate + lactofen and were applied on newly emerged Palmer amaranth of 5 to10 cm in height.

Treatments that included a PRE followed by a POST offered greater Palmer amaranth control 8 weeks after planting compared to PRE-only, POST-only, and burndown-only treatments. All treatments that included glyphosate POST provided complete control of large crabgrass compared to less than 43% control with PRE-only treatments. Soybean grain yield was greater in treatments that contained a PRE followed by POST, compared to all single pass treatments. Genetically modified soybean resistant to dicamba and glyphosate offer a new

management strategy for controlling glyphosate-resistant Palmer amaranth in no-till double-crop soybean after winter wheat if a program that consists of a PRE followed by POST is implemented.

INTRODUCTION

In 1996, glyphosate-resistant (GR) crops revolutionized the farming industry, by providing producers with a POST herbicide that had effective broad-spectrum weed control, and provided an economical alternative to selective herbicides (Feng et al. 2010). Adoption of the technology was rapid and as of 2017, 94% of the soybeans planted in the United States were genetically engineered, herbicide-resistant varieties (USDA-NASS 2017). The result of this rapid adoption reduced the use of other herbicide sites of action (SOA), and due to heavy selection pressure from repeated use of glyphosate, many weed species, particularly Palmer amaranth, began to develop resistance to glyphosate (Johnson et al. 2010).

Palmer amaranth is a summer annual dioecious species that is native to the southwestern United States and was observed as early as 1901 in New Mexico (Sauer 1957). However, even with its long history in the United States, the earliest occurrence of Palmer amaranth on any list of troublesome weeds was as recent as 1989 in a Southern Weed Science Society survey of South Carolina (Webster and Coble 1997). In 2016, Palmer amaranth was rated the most troublesome weed in the United States and Canada by weed scientists in a survey conducted by the Weed Science Society of America (Van Wychen 2016).

There are several attributes that allow Palmer amaranth to be competitive in cropping systems: it is a prolific seed producer (Keeley and Thullen 1989), it utilizes the C_4 photosynthetic pathway (Ehleringer 1983), it has an extended emergence period (Jha and Norsworthy 2009), and it is resistant to 6 herbicide SOA (Heap 2018). The seed production potential of Palmer amaranth allows for minor infestations to develop into high population densities relatively quickly (Burke et al. 2007, Norsworthy et al. 2014). The robust physical size of Palmer amaranth, compared to other Amaranthus spp. (Horak and Loughin 2000), can slow harvest (Smith et al. 2000), increase grain moisture, and increase harvest loss (Moore et al. 2004). These physiological characteristics of Palmer amaranth give it a distinct advantage over soybean, a C_3 species. Palmer amaranth infestations have been found to dramatically decrease soybean yield, with yield reductions up to 78% in densities of up to eight plants m^{-2} (Bensch et al. 2003).

Large crabgrass is a summer annual weed that is commonly a problem in cotton (Buchanan and Burns 1970), peppers (Fu and Ashley 2006), watermelon (Monks and Schultheis 1998), and grain sorghum (Smith et al. 2010). In 2016, crabgrass spp. were voted the fifth most common weed among all broadleaf crops, fruits, and vegetables in a survey of weed scientists in the United States and Canada (Van Wychen 2016). While large crabgrass can be a serious problem, it is extremely susceptible to glyphosate (Culpepper et al. 2001) and is fairly easily controlled in GR cropping systems.

Soybean is the second most popular crop in the United States, with 33.8 and 36.5 million ha^{-1} of soybean planted in 2016 and 2017, respectively (USDA-NASS 2017). In Kansas, full season and double-crop soybean (DCS) make up the third most popular crop with 1.6 and 2.1 million ha^{-1} planted in 2016 and 2017, respectively (USDA-NASS 2017). National soybean planted hectares increased 10% from 2016 to 2017, and in Kansas, planted hectares rose 27% over the same period. Dicamba/glyphosate resistant soybean (DGRS), commercially sold as Roundup Ready 2 Xtend soybeans, were introduced in 2016 (Monsanto Company, St. Louis, MO 63167). One year later, low-volatile formulations of dicamba (Xtendimax with VaporGrip Technology, Fexapan herbicide plus VaporGrip Technology, and Engenia herbicide) (Anonymous 2018a, 2018b, 2018c) were approved for use as preplant (PP), PRE, and POST applications in DGRS.

Double-crop soybean planted after winter wheat harvest accounts for approximately 10% of the soybean hectares planted in Kansas (USDA-NASS 2017). Soybean planted at this time of year can face many challenges due to lack of moisture, poor soybean emergence, and limited yield potential (Hay 2017). However, DCS can be a profitable option for producers in central and eastern Kansas that have wheat in their rotation (Ibendahl et al. 2015).

Palmer amaranth control in DCS can be difficult to manage because it is most susceptible to management before emergence occurs (Jha and Norsworthy 2009). In many instances, weeds are suppressed by the wheat canopy, however there are still weeds that are allowed to emerge (Anderson 2008). If Palmer amaranth is able to reach sizes that are too large for herbicidal control, they can spread and infest a field very rapidly (Norsworthy et al. 2014). Reduced herbicide efficacy has been observed when the herbicide is not able to reach the soil surface because of large quantities of biomass covering the soil (Banks and Robinson 1982). Although this can be overcome by simply increasing the herbicide rate (Locke et al. 2002), it increases herbicide costs and overall cost of production.

Producers of DCS must take special precautions to avoid major Palmer amaranth escapes. PRE herbicides should be applied as soon as possible after wheat harvest, and followed by an overlapping residual herbicide POST within 17 to 21 days (Farmer et al. 2017). It is important to make timely weed management decisions in regards to amaranthus spp., because time of emergence is a major factor in determining yield loss in soybean (Dieleman et al. 1995, 1996). It is also recommended that producers in all cropping systems follow simple and effective best management practices in order to reduce the risk of creating and spreading resistant weeds (Norsworthy et al. 2012).

The objective of this experiment was to evaluate various PRE and POST herbicide treatment options for control of Palmer amaranth and large crabgrass in double-crop DGRS after winter wheat.

MATERIALS AND METHODS

General

Field experiments were established at two Kansas State University research locations near Manhattan and Hutchinson, KS in 2016 and 2017. Natural populations of Palmer amaranth were present at both Manhattan and Hutchinson locations, with 23 or more plants m^{-2}. Herbicide application date, soybean planting date, and soil properties are listed in Table 1.1. The experiment was arranged in a randomized complete block design with four replications of each treatment. Plots were 3 m by 8.5 m with four rows spaced at 76 cm. Experiments consisted of 17 herbicide treatments and one non-treated weedy check (Table 1.2 Table 1.3). Herbicide treatments were selected to assess control of Palmer amaranth through various burndown, burndown plus residual (PRE), or PRE followed by (fb) POST (PFBP) treatments. All treatments were applied at 5 or more days after winter wheat harvest to allow for regrowth of Palmer amaranth injured by the combine during wheat harvest. Preemergence treatments were applied with a 3 m hand-held spray boom equipped with 6 nozzles delivering 140 L ha^{-1} at 241 kPa. Postemergence treatments were applied with a 1.9 m hand-held spray boom equipped with 4 nozzles delivering 140 L ha^{-1} at 276 kPa. Percent Palmer amaranth control was rated visually at 2, 4, and 8 weeks after planting (WAP). Visual ratings were based on a scale of 0% to 99%, where 0% equals no control and 99% equals complete control.

Data Analysis

Data were analyzed in JMP Pro 12 (SAS Institute Inc, Cary, NC) using the Mixed Procedure. Means were separated using Fisher's Protected Least Significant Difference (LSD) at $\alpha = 0.05$. All possible main effects and interactions were tested and each combination of site-year were considered an environment (Carmer et al. 1989). Environments, replications (nested within environment) and all other interactions were considered random effects. Treatment was considered as a fixed effect. Considering environment as a random effect permits inferences about treatments to be made across a range of environments (Hager et al. 2003, Hay 2017, Johnson et al. 2014, Stephenson IV et al. 2004, Zhang et al. 2005). Orthogonal contrasts for each individual site year of Palmer amaranth control (8 WAP) and grain yield were conducted to evaluate differences between various treatment groups. Treatments were compared based on application timing (PFBP vs. POST-only vs. PRE-only vs. burndown-only) and different foliar applied burndown herbicides (dicamba + glyphosate vs. glyphosate vs. paraquat vs. glufosinate).

Herbicide Application

All PRE and POST applications not containing dicamba were made using TeeJet (TeeJet Technologies, Springfield, IL) Turbo TeeJet (TT) 110015 nozzles. All PRE and POST applications containing dicamba were made using Turbo TeeJet Air Induction (TTI) 110015 nozzles, per label requirements. POST applications were made within 18 to 21 day after PRE treatment when newly emerged Palmer amaranth were between 5 to 10 cm in height. Appropriate adjuvants were used per label recommendations (Table 1.3).

Soybean

“Asgrow 40X6” DGRS (Monsanto Company, St. Louis, MO 63167) were no-till planted at 345,800 seeds ha^{-1}, into wheat residue five or more days after grain harvest. In Manhattan, grain was harvested from the center two rows of the four row plots with a Wintersteiger (Wintersteiger, Salt Lake City, UT 84116) plot combine. In Hutchinson, grain was hand-harvested from the right of center row and threshed with a Wintersteiger plot combine in 2016 and an Almaco (Almaco, Nevada, IA, 50201) plot thresher in 2017. All grain yield estimates were adjusted to 13.5% moisture.

RESULTS AND DISCUSSION

Adequate rainfall ($\geq$ 1.9 cm) for herbicidal activation was achieved within 1 week after PRE across all site years (Table 1.4). In 2016, consistent precipitation was received during the first 7 weeks after PRE at both locations. In 2017, very little rainfall occurred at either Manhattan or Hutchinson following the first week after PRE, which led to uneven emergence and poor soybean stands in Hutchinson (data not shown).

Palmer amaranth

Visual rating

The greatest levels of Palmer amaranth control were achieved with a program approach that contained a PFBP (Table 1.5). Dicamba + glyphosate + sulfentrazone + metribuzin fb dicamba + glyphosate + acetochlor provided 98% control 8 WAP. Preemergence followed by

POST treatments provided 93% or better Palmer amaranth control by 8 WAP, with the exception of glyphosate + acetochlor fb dicamba + glyphosate + acetochlor, which only provided 82% control. This was likely due to poor initial control of large Palmer amaranth with the PRE treatment. Treatments that contained a PRE-only (paraquat or glufosinate + flumioxazin + pyroxasulfone) resulted in 86% and 74% control 8 WAP. The POST-only treatment of dicamba + glyphosate, which was applied 3 WAP, provided only 75% control 8 WAP. Burndown-only treatments that contained no residual herbicide, (paraquat, dicamba + glyphosate, or glufosinate) provided the least Palmer amaranth control, and ranged from 23% to 35% 8 WAP.

Biomass

The non-treated weedy check contained 188 g m^{-2} of Palmer amaranth biomass while biomass in PFBP treatments ranged from 2 to 30 g m^{-2}, with one exception (Table 1.6). The PFBP treatment of glyphosate + acetochlor fb dicamba + glyphosate + acetochlor contained more biomass than most of the other PFBP treatments, because of poor Palmer amaranth burndown with the PRE. The PRE-only treatment of paraquat + flumioxazin + pyroxasulfone had similar Palmer amaranth biomass to the PFBP treatments, but contained more large crabgrass (Table 1.7), which likely suppressed the Palmer amaranth. Palmer amaranth biomass in the POST-only treatment of dicamba + glyphosate was greater than the PFBP treatments and approximately half of the non-treated weedy check. The greatest Palmer amaranth biomass in treated plots occurred in the burndown-only treatments with no residual control of weeds.

Density

The non-treated weedy check had a population of 23 plants m^{-2}, while the PFBP treatments had the fewest number of Palmer amaranth ranging between 0.1 to 3.0 plants m^{-2} (Table 1.6). The PFBP treatments that had the greatest density of Palmer amaranth were dicamba

+ glyphosate + acetochlor fb dicamba + glyphosate + acetochlor and glyphosate + acetochlor fb dicamba + glyphosate + acetochlor, with 3 and 1.3 plants m^{-2}, respectively. The POST-only treatment of dicamba + glyphosate contained 3.5 plants m^{-2}. The greatest number of Palmer amaranth in treated plots were observed in the burndown-only treatments, and ranged from 8.7 to 13 plants m^{-2}.

Large Crabgrass

Visual control

All POST treatments with glyphosate provided complete large crabgrass control 8 WAP (Table 1.7). PRE-only treatments of paraquat or glufosinate + flumioxazin and pyroxasulfone and the burndown-only treatment of glufosinate gave 40% to 43% control of large crabgrass 8 WAP. Large crabgrass was tillered and beyond optimal treatment stage for effective control with glufosinate and paraquat at the time of the PRE application. The burndown-only treatment of dicamba + glyphosate provided the greatest level of large crabgrass control of any treatment that was not followed by a POST, with 69% control 8 WAP, and is likely due to excellent burndown activity on large crabgrass by glyphosate. Paraquat alone provided the least large crabgrass control with only 11% 8 WAP.

Biomass

The non-treated weedy check contained 224 g m^{-2} of large crabgrass biomass, but all treatments that contained glyphosate in the POST contained 0 g m^{-2} (Table 1.7). Of the burndown-only treatments, paraquat provided the least control with 207 g m^{-2} of large crabgrass biomass, but glyphosate + dicamba and glufosinate provided the greatest control with 92 g m^{-2} and 123 g m^{-2}, respectively. The PRE-only treatments provided similar levels of control and resulted in comparable biomass yields of 149 to 207 g m^{-2}.

Grain Yield

The non-treated weedy check had a grain yield of 267 kg ha^{-1}, compared to best PFBP treatments that ranged from 1792 to 2081 kg ha^{-1} (Table 1.5). Paraquat + flumioxazin + pyroxasulfone fb glyphosate + lactofen and glyphosate + acetochlor fb dicamba + glyphosate + acetochlor tended to have the lowest grain yields of the PFBP treatments, with 1721 and 1571 kg ha^{-1}, respectively. The decrease in grain yield in these two treatments is attributed to poor early season control of large crabgrass in the paraquat + flumioxazin & pyroxasulfone fb glyphosate + lactofen treatment, and poor early season control of Palmer amaranth in the glyphosate + acetochlor fb dicamba + glyphosate + acetochlor treatment. The PRE-only, POST-only, and burndown-only treatments had lower yields than all PFBP treatments.

Orthogonal Contrasts

PFBP vs. PRE-only

Palmer amaranth control in PFBP treatments were significantly better than PRE-only treatments in Hutchinson 2016 ($P = 0.0001$) and Manhattan 2017 ($P \leq 0.0001$), but not significantly greater in the other two site years (Table 1.8). However, grain yield for PFBP treatments were greater ($P \leq 0.0001$) than PRE-only in all years that grain harvest was measured. Although differences in visual control ratings of Palmer amaranth were not significant for all sites, large crabgrass control was very poor (Table 1.8) and outcompeted the Palmer amaranth in Manhattan 2016 and Hutchinson 2017, which would explain why grain yield was greater in PFBP than PRE-only for all site years.

PFBP vs. POST-only

Preemergence followed by POST treatments provided significantly ($P = 0.01$ to $\leq$ 0.0001) greater control of Palmer amaranth than the POST-only treatment (dicamba +

glyphosate) across every site year (Table 1.8). Applying the POST-only treatments, with no PRE, 3 WAP allowed for Palmer amaranth to grow far beyond the labelled size of 10 cm and made acceptable control (≥97%) unattainable. Grain yield for PFBP treatments was also greater (P = 0.05 to ≤ 0.001) than POST-only treatments at all sites where grain yield was measured. With the critical weed free period in soybean being from VE to V3 (Acker et al. 1993), early season weed competition with soybean can cause dramatic losses in yield.

PRE-only vs. Burndown-only

Palmer amaranth control with PRE-only treatments that included a residual (paraquat or glufosinate + flumioxazin + pyroxasulfone) were greater (P = 0.01 to ≤ .0001) than burndown only treatments (glufosinate, dicamba + glyphosate, paraquat) that had minimal residual activity. Season-long control of weeds should not be expected with either a PRE-only or burndown-only. Residual herbicides must be in the mixtures in order to allow time for canopy closure. Hutchinson 2016 and Manhattan 2017 grain yield was significantly (P = 0.05 to 0.0001) greater for PRE treatments, but soybean grain yield in Manhattan 2016 was not significantly different. In Manhattan 2016, high quality burndown of large crabgrass was not achieved with the PRE treatments, therefore, soybean was left to compete with large crabgrass the entire growing season, which could have contributed to the lack of difference in yield.

PFBP treatments with Dicamba PRE and POST vs. PFBP treatments with Dicamba POST

Palmer amaranth control was not different between PFBP treatments where dicamba was in the PRE and POST applications versus PFBP treatments where dicamba was applied only in the POST application, with the exception of Hutchinson in 2016, where treatments that contained dicamba in both the PRE and the POST achieved 93% vs. 83% control in treatments that contained dicamba only in the POST application (Table 1.8). Grain yield was significantly (P =

0.0001) greater in Hutchinson 2016 (1049 vs 789 kg ha^{-1}) and Manhattan 2017 (1922 vs. 1624 kg ha^{-1}) for treatments containing dicamba in the PRE and POST applications versus POST-only applications. This is likely attributed to the lack of Palmer amaranth control early in the season in treatments that did not contain dicamba in the PRE application, because the populations were natural and had varying degrees of glyphosate resistance.

PFBP Dicamba vs. PFBP no Dicamba

Palmer amaranth control was not different between PFBP treatments that contained dicamba in any PRE or POST application versus PFBP treatments the contained no dicamba in any application timing (Table 1.8). This was likely due to the ability of the herbicides to achieve a high level of burndown and maintain residual Palmer amaranth control until the POST application. In Manhattan 2017, grain yield was significantly (P = 0.01) greater in treatments that contained dicamba compared to treatments that did not contain dicamba. This may have been a result of very little early season rain followed by heavy rainfall in weeks 5-8 after planting. The lack of early season rainfall combined with the lack of an overlapping residual herbicide in the non-dicamba treatments could account for the difference in grain yield.

CONCLUSIONS

Overall, the best Palmer amaranth and large crabgrass control, as well as, the highest grain yield were achieved with a two pass program approach that contained one or a combination of dicamba + glyphosate, glufosinate, or paraquat in the PRE treatment and were followed by a POST containing dicamba + glyphosate + acetochlor or glyphosate + lactofen. Control of Palmer amaranth and large crabgrass should be achieved before the critical period of weed removal

(Knezevic et al. 2003, Sartorato et al. 2011) to prevent yield loss in soybean. A PRE-only herbicide program, although cheaper than a two pass program, will not provide consistent season-long control of Palmer amaranth. POST-only programs also are not sufficient for weed management and resistance management, because weeds are allowed to grow to sizes that are off-label and generally too large for effective herbicidal control. Finally, careful consideration of environmental elements (wind speed, temperature, humidity, and soil moisture) must be considered by producers utilizing dicamba in double-crop settings to ensure crop safety to actively growing susceptible neighboring fields.

TABLES

Table 1.1. Soybean planting dates, herbicide application dates, and soil characteristics.[a,b]

	2016		2017	
Site Characteristics	Manhattan	Hutchinson	Manhattan	Hutchinson
Planting Date	June 29	July 11	June 26	June 27
PRE and burndown application date	June 28	July 8	June 26	June 27
POST application date	July 19	July 26	July 17	July 18
Soil series	Reading[c]	Darlow[d]	Reading	Darlow
Soil texture	silt loam	silt loam	silt loam	silt loam
Soil organic matter (%)	2.6	1.9	3.2	2.2
Soil pH	6.1	4.8	6.3	5.4

[a] Abbreviations: PRE, preemergence; POST, postemergence.

[b] Soil characteristics from sample depth of 0 to 15 cm.

[c] Fine-silty, mixed superactive, mesic Pachic Argiudolls.

[d] Fine-loamy, mixed, superactive, mesic Vertic Natrustalfs.

Table 1.2. Herbicides, trade names, and manufacturers for all treatments.

Herbicide/Adjuvant/ Drift Reduction Agent[a]	Abbreviation	Trade Name	Manufacturer	Location
Dicamba	Dic	Xtendimax with VaporGrip	Monsanto Company	St. Louis, MO
Glyphosate	Gly	Roundup Powermax	Monsanto Company	St. Louis, MO
Acetochlor	Ace	Warrant	Monsanto Company	St. Louis, MO
Flumioxazin	Flu	Valor SX	Valent U.S.A Corporation	Walnut Creek, CA
Sulfentrazone & Metribuzin	Sul & Met	Authority MTZ DF	FMC Corporation	Philadelphia, PA
Metribuzin	Met	Tricor DF	United Phosphorus Incorporate	King of Prussia, PA
Paraquat	Par	Gramoxone SL 2.0	Syngenta Crop Protection, LLC	Greensboro, NC
Flumioxazin & Pyroxasulfone	Flu & Pyr	Fierce	Valent U.S.A Corporation	Walnut Creek, CA
Lactofen	Lac	Cobra	Valent U.S.A Corporation	Walnut Creek, CA
Glufosinate	Glu	Liberty 280 SL	Bayer CropScience	Research Triangle Park, NC
Drift Reduction Agent	DRA	Intact	Precision Laboratories, LLC	Waukegan, IL
Crop Oil Concentrate	COC	Prime Oil	Winfield Solutions, LLC	St. Paul, MN
Ammonium Sulfate	AMS	N-Pak AMS	Winfield Solutions, LLC	St. Paul, MN

[a] &, indicates premix.

Table 1.3. Herbicides, rates, adjuvants, and drift reduction agent for preemergence and postemergence applications.[a]

Herbicide Treatment[b]	Rate	Application Timing	Adjuvant
	g ai or ae ha^{-1}		
Dic + gly fb dic + gly + ace	560 + 1266 fb 560 + 1266 + 1260	PRE fb POST	DRA
Dic + gly + flu fb dic + gly + ace	560 + 1266 + 72 fb 560 + 1266 + 1260	PRE fb POST	DRA
Dic + gly + sul & met fb dic + gly + ace	560 + 1266 + 202 + 303 fb 560 + 1266 + 1260	PRE fb POST	DRA
Dic + gly + flu + met fb dic + gly + ace	560 + 1266 + 72 + 262 fb 560 + 1266 + 1260	PRE fb POST	DRA
Dic + gly + ace fb dic + gly + ace	560 + 1266 + 1260 fb 560 + 1266 + 1260	PRE fb POST	DRA
Gly + flu fb dic + gly + ace	1266 + 72 fb 560 + 1266 + 1260	PRE fb POST	DRA
Gly + sul & met fb dic + gly + ace	1266 + 202 + 303 fb 560 + 1266 + 1260	PRE fb POST	DRA
Gly + flu + met fb dic + gly + ace	1266 + 72 + 262 fb 560 + 1266 + 1260	PRE fb POST	DRA
Gly + ace fb dic + gly + ace	1266 + 1260 fb 560 + 1266 + 1260	PRE fb POST	DRA
Par + flu & pyr fb gly + lac	840 + 70 + 59 fb 1266 + 218	PRE fb POST	COC fb AMS
Glu + flu & pyr fb gly + lac	594 + 70 + 59 fb 1266 + 218	PRE fb POST	AMS fb AMS
Dic + gly	560 + 1266	POST	DRA
Paraquat	840	Burndown	COC
Dic + gly	560 + 1266	Burndown	DRA
Glufosinate	594	Burndown	AMS
Par + flu & pyr	840 + 70 + 59	PRE	COC
Glu + flu & pyr	594 + 70 + 59	PRE	AMS

[a] Abbreviations: Dic, Dicamba; Gly, Glyphosate; Ace, Acetochlor; Flu, Flumioxazin; Sul, Sulfentrazone; Met, Metribuzin; Par, Paraquat; Pyr, Pyroxasulfone; Lac, Lactofen; Glu, Glufosinate; PRE, Preemergence; POST, Postemergence; DRA, drift reduction agent; COC, crop oil concentrate; AMS, ammonium sulfate; fb, followed by.
[b] &; indicates premix.
[c] Adjuvant rates: DRA, 1% v/v; COC, 1% v/v; AMS, 2.8 kg ai ha^{-1}.

Table 1.4. Weekly precipitation through 8 weeks after preemergence application.[a]

				Precipitation, weeks after PRE application							
Location	Year	PRE[b]	POST[c]	1	2	3	4	5	6	7	8
				cm							
Manhattan	2016	June 28	July 19	6.7	1.62	5.1	0.2	4.1	3.4	1.9	4.6
Hutchinson	2016	July 8	July 26	5.6	1.1	2.1	1.3	2.7	5.1	5.5	0.0
Manhattan	2017	June 26	July 17	6.4	0.0	0.0	1.0	2.2	9.6	2.4	1.4
Hutchinson	2017	June 27	July 18	1.9	0.0	0.8	0.3	0.4	3.4	1.9	0.4

[a] Abbreviations: PRE, Preemergence; POST, Postemergence
[b] Date of PRE herbicide application for each site.
[c] Date of POST herbicide application for each site.

Table 1.5. Palmer amaranth control and double-crop soybean grain yield, averaged across all sites.[a]

Herbicide Treatment[c]	Application timing	Palmer amaranth Control[b] 2WAP	4WAP	8WAP	Soybean Grain yield[b]
		%			kg ha^{-1}
Dic + gly fb dic + gly + ace	PRE fb POST	74cde	89abc	94ab	1792abc
Dic + gly + flu fb dic + gly + ace	PRE fb POST	90ab	94ab	97ab	1934ab
Dic + gly + sul & met fb dic + gly + ace	PRE fb POST	91ab	95a	98a	1905ab
Dic + gly + flu + met fb dic + gly + ace	PRE fb POST	91ab	93abc	94ab	2081a
Dic + gly + ace fb dic + gly + ace	PRE fb POST	94a	95a	97ab	2069a
Gly + flu fb dic + gly + ace	PRE fb POST	75cde	89abc	93abc	1925ab
Gly + sul & met fb dic + gly + ace	PRE fb POST	82bcd	91abc	96ab	1840abc
Gly + flu + met fb dic + gly + ace	PRE fb POST	86abc	90abc	96ab	1798abc
Gly + ace fb dic + gly + ace	PRE fb POST	73dc	82c	82cd	1571cd
Par + flu & pyr fb gly + lac	PRE fb POST	96a	98a	97ab	1721bc
Glu + flu & pyr fb gly + lac	PRE fb POST	95a	97a	96ab	1865abc
Dic + gly	POST	0g	70d	75d	1302de
Paraquat	Burndown	65ef	46ef	38e	710g
Dic + gly	Burndown	71de	55e	35e	1089ef
Glufosinate	Burndown	54f	36f	23f	717g
Par + flu & pyr	PRE	96a	92abc	86bc	973fg
Glu + flu & pyr	PRE	90ab	84bc	74d	1084ef
Non-treated weedy check	-	-	-	-	267h
P-value		< 0.0001	< 0.0001	< 0.0001	< 0.0001

[a] Abbreviations: Dic, Dicamba; Gly, Glyphosate; Ace, Acetochlor; Flu, Flumioxazin; Sul, Sulfentrazone; Met, Metribuzin; Par, Paraquat; Pyr, Pyroxasulfone; Lac, Lactofen; Glu, Glufosinate; PRE, Preemergence; POST, Postemergence; fb, followed by; WAP, weeks after planting.
[b] Means with the same letter are not significantly different according to Fisher's Protected LSD ($\alpha = 0.05$).
[c] &, indicates premix.

Table 1.6. Palmer amaranth biomass, density, and height at double-crop soybean maturity, averaged across all locations.[a,b]

Herbicide Treatment[c]	Application timing	Biomass	Density	Height
		(g m^{-2})	(m^{-2})	(cm)
Dic + gly fb dic + gly + ace	PRE fb POST	18ab	0.6abc	28bc
Dic + gly + flu fb dic + gly + ace	PRE fb POST	8a	0.3ab	32bcde
Dic + gly + sul & met fb dic + gly + ace	PRE fb POST	13ab	0.5abc	21ab
Dic + gly + flu + met fb dic + gly + ace	PRE fb POST	8a	0.4abc	24abc
Dic + gly + ace fb dic + gly + ace	PRE fb POST	19ab	3.0cdef	22abc
Gly + flu fb dic + gly + ace	PRE fb POST	14ab	0.2a	24abc
Gly + sul & met fb dic + gly + ace	PRE fb POST	7a	0.2a	28bc
Gly + flu + met fb dic + gly + ace	PRE fb POST	14ab	0.2a	18a
Gly + ace fb dic + gly + ace	PRE fb POST	50bc	1.3bcd	29bc
Par + flu & pyr fb gly + lac	PRE fb POST	2a	0.1a	23abc
Glu + flu & pyr fb gly + lac	PRE fb POST	30ab	0.3ab	32cd
Dic + gly	POST	94d	3.5de	29bc
Paraquat	Burndown	114d	10.5efg	47ef
Dic + gly	Burndown	153e	13.0fg	51f
Glufosinate	Burndown	161e	8.7efg	51f
Par + flu & pyr	PRE	39abc	1.3bcd	46ef
Glu + flu & pyr	PRE	78cd	1.6cd	42def
Non-treated weedy check	-	188e	23.1g	53f
P-value		< 0.0001	< 0.0001	< 0.0001

[a] Abbreviations: Dic, Dicamba; Gly, Glyphosate; Ace, Acetochlor; Flu, Flumioxazin; Sul, Sulfentrazone; Met, Metribuzin; Par, Paraquat; Pyr, Pyroxasulfone; Lac, Lactofen; Glu, Glufosinate; PRE, Preemergence; POST, Postemergence; fb, followed by.
[b] Means with the same letter are not significantly different according to Fisher's Protected LSD ($\alpha = 0.05$).
[c] &; indicates premix.

Table 1.7. Large Crabgrass control and biomass in double-crop soybean, averaged across all sites.[a]

Herbicide Treatment[c]	Application timing	Large Crabgrass Control[b] 4WAP	8WAP	Large Crabgrass Biomass[b]
		%	%	(g m^{-2})
Dic + gly fb dic + gly + ace	PRE fb POST	98a	99a	0a
Dic + gly + flu fb dic + gly + ace	PRE fb POST	98a	99a	0a
Dic + gly + sul & met fb dic + gly + ace	PRE fb POST	97a	99a	0a
Dic + gly + flu + met fb dic + gly + ace	PRE fb POST	95ab	99a	0a
Dic + gly + ace fb dic + gly + ace	PRE fb POST	98a	99a	0a
Gly + flu fb dic + gly + ace	PRE fb POST	99a	99a	0a
Gly + sul & met fb dic + gly + ace	PRE fb POST	98a	99a	0a
Gly + flu + met fb dic + gly + ace	PRE fb POST	99a	99a	0a
Gly + ace fb dic + gly + ace	PRE fb POST	96a	99a	0a
Par + flu & pyr fb gly + lac	PRE fb POST	99a	99a	0a
Glu + flu & pyr fb gly + lac	PRE fb POST	95ab	99a	0a
Dic + gly	POST	89ab	99a	0a
Paraquat	Burndown	44e	11d	214d
Dic + gly	Burndown	81b	69b	92b
Glufosinate	Burndown	60cd	43c	123bc
Par + flu & pyr	PRE	47de	40c	207cd
Glu + flu & pyr	PRE	62c	42c	149bcd
Non-treated weedy check	-	-	-	224d
P-value		< 0.0001	< 0.0001	< 0.0001

[a] Abbreviations: Dic, Dicamba; Gly, Glyphosate; Ace, Acetochlor; Flu, Flumioxazin; Sul, Sulfentrazone; Met, Metribuzin; Par, Paraquat; Pyr, Pyroxasulfone; Lac, Lactofen; Glu, Glufosinate; PRE, Preemergence; POST, Postemergence; fb, followed by; WAP, weeks after planting.
[b] Means with the same letter are not significantly different according to Fisher's Protected LSD ($\alpha = 0.05$).
[c] &; indicated premix.

Table 1.8. Orthogonal contrasts of several treatments for Palmer amaranth control and double-crop soybean grain yield at Manhattan and Hutchinson, KS in 2016 and 2017.[a,b]

	Manhattan 2016		Hutchinson 2016		Manhattan 2017		Hutchinson 2017	
Orthogonal Contrasts[c]	8WAP	Grain yield	8WAP	Grain yield	8WAP	Grain yield	8WAP	Grain yield[d]
PFBP treatments vs. PRE-only treatments	97 vs. 96 NS	2946 vs. 1651 ****	89 vs. 70 ***	909 vs. 590 ****	97 vs. 59 ****	1726 vs. 901 ****	96 vs. 97 NS	-
PFBP treatments vs. POST-only treatment	99 vs. 82 ***	3006 vs. 1986 ****	93 vs. 60 ****	990 vs. 459 ****	97 vs. 78 ***	1793 vs. 1462 **	98 vs. 79 **	-
PFBP treatments vs. burndown treatments	96 vs. 57 ****	1651 vs. 1533 NS	70 vs. 45 ***	590 vs. 406 **	59 vs. 0 ****	901 vs. 590 ***	97 vs. 26 ****	-
PFBP trts with dic in PRE and POST vs. PFBP trts with dic in POST only	99 vs. 95 NS	3022 vs. 2857 NS	93 vs. 83 *	1049 vs 789***	97 vs. 97 NS	1922 vs. 1624 ***	98 vs.93 NS	-
PFBP trts with dic in PRE and POST or POST only vs. PFBP trts with no dic in PRE or POST	97 vs. 99 NS	2939 vs. 2973 NS	88 vs. 93 NS	919 vs. 870 NS	97 vs. 96 NS	1773 vs. 1536 **	95 vs. 98 NS	-

[a] Abbreviations: WAP, weeks after planting; PFBP, PRE followed by POST; dic, dicamba; par, paraquat; glu, glufosinate; fb, followed by; NS, not significant.
[b] % Palmer amaranth control 8 weeks after planting (WAP).
[c] Means of contrast different at *P = 0.1 to 0.05, **P = 0.05 to 0.01, ***P = 0.01 to 0.0001, ****P ≤ 0.0001 levels.
[d] Grain yield for Hutchinson discarded due to inconsistent stands.

Chapter 2 - Dicamba and 2,4-D Efficacy on Palmer Amaranth (*Amaranthus palmeri*) and Common Waterhemp (*Amaranthus rudis*)

ABSTRACT

Auxin herbicides have been widely used for broadleaf weed control since the mid-1940's. With new auxinic herbicide-resistant traits in corn, soybean, and cotton, use of these herbicides is likely to increase. Glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) and common waterhemp (*Amaranthus rudis*) are primary problematic weed species that will be targeted with dicamba and 2,4-D in the new systems. Both herbicides have been used to control the Amaranthus spp, but there are few direct comparisons of these two herbicides for control of these two species. In 2017, four site-years of field research were conducted near Manhattan and Ottawa, KS to evaluate dicamba and 2,4-D postemergence (POST) efficacy on Palmer amaranth and common waterhemp.

Five rates of dicamba (140, 280, 560, 1121, and 2242 g ae ha^{-1}) and 2,4-D (140, 280, 560, 1121, and 2242 g ae ha^{-1}) were evaluated for control of the Amaranthus spp. Two runs of the experiment were conducted near Manhattan with a natural population of Palmer amaranth (>200 plants m^{-2}) and two runs of the experiment were conducted near Ottawa with a natural population of common waterhemp (>240 plants m^{-2}). All treatments were applied to weeds less than 10 cm tall with a backpack sprayer calibrated to deliver 140 L ha^{-1} with the recommended spray nozzles for each herbicide.

Dicamba provided better Palmer amaranth and common waterhemp control than 2,4-D across the rates evaluated. Control of Palmer amaranth was 94% and 99% with dicamba rates of 1121 and 2242 g ae h^{-1}, respectively, while 2,4-D never provided more than 80% control at any rate. The highest rates of both dicamba and 2,4-D provided greater than 90% common waterhemp control, but control was less than 78% with all other rates of either herbicide. Palmer amaranth and common waterhemp control did not exceed 73% with the highest labelled POST

rates of either dicamba or 2,4-D. Efficacy may have been reduced in this research because of the high populations and spray coverage issues. Dicamba and 2,4-D need to be part of an integrated weed management program in traited soybean to achieve acceptable Amaranthus spp control and minimize the potential for developing herbicide resistance.

INTRODUCTION

2,4-D is one of the oldest selective herbicides in the world, and has been used in agriculture since the 1940's because of its selectivity, efficacy, wide spectrum of weed control, and low cost of application (Kirby 1980, Mithila et al. 2011). The overwhelming popularity of 2,4-D use in cropping systems, lawns, and turf led to the synthesis of other auxinic herbicides such as dicamba. Dicamba was introduced in the early 1960's for use in agriculture (Monaco et al. 2002, Sterling and Hall 1997). Dicamba and 2,4-D are still among the most widely used herbicides in the world. Dicamba and 2,4-D use has increased in recent years due to expanded hectares of application and the introduction of dicamba and 2,4-D genetically engineered herbicide-resistant soybean and cotton varieties (Egan et al. 2014). The introduction of dicamba and 2,4-D resistant soybean and cotton are due, in large part, to the evolution of glyphosate-resistant (GR) Palmer amaranth in 2004 and common waterhemp in 2005 (Culpepper et al. 2006, Johnson et al. 2010, Kniss 2018, Legleiter and Bradley 2008).

The first documented cases of 2,4-D herbicide-resistance was in spreading dayflower (*Commelina diffusa*) and wild carrot (*Daucus carota*) in 1957 in Hawaii and Ontario, respectively (Hilton 1957, Whitehead and Switzer 1963). This was also the first known case of herbicide-resistance ever documented (Heap 2018). Resistance to dicamba was not observed until 1990, when it was documented in wild mustard (*Sinapis arvensis*), in Manitoba (Heap and Morrison 1992). Although auxinic herbicides have been used more extensively and applied over more hectares than any other herbicide in the world (Heap 2014), there was only a combined 37 documented accounts of resistant to the auxinic herbicides by 2018 (Heap 2018). For this reason and because of the rise of GR broadleaf weeds, dicamba and 2,4-D resistant soybean and cotton were developed for commercial production (Behrens et al. 2007).

Glyphosate-resistant crops had a 94-fold increase in hectares planted from 1996 to 2011, making it the most widely and quickly adopted technology in agricultural history (James 2011). However, since the introduction of GR crops, there have been 41 weed species documented with glyphosate-resistance and over 293 weed biotypes reported worldwide (Heap 2018). In addition, no new herbicide site of action (SOA) has been introduced since p-hydroxyphenylpyruvate dioxygenase (HPPD) inhibitors were approved in the early 1990's (Beaudegnies et al. 2009). Due to the lack of introduction of a new SOA, focus has shifted to the development of transgenic crops that are resistant to old herbicide SOA (i.e. dicamba and 2,4-D resistant soybean) that previously were not suitable for use in susceptible crops (Behrens et al. 2007, Duke 2012). The release of dicamba and 2,4-D resistant soybean and cotton that are also stacked with resistance to glyphosate and/or glufosinate will add another SOA for producers that previously could not apply auxinic herbicides for broad-spectrum broadleaf weed control in those susceptible crops.

Palmer amaranth and common waterhemp have documented resistance to 6 different herbicide SOA (Heap 2018). Both species have developed resistance to EPSPS-, ALS-, PPO-, HPPD-, and PS-II-inhibiting herbicides, while Palmer amaranth has also developed resistance to microtubule inhibitors (trifluralin) (Gossett et al. 1992), and a population of common waterhemp has developed resistance to an auxinic herbicide (2,4-D) (Bernards et al. 2012).

Palmer amaranth and common waterhemp utilize the C_4 photosynthetic pathway, which make them highly competitive with C_3 crops such as soybean or cotton (Ehleringer 1983). Palmer amaranth and common waterhemp were able to continue growth and reproduction, by increasing specific leaf area, even when shading levels were above 40% (Jha et al. 2008, Steckel et al. 2003). Palmer amaranth and common waterhemp have several other physiological characteristics that make them difficult to control: they are prolific seed producers (Keeley and Thullen 1989), have aggressive growth rates (Horak and Loughin 2000), and have extended emergence that lasts for several months (Jha and Norsworthy 2009). Palmer amaranth densities of 8 plants m^{-2} have been found to cause 78% yield loss and common waterhemp densities of 11 plants m^{-2} have been found to cause 56% yield loss in soybean (Bensch et al. 2003).

Palmer amaranth and common waterhemp were rated the number 1 and 5 most troublesome weeds in the United States and Canada by weed scientists in a 2016 survey conducted by the Weed Science Society of American (Van Wychen 2016). Palmer amaranth and common waterhemp are extremely competitive “driver weeds” (Hay 2017) that influence weed management decisions that growers face when evaluating weed control strategies (Ward et al. 2013).

There are several strategies of weed control that can and should be used when facing challenging Amaranthus spp (Norsworthy et al. 2012). Cultural practices like tillage (DeVore et al. 2013, Farmer et al. 2017), narrow row spacing (Bell et al. 2015, Knezevic et al. 2003), and crop rotation can all have positive weed control effects (Beckie 2006, Swanton and Weise 1991). Herbicide rotation and mixtures of different effective SOA can be effective strategies that increase weed control and decrease the potential for herbicide-resistance (Beckie and Reboud 2009, Evans et al. 2015). However, the need for improved weed control strategies and the introduction of significant weeds like Palmer amaranth and common waterhemp are two of the greatest concerns for producers (Norsworthy 2003, Wilson et al. 2008)

The objective of this research was to evaluate dicamba and 2,4-D POST efficacy on Palmer amaranth and common waterhemp.

MATERIALS AND METHODS

General

Field experiments were established at two Kansas State University research locations near Manhattan and Ottawa, KS, in 2017. Natural populations of Palmer amaranth in Manhattan and common waterhemp in Ottawa were present at 200 and 240 plants m^{-2}, respectively. The experiment was conducted twice at each location, for a total of 2 site years for each species. Applications were made on June 9 and July 13 at the Manhattan location, and on June 8 and June 27 at the Ottawa location. The experiment was arranged in a randomized complete block design with four replications of each treatment. Plot areas were 3 m by 7.6 m with the center 1.9 m sprayed for evaluation of herbicide efficacy. All treatments were applied with a CO_2 backpack sprayer and a 1.9 m hand-held spray boom equipped with 4 nozzles delivering 140 L ha^{-1} at 276 kPa. Experiments consisted of 10 herbicide treatments and one non-treated weedy check (Table 2.1). All treatments were applied when Palmer amaranth and common waterhemp were 5 to 10 cm in height, and in the absence of a crop. Percent Palmer amaranth and common waterhemp control were visually rated at 4 weeks after treatment (WAT) to assess POST efficacy only, no residual activity was factored into ratings. Visual ratings were based on a scale of 0% to 99%, where 0% equals no control and 99% equal complete control. Plant biomass, density, and height were collected at 4 WAT.

Herbicide Application

Treatments were selected to evaluate differences in POST control of Palmer amaranth and common waterhemp with dicamba and 2,4-D. Five uniform rates (Table 2.1) of both dicamba and 2,4-D were used for evaluation of Palmer amaranth and common waterhemp control. Applications of 2,4-D were made using TeeJet (TeeJet Technologies, Springfield, IL) Air Induction Extended Range (AIXR) 110015 nozzles. Applications of dicamba were made using Turbo TeeJet Induction (TTI) 110015 nozzles, per label requirements on traited soybeans and cotton.

Herbicide Rates

In the Roundup Ready II Xtend soybean cropping system, there are two set rates of dicamba that can be applied PRE and POST. In a PRE scenario, 560 or 1121 g ae ha^{-1} of dicamba are permitted for application (Anonymous 2018a). In a POST scenario, 560 g ae ha^{-1} of dicamba is the only rate legally allowed to be applied over an actively growing soybean crop. A total of 2242 g ae ha^{-1} of dicamba are permitted per year.

In the Enlist soybean cropping system, there is a range of 2,4-D rates that are permitted to be applied PRE and POST. In both the PRE and POST scenario, 798 to 1065 g ae ha^{-1} of 2,4-D choline are permitted for application (Anonymous 2018d). A total of 3196 g ae ha^{-1} of 2,4-D are permitted per year. Comparison of dicamba and 2,4-D labelled POST use efficacy can be challenging due to the differences in the labelled rate structures. With labelled rate structures of dicamba and 2,4-D being different, a uniform range of rates were selected that would allow for both a direct comparison of rates, as well as a comparison across the approved labelled rates for traited soybeans.

Data Analysis

Visual ratings were subjected to analysis of variance (ANOVA) using JMP Pro 12 (SAS Institute Inc, Cary, NC) with means separated by Fisher's Protected Least Significant Difference (LSD) at $\alpha = 0.05$. Experiment runs at each location (i.e. Manhattan) were combined and species (i.e. Palmer amaranth or common waterhemp) were analyzed separately. Orthogonal contrasts were conducted to make direct overall comparisons between herbicides (dicamba vs 2,4-D) for each species. Biomass, density, and height were subjected to transformation to better meet assumptions of normality and equal variance. Because none of the transformations suggested in the literature improved these assumptions, the Kenward-Rogers adjustment was used (Kenward and Roger 2009).

RESULTS AND DISCUSSION

Palmer amaranth

Visual ratings

The two highest rates of dicamba (1121 and 2242 g ae ha^{-1}) provided the greatest levels of control, achieving 94% and 99% control of Palmer amaranth 4 WAT (Table 2.2). However, neither rate (1121 or 2242 g ae ha^{-1}) of dicamba are labelled for POST use in dicamba/glyphosate resistant soybean (Anonymous 2018a, 2018b, 2018c). The POST field use rate of dicamba (560 g ae ha^{-1}) provided 73% control of Palmer amaranth, which was significantly greater than the

POST field use rate of 2,4-D (1121 g ae ha^{-1}) (Anonymous 2018d), which provided only 52% control of Palmer amaranth. Palmer amaranth control did not exceed 79% with any rate of 2,4-D that was applied in this experiment. The only labelled use rate of either herbicide that achieved greater than 90% control was the PRE-only (1121 g ae ha^{-1}) use rate of dicamba. When comparing across all rates, orthogonal contrast ($p < 0.0001$) confirm that dicamba provided greater Palmer amaranth control (68%) than 2,4-D (35%)(Table 2.3). Comparing dicamba and 2,4-D across rates could put 2,4-D at a disadvantage because of the way the rates are structured. Control of Palmer amaranth did not exceed 44% control with any rate of dicamba or 2,4-D lower than the labelled POST rates.

Biomass, Density, and Height

The greatest quantity of Palmer amaranth biomass (537 g m^{-2}), density (325 plants m^{-2}), and height (99cm) were found in the non-treated weedy check (Table 2.4). The greatest reductions in Palmer amaranth biomass (0, 1, 39, and 40 g m^{-2}) and densities (0, 1, 29, and 52 plants m^{-2}) occurred with the three highest rates of dicamba (560, 1121, 2242 g ae h^{-1}) and the highest rate of 2,4-D (2242 g ae h^{-1}). Palmer amaranth height did not follow this trend, with the greatest reduction in height (0, 8 cm) found only in the highest rates of dicamba (1121, 2242 g ae h^{-1}). The least reduction in treated Palmer amaranth biomass (309 g m^{-2}), density (243 plants m^{-1}), and height (60 cm) all occurred with the lowest rate of 2,4-D (140 g ae h^{-1}). Palmer amaranth biomass reduction was greater with labelled POST use rates of dicamba (560 g ae ha^{-1}) than for the labelled POST use rate of 2,4-D (1121 g ae ha^{-1}) at 40 and 97 g m^{-2}, respectively. However, there was no difference in reduction of density (52 and 103 plants m^{-2}) and height (12 and 21 cm) with labelled POST use rates of dicamba (560 g ae ha^{-1}) or 2,4-D (1121 g ae ha^{-1}). Overall, Palmer amaranth biomass, density and height measurements followed the same trends that were observed in visual herbicide ratings.

Common waterhemp

Visual ratings

The greatest levels of common waterhemp control achieved were 99% and 92%, and were provided by the highest rates (2242 g ae ha^{-1}) of both dicamba and 2,4-D, respectively (Table 2.5). The labelled POST rate of 2,4-D (1121 g ae ha^{-1}) provided 59% common waterhemp control, and was greater than the 45% common waterhemp control that was achieved with the labelled POST rate of dicamba (560 g ae ha^{-1}). The labelled PRE rate of dicamba (1121 g ae ha^{-1}) provided 77% common waterhemp control, which was the greatest level of common waterhemp control that was achieved with any labelled rate of either dicamba or 2,4-D. It is possible that common waterhemp control was compromised by high densities (240 plants m^{-2}) and spray coverage issues. No other rate of dicamba or 2,4-D provided greater than 26% control of common waterhemp. Across all rates tested, orthogonal contrast ($P = <0.0001$) confirm that dicamba provided a greater level of common waterhemp control than 2,4-D, achieving 53% compared to 39%, respectively (Table 2.3). Comparing dicamba and 2,4-D across rates could put 2,4-D at a disadvantage because of the way the rates are structured.

Biomass, Density, and Height

The greatest quantity of common waterhemp biomass (157 g m^{-2}), density (244 plants m^{-2}), and height (44 cm) were found in the non-treated weedy check (Table 2.6). The greatest reduction in common waterhemp biomass (0 and 10 g m^{-2}) occurred with the highest rates (2242 g ae ha^{-1}) of both dicamba and 2,4-D. The greatest reductions in common waterhemp density (0, 8, and 33 plants m^{-2}) occurred with the two highest rates (1121 and 2242 g ae ha^{-1}) of dicamba and the highest rate (2242 g ae ha^{-1}) of 2,4-D. Common waterhemp height varied from these trends, with the greatest reduction in height (0 cm) from the highest rate (2242 g ae ha^{-1}) of dicamba. The least reduction in common waterhemp biomass (73, 86, and 86 g m^{-2}), density (175, 189, and 201 plants m^{-2}), and height (25 and 30 cm) occurred with the lowest rates (140 g and 280 ae ha^{-1}) of dicamba and 2,4-D. Common waterhemp biomass (37 and 65 g m^{-2}) and density (70 and 122 plants m^{-2}) reductions were greater with labelled POST use rates of 2,4-D (1121 g ae ha^{-1}) than with dicamba (560 g ae ha^{-1}). However, there were no differences in the labelled POST use rates of dicamba (560 g ae ha^{-1}) or 2,4-D (1121 g ae ha^{-1}) in regards to common waterhemp height. Overall, common waterhemp biomass, density and height measurements followed similar trends to visual weed control ratings.

CONCLUSIONS

Overall, dicamba provided better Palmer amaranth and common waterhemp control than 2,4-D across all rates and sites evaluated. In this experiment, no labelled POST field use rate of either herbicide in traited soybean provided more than 73% control of either amaranthus spp. Based on the results of this experiment, both dicamba and 2,4-D should be part of an integrated weed management program, and should be applied at the highest labelled rates on Palmer amaranth and common waterhemp that are <10 cm in height to maximize weed control (Norsworthy et al. 2012, Swanton and Weise 1991). Furthermore, one herbicide site of action is never a good resistance management or control strategy for Palmer amaranth, common waterhemp or any other weed species (Evans et al. 2015). Rotation of crop, herbicide, herbicide mixture, and cultural practices should be implemented to prevent herbicide resistance (Shoup

2000, Valverde and Itoh 2001). Finally, proper stewardship is extremely important when implementing either dicamba or 2,4-D traited cropping systems and herbicides, because these chemistries are very important in many other cropping systems (i.e. corn, grain sorghum, and fallow). The development of dicamba or 2,4-D resistance in currently susceptible weed species as a result of intensified use in traited soybean would certainly affect the ability to control broadleaf weeds in other cropping systems.

TABLES

Table 2.1. Herbicides, rates, trade name, and manufacturer for all treatments.

Herbicide	Rates (g ae ha^{-1})	Trade Name	Manufacturer	Location
Dicamba	140 280 560 1121 2242	Xtendimax with VaporGrip	Monsanto Company	St. Louis, MO
2,4-D	140 280 560 1121 2242	Enlist One	Dow AgroSciences LLC	Indianapolis, IN

Table 2.2. Palmer amaranth control at Manhattan, KS in 2017.[a,b]

	Palmer amaranth control 4WAT	
Rate (g ae ha^{-1})	Dicamba	2,4-D
	%	
140	25e	7f
280	43d	9f
560	73b	23e
1121	94a	52c
2240	99a	79b

[a] Abbreviations: WAT, weeks after treatment**.**
[b] Means with the same letter are not significantly different according to Fisher's Protected LSD ($\alpha = 0.05$).

Table 2.3. Orthogonal contrasts of herbicide treatments for Palmer amaranth and common waterhemp 4 WAT at Manhattan and Ottawa, KS.[a,b]

	Manhattan	Ottawa
Orthogonal Contrast[c]	Palmer amaranth 4WAT	Common waterhemp 4WAT
Dicamba treatments vs. 2,4-D treatments	68 vs 35 ****	53 vs. 39 ****

[a] Abbreviation: WAT, weeks after treatment.
[b] % weed control 4 weeks after treatment (WAT).
[c] Means of contrast at ****$P = \leq 0.0001$

Table 2.4. Palmer amaranth biomass, density, and height at Manhattan KS in 2017.[a]

Herbicide	Rate	Biomass	Density	Height
	(g ae ha^{-1})	(g m^{-2})	(m^{-2})	(cm)
Dicamba	140	155c	170cd	30d
Dicamba	280	97b	131cd	19c
Dicamba	560	40a	52ab	12bc
Dicamba	1121	1a	1a	8ab
Dicamba	2242	0a	0a	0a
2,4-D	140	309e	243e	60f
2,4-D	280	212d	183de	50e
2,4-D	560	160cd	161cd	37d
2,4-D	1121	97b	103bc	21c
2,4-D	2242	39a	29a	15bc
Non-treated weedy check	0	537f	325f	99g

[a] Means with the same letter are not significantly different according to Fisher's Protected LSD (α = 0.05).

Table 2.5. Common waterhemp control at Ottawa, KS in 2017.[a,b]

Rate (g ae ha^{-1})	Common waterhemp control 4WAT	
	Dicamba	2,4-D
	%	
140	19ef	6g
280	25e	13fg
560	45d	26e
1121	77b	59c
2240	99a	92a

[a] Abbreviations: WAT, weeks after treatment.

[b] Means with the same letter are not significantly different according to Fisher's Protected LSD (α = 0.05).

Table 2.6. Common waterhemp biomass, density, and height at Ottawa, KS in 2017.[a]

Herbicide	Rate	Biomass	Density	Height
	(g ae ha^{-1})	(g m^{-2})	(m^{-2})	(cm)
Dicamba	140	86f	175de	20cd
Dicamba	280	66de	132cd	19c
Dicamba	560	65de	122c	16c
Dicamba	1121	29b	33ab	11b
Dicamba	2242	0a	0a	0a
2,4-D	140	86f	201ef	30e
2,4-D	280	73ef	189e	25de
2,4-D	560	50cd	133cd	19c
2,4-D	1121	37bc	70b	16c
2,4-D	2242	10a	8a	8b
Non-treated weedy check	0	157g	244f	44f

[a] Means with the same letter are not significantly different according to Fisher's Protected LSD (α = 0.05).

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