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Interaction of dicamba, fluthiacet-methyl, and glyphosate for control of velvetleaf (*Abutilon theophrasti*) in dicamba/glyphosate–resistant soybean

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Abstract

Velvetleaf is an economically important weed in agronomic crops in Nebraska and the United States. Dicamba applied alone usually does not provide complete velvetleaf control, particularly when velvetleaf is taller than 15 cm. The objectives of this experiment were to evaluate the interaction of dicamba, fluthiacet-methyl, and glyphosate applied alone or in a mixture in two- or three-way combinations for velvetleaf control in dicamba/glyphosate–resistant (DGR) soybean and to evaluate whether velvetleaf height (≤12 cm or ≤20 cm) at the time of herbicide application influences herbicide efficacy, velvetleaf density, biomass, and soybean yield. Field experiments were conducted near Clay Center, NE in 2019 and 2020. The experiment was arranged in a split-plot with velvetleaf height (≤12 cm or ≤20 cm) as the main plot treatment and herbicides as subplot treatment. Fluthiacet provided ≥94% velvetleaf control 28 d after treatment (DAT) and ≥96% biomass reduction regardless of application rate or velvetleaf height. Velvetleaf control was 31% to 74% at 28 DAT when dicamba or glyphosate was applied alone to velvetleaf ≤20 cm tall compared with 47% to 100% control applied to ≤12-cm-tall plants. Dicamba applied alone to ≤20-cm-tall velvetleaf provided <75% control and <87% biomass reduction 28 DAT compared with ≥90% control with dicamba at 560 g ae ha^{-1} + fluthiacet at 7.2 g ai ha^{-1} or glyphosate at 1,260 g ae ha^{-1}. Dicamba at 280 g ae ha^{-1} + glyphosate at 630 g ae ha^{-1} applied to ≤20-cm-tall velvetleaf resulted in 86% control 28 DAT compared with the expected 99% control. The interaction of dicamba + fluthiacet + glyphosate was additive for velvetleaf control and biomass reduction regardless of application rate and velvetleaf height.

Introduction

Velvetleaf is an invasive weed native to China (Sattin et al. 1992). It was introduced to North America in the 17th century primarily for fiber production (Spencer 1984). Velvetleaf is a self-pollinated species, and a single plant can produce up to 17,000 large, hard-coated seeds that may persist up to 50 yr in the soil and emerge throughout the crop growing season when conditions are favorable (Lueschen and Anderson 1980; Warwick and Black 1988). Toole and Brown (1946) reported up to 48% viability of velvetleaf seeds after 39 yr of seed burial. Velvetleaf seed viability after 17 yr of burial was reported at 25% and 35% in eastern and western Nebraska, respectively (Burnside et al. 1996). The allelopathic effect of velvetleaf plant extract on seed germination and seed root elongation was reported in soybean (Bhowmik and Doll 1982, Colton and Einhellig 1980), corn (*Zea mays* L.) (Bhowmik and Doll 1982), alfalfa (*Medicago sativa* L.) (Gressel and Holm 1964), radish (*Raphanus sativus* L.) (Gressel and Holm 1964), turnip [*Rapistrum rugosum* (L.) All.] (Elmore 1980; Gressel and Holm 1964), and cress (*Lepidium sativum* L.) (Sterling et al. 1987).

Velvetleaf is a highly competitive weed that can reach up to 2.5 m height depending on growing conditions and competition from crops and weeds (Warwick and Black 1988). Its large canopy architecture and aggressive growth potential enable it to compete for light with most agronomic crops (Bazzaz et al. 1989). Eaton et al. (1976) reported up to 66% soybean yield loss with season-long interference of velvetleaf at a density of 130 to 240 plants m^{-2}. Hagood et al. (1980) reported that velvetleaf reduced soybean yield and leaf area index due to early-season competition when velvetleaf and soybean emerged at the same time. Munger et al. (1987) reported 41% to 47% soybean yield loss when velvetleaf at a density of 5 plants m^{-2} was allowed to coexist with soybean throughout the growing season. Therefore, management of velvetleaf is required to avoid crop yield loss and allelopathic effects.

The use of dicamba for POST broadleaf weed control in dicamba/glyphosate–resistant (DGR) soybean has increased significantly since 2017. Dicamba can control 120 annual, 19

Figure 1. Velvetleaf escape after dicamba applied POST in dicamba/glyphosate–resistant soybean in south central Nebraska (Photo credit: Amit Jhala).

biennial, and 65 perennial broadleaf weeds (Anonymous 2020). Growers rely on dicamba for POST broadleaf weed control, including control of glyphosate–resistant Palmer amaranth (*Amaranthus palmeri* S.Watson) in DGR soybean (De Sanctis et al. 2021); however, velvetleaf escape has been observed where dicamba was the only herbicide applied POST (Figure 1). Murphy and Lindquist (2002) reported poor control of velvetleaf with dicamba at 318 g ae ha^{-1} under field conditions. Hart (1997) reported 87% velvetleaf biomass reduction with dicamba at 140 g ae ha^{-1} + halosulfuron-methyl at 9 g ai ha^{-1}. Herbicide efficacy can be affected by velvetleaf plant height. Knezevic et al. (2009) reported 84% and 68% velvetleaf control with glyphosate at 1,059 g ae ha^{-1} when plants were 12 cm and 25 cm tall, respectively, at the time of glyphosate application. Ganie and Jhala (2021) reported velvetleaf density of 1 plant m^{-2} with glyphosate at 1,060 g ae ha^{-1} applied to 8- to 12-cm-tall plants compared with 7 plants m^{-2} in the nontreated control.

Velvetleaf has been listed on the dicamba label (Anonymous 2020); however, control is variable and partial when plants are taller than 15 cm at dicamba application (Figure 1). Although glyphosate-resistant velvetleaf has not been confirmed, variable response of velvetleaf to glyphosate has been reported in several states in the Midwest (Hartzler and Battles 2001; Krausz et al. 1996; Robinson et al. 2012). Waltz et al. (2004) reported that the efficacy of glyphosate on velvetleaf varies with the application time of day: for example, glyphosate at 840 g ae ha^{-1} applied before sunrise, at midday, and after sunset provided 69%, 100%, and 37% velvetleaf control, respectively, in a field study in Nebraska. Feng et al. (2000) reported that the greatest uptake of glyphosate in velvetleaf occurred within 24 h after treatment, so weather conditions after application can affect glyphosate uptake and efficacy. In contrast, velvetleaf is very sensitive to fluthiacet-methyl (Anonymous 2011). Barnes et al. (2020) reported that herbicide programs that included fluthiacet-methyl provided greater than 98% control of velvetleaf in popcorn [*Zea mays* L. var. *everta* (Sturtev.) L.H. Bailey]. Similarly, Sarangi and Jhala (2018) reported 97% control of velvetleaf with fluthiacet-methyl at 5 g ai ha^{-1} applied when velvetleaf was 12 cm tall in conventional soybean.

It is likely that growers will mix dicamba with glyphosate and/or fluthiacet for effective control in DGR soybean because of the partial control of velvetleaf with dicamba alone; however, their interaction effect for velvetleaf control is not known. Harre et al. (2018) reported antagonistic interactions of glyphosate + dicamba in which glyphosate at 840 g ae ha^{-1} + dicamba at 50 g ae ha^{-1} resulted in 79% glyphosate-resistant giant ragweed (*Ambrosia trifida* L.) control compared with 91% estimated control based on Colby's analysis. Ou et al. (2018) reported 45% control of dicamba/glyphosate–resistant kochia [*Bassia scoparia* (L.) A.J.Scott] with glyphosate at 840 g ae ha^{-1} compared with 30% control when glyphosate was mixed with dicamba at 280 g ae ha^{-1} in a greenhouse study. The same study reported that glyphosate translocation in treated leaves was reduced when glyphosate was mixed with dicamba in both glyphosate/dicamba–resistant and susceptible kochia compared to glyphosate applied alone.

Scientific literature is not available about the interaction of dicamba, glyphosate, and/or fluthiacet for controlling velvetleaf. Therefore, the objectives of this study were (1) to determine the interaction of dicamba, fluthiacet-methyl, and/or glyphosate applied alone or in mixture at higher and lower labeled rates on velvetleaf control, density, and biomass in DGR soybean, and (2) to evaluate whether velvetleaf height (≤12 cm or ≤20 cm) at the time of herbicide application influences efficacy and the effect on velvetleaf control, density, biomass, and DGR soybean yield.

Materials and Methods

Site Description

A field study was conducted at the University of Nebraska Lincoln's South Central Agricultural Laboratory, near Clay Center, NE (40.5752°N, 98.1428°W) during the 2019 and 2020 growing seasons. The soil texture at the research site was Hastings silt loam (montmorillonitic, mesic, Pachic Argiustolls; 17% sand, 58% silt, and 25% clay) with a pH of 6.5 and 3.0% organic matter. The previous crop at the research site was soybean, and no fertilizers were applied. Glufosinate at 590 g ai ha^{-1} + ammonium sulfate 3% v/v was applied 3 wk before planting DGR soybean at the research site for control of winter annual weeds such as horseweed [*Conyza canadensis* (L.) Cronquist] and henbit (*Lamium amplexicaule* L.) during both years.

Experimental Design and Treatments

The treatments were arranged in a split-plot design with four replications; the main plot consisted of velvetleaf heights (≤12 cm or ≤20 cm), and the subplot consisted of herbicide treatments. A nontreated control was included for comparison. Herbicides applied in this study included dicamba (XtendiMax®; Bayer Crop Science, St. Louis, MO 63167), glyphosate (Roundup PowerMax®; Bayer Crop Science, St. Louis, MO 63167), and fluthiacet-methyl (Cadet®; FMC Corp., Philadelphia, PA 19104) applied alone or in a two- or three-way mixture (Table 1).

Dicamba/glyphosate–resistant soybean (S29 K3X; Syngenta®, Greensboro, NC 27409) was planted on May 13 in 2019 and May 15 in 2020 at 345,000 seeds ha^{-1} with 76.2 cm between rows and 3 to 4 cm deep. Herbicide applications were made using a handheld CO_2-pressurized backpack sprayer equipped with AIXR 110015 flat-fan nozzles (TeeJet® Technologies, Spraying Systems Co., Wheaton, IL 60187) spaced 51 cm apart and calibrated to deliver 140 L ha^{-1} at 276 kPa at a constant speed of 4.8 km h^{-1}. Dicamba-containing treatments were applied with TTI 11005 flat-fan nozzles (TeeJet® Technologies). Herbicides were applied when velvetleaf was ≤12 cm tall on June 12 and June 18 in 2019 and 2020, respectively, or when velvetleaf was ≤20 cm tall on June 20 in 2019 and June 28 in 2020. The soybean growth stages at the time of application were V4 and V6 in 2019 and V5 and R1 in 2020 for early and late applications, respectively.

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Table 1. List of herbicide products, rates, and adjuvants used to evaluate the interaction of dicamba, fluthiacet-methyl, and glyphosate for velvetleaf control in dicamba/glyphosate–resistant soybean in field experiments conducted at South Central Agriculture Laboratory, near Clay Center, NE, in 2019 and 2020.[a]

Herbicide [b]	Rate	Adjuvants
	g ae/ai ha^{-1}	
Dicamba	560	DRA (Intact®) 0.5% (v/v) + Class Act® Ridion® 1% (v/v)
Dicamba	280	DRA (Intact®) 0.5% (v/v) + Class Act® Ridion® 1% (v/v)
Fluthiacet	7.2	AMS 3% (v/v) + COC 0.5% v/v
Fluthiacet	4.8	AMS 3% (v/v) + COC 0.25% v/v
Glyphosate	1,260	AMS 3% (v/v) + NIS 0.25% (v/v)
Glyphosate	630	AMS 3% (v/v) + NIS 0.25% (v/v)
Dicamba +fluthiacet	560 + 1,260	DRA (Intact®) 0.5% (v/v) + Class Act® Ridion®1% (v/v)
Dicamba + fluthiacet	280 + 630	DRA (Intact®) 0.5% (v/v) + Class Act® Ridion® 1% (v/v)
Dicamba + glyphosate	560 +7.2	DRA (Intact®) 0.5% (v/v) + Class Act® Ridion® 1% (v/v)
Dicamba + glyphosate	280 + 4.8	DRA (Intact®) 0.5% (v/v) + Class Act® Ridion® 1% (v/v)
Fluthiacet + glyphosate	7.2 + 1,260	AMS 3% (v/v) + NIS 0.25% (v/v)
Fluthiacet + glyphosate	4.8 + 630	AMS 3% (v/v) + NIS 0.25% (v/v)
Dicamba + fluthiacet + glyphosate	560 + 7.2 + 1,260	DRA (Intact®) 0.5% (v/v) Class Act® Ridion® 1% (v/v)
Dicamba + fluthiacet + glyphosate	280 + 4.8 + 630	DRA (Intact®) 0.5% (v/v) + Class Act® Ridion® 1% (v/v)

[a]Each herbicide was applied when velvetleaf was ≤12 cm or ≤20 cm. See text for details.
[b]Abbreviations: AMS, ammonium sulfate (Amsol; Winfield Solutions LLC, St Paul, MN); COC, crop oil concentrate (Agri-Dex®; Helena Chemical Co., Collierville, TN); DRA, drift-reducing agent (Intact™; Precision Laboratories LLC, Waukegan, IL); NIS, nonionic surfactant (Induce®; Helena Chemical Co., Collierville, TN); Class Act® Ridion® (Winfield Solutions LLC, St Paul, MN).

Data Collection

Control of velvetleaf was assessed visually at 14, 28, and 56 DAT based on a scale of 0% to 100%, with 0% representing no control and 100% representing complete control. At 15 d after each application, a 1-m^2 quadrant was randomly placed between the middle two soybean rows within the corresponding plot, and velvetleaf density and biomass were collected. Soybean injury was assessed on a scale of 0% to 100%, with 0% representing no injury and 100% representing plant death at 7, 14, and 28 DAT. Aboveground biomass was obtained by clipping plants at the soil level, drying them in paper bags at 65 C for 10 d until they had reached a constant mass, and then weighing them. Velvetleaf biomass reduction was calculated using the formula:

$$VBR(\%) = 100 \times (1 - P/C) \qquad [1]$$

where VBR is velvetleaf biomass reduction percentage relative to the nontreated control, P is the treatment plot dry weight, and C is the dry weight of the nontreated control plot. Soybean yield was harvested using a plot combine from the center two rows and corrected to 13% moisture content in 2020. A severe hailstorm at the R6 soybean growth stage resulted in significant soybean injury and pod loss with yield losses up to 60% to 70%; therefore, plots were not harvested for soybean grain yield in 2019.

Statistical Analysis

Data were subjected to ANOVA to test for significance. Replications were treated as a random effect and year, velvetleaf height, and herbicide treatments as fixed effects. Soybean yield data were subjected to ANOVA; however, year effect was not included as a fixed effect because of the availability of only 1 yr of data. Fisher's Protected LSD test was used to separate means at $\alpha = 0.05$. Statistical analysis was performed in R utilizing the base packages (R Core Team 2019). Velvetleaf control, biomass, and density data were square root-transformed before analysis to improve the homogeneity of variance and normality of the residuals; however, back-transformed mean values are presented based on interpretation from the transformed values.

A Colby analysis was conducted to evaluate the nature of herbicide interactions. Expected values for two-way herbicide mixtures were calculated using the equation (Colby 1967):

$$E = (X + Y) - (XY/100) \qquad [2]$$

where E is the expected velvetleaf control or biomass reduction with application of herbicide A + B in a mixture, and X and Y are the observed velvetleaf control or biomass reduction with the application of herbicide A and B, respectively. Expected values for three-way herbicide mixtures were calculated using the equation (Colby 1967):

$$E = (X + Y + Z) - \frac{(XY + XZ + YZ)}{100} + \frac{XYZ}{10,0000} \qquad [3]$$

where E is the expected velvetleaf control or biomass reduction with application of herbicide A + B + C in a mixture, and X, Y, and Z are the observed velvetleaf control or biomass reduction with the application of herbicide A, B, and C, respectively. The expected and observed velvetleaf control or biomass reduction values were subjected to t-tests to determine whether means differed. The herbicide mixture was considered antagonistic if the expected mean was significantly greater than the observed mean, and an herbicide mixture was considered synergistic if the expected mean was significantly lower than the observed mean. The nature of the herbicide mixture was considered additive when means were not significantly different (Colby 1967).

Results and Discussion

The interaction was significant for velvetleaf height-by-herbicide treatment for velvetleaf control estimates, density, and biomass reduction; therefore, treatment means are presented within each velvetleaf height (≤12 cm or ≤20 cm).

Velvetleaf Control

Dicamba applied at 280 g ae ha^{-1} controlled velvetleaf 43% and 47% compared with 86% and 89% control at 560 g ae ha^{-1} 14 and 28 DAT, respectively, when plants were ≤12 cm tall

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(Table 2). Fluthiacet or glyphosate applied alone or in a mixture regardless of application rate provided 99% to 100% control of velvetleaf. Dicamba at 280 g ae ha^{-1} + glyphosate at 630 g ae ha^{-1} controlled velvetleaf 87% and 86% 14 and 28 DAT, respectively. The expected velvetleaf control based on Colby's analysis in this treatment mixture was 98% and 99% at 14 and 28 DAT, respectively, indicating 11% and 13% less velvetleaf control (Table 2). The three-way mixture of dicamba + fluthiacet + glyphosate controlled velvetleaf 100% regardless of application rate 14 and 28 DAT; thus, the interaction was additive. Jha et al. (2020) reported 75% control with dicamba at 560 g ae ha^{-1} + glyphosate at 1,025 g ae ha^{-1} applied to 8-cm-tall velvetleaf plants.

At 56 DAT, dicamba at 280 g ae ha^{-1} provided 66% velvetleaf control compared to 74% control with dicamba at 560 g ae ha^{-1} without difference between them (Table 2). Dicamba + glyphosate at the lower labeled rate provided 82% velvetleaf control (10% less than expected) compared to 96% control with the higher labeled rate 56 DAT. Dicamba + fluthiacet controlled velvetleaf 90% (7% to 9% less than expected) regardless of the application rate 56 DAT. It must be noted that the Colby's equation is most accurate when observed values are around 50%, because this approximates the level at which the dose–response curves deviate least from linearity (Colby 1967). The three-way mixture of dicamba, fluthiacet, and glyphosate at the lower rate provided 90% velvetleaf control (9% less than expected) compared to 97% control with the higher rates (Table 2).

Velvetleaf control was reduced with dicamba or glyphosate applied to ≤20-cm-tall plants compared with ≤12-cm-tall plants (Table 2). Dicamba at 280 g ae ha^{-1} controlled velvetleaf 34% and 31% 14 and 28 DAT compared to 75% and 74% control with dicamba at 560 g ae ha^{-1}, respectively (Table 2). Similarly, glyphosate at 630 g ae ha^{-1} controlled velvetleaf 43% and 46% compared to 89% and 93% control with glyphosate at 1,260 g ae ha^{-1} at 14 and 28 DAT, respectively. Thus, a higher rate of glyphosate can improve efficacy for velvetleaf control, particularly when plants are ≥12 cm tall. Similarly, Hartzler and Battles (2001) reported 46% to 86% velvetleaf survival with glyphosate at 420 g ae ha^{-1} compared to 13% to 37% survival with glyphosate at 840 g ae ha^{-1}.

Fluthiacet at 4.8 or 7.2 g ai ha^{-1} controlled velvetleaf 94% to 99% regardless of the application rate at 14 and 28 DAT (Table 2), indicating a higher sensitivity of velvetleaf to fluthiacet. Dicamba + fluthiacet provided similar velvetleaf control (82% to 90%) regardless of the application rate 14 and 28 DAT; however, a 9% to 17% reduction in velvetleaf control was observed compared to the expected control (95% to 99%). Dicamba + glyphosate at the lower rate provided 57% and 63% velvetleaf control compared to 91% and 92% control with the higher rate at 14 and 28 DAT, respectively (Table 2). Thus, higher rates of this herbicide mixture improved velvetleaf control. Similarly, Meyer et al. (2015) reported 78% to 99% velvetleaf control when 15- to 20-cm-tall plants were sprayed with dicamba (560 g ae ha^{-1}) + glyphosate (867 g ae ha^{-1}). In contrast, fluthiacet + glyphosate controlled velvetleaf 93% to 100% regardless of the application rate. Further, dicamba + fluthiacet + glyphosate controlled velvetleaf 87% to 100% and was comparable with the expected control of 96% to 100% (Table 2). Thus, this three-way mixture can be applied in DGR soybean for control of velvetleaf as well as other broadleaf and grass weeds. In addition, the three-way mixture includes herbicides with three distinct sites of action that reduce changes in individual herbicide selection pressure.

Table 2. Velvetleaf control (observed and expected) at 14, 28, and 56 d after treatment (DAT) in dicamba/glyphosate–resistant soybean in field experiments conducted at South Central Agriculture Laboratory near Clay Center, NE, in 2019 and 2020. Herbicides were applied when velvetleaf was ≤12 cm or ≤20 cm tall.

		Control of velvetleaf ≤12 cm tall[a,b]						Control of velvetleaf ≤20 cm tall[a,b]					
		14 DAT		28 DAT		56 DAT		14 DAT		28 DAT		56 DAT	
Herbicide	Rate	Observed	Expected	Observed	Expected	Observed	Expected	Observed	Expected	Observed	Expected	Observed	Expected
	g ae/ai ha^{-1}	%											
Nontreated control	–	–	–	–	–	–	–	–	–	–	–	–	–
Dicamba	560	86 c	–	89 c	–	74 c	–	75 d	–	74 d	–	86 ab	–
Fluthiacet	7.2	100 a	–	100 a	–	91 a	–	98 ab	–	97 a	–	94 ab	–
Glyphosate	1,260	100 a	–	100 a	–	97 a	–	89 abc	–	93 abc	–	97 a	–
Dicamba + fluthiacet	560 + 7.2	100 a	100	100 a	100	90 ab	97* [c]	82 cd	99*	90 abc	99*	96 ab	99
Dicamba + glyphosate	560 + 1,260	100 a	100	98 ab	100	96 a	99	91 abc	97*	92 abc	98*	86 ab	99*
Fluthiacet + glyphosate	7.2 + 1,260	100 a	97	100 a	100	91 a	100*	100 a	99	100 a	99	96 ab	100
Dicamba + Fluthiacet + glyphosate	560 + 7.2 + 1,260	100 a	100	100 a	100	97 a	97	99 ab	99	99 ab	100	99 a	99
Dicamba	280	43 d	–	47 d	–	66 c	–	34 f	–	31 f	–	45 d	–
Fluthiacet	4.8	100 a	–	100 a	–	97 a	–	99 ab	–	94 abc	–	82 b	–
Glyphosate	630	99 ab	–	99 ab	–	92 a	–	43 f	–	46 e	–	90 ab	–
Dicamba + fluthiacet	280 + 4.8	96 b	100	95 b	100	90 ab	99*	86 bcd	95*	86 c	95*	86 ab	90
Dicamba + glyphosate	280 + 630	87 c	98*	86 c	99*	82 b	92*	57 e	63	64 d	63	67 c	94*
Fluthiacet + glyphosate	4.8 + 630	100 a	100	100 a	100	96 a	99	93 abc	96	94 abc	96	94 ab	98
Dicamba + fluthiacet + glyphosate	280 + 4.8 + 630	100 a	100	100 a	100	90 ab	99*	87 abcd	96	89 bc	96	87 ab	96

[a]Means presented within the same column with no common letter(s) are significantly different according to Fisher's Protected LSD test.
[b]Expected values were determined by the Colby's equation (Colby 1967).
[c]Asterisks indicate significantly different from the observed value ($P < 0.05$) as determined by *t*-test, indicating antagonistic interactions of herbicides applied in a mixture based on Colby's equation.

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Table 3. Herbicide treatment effects on velvetleaf density and biomass reduction (expected and observed) at 14 d after treatment (DAT) in dicamba/glyphosate–resistant soybean in field experiments conducted at South Central Agriculture Laboratory, near Clay Center, NE, in 2019 and 2020. Herbicides were applied when velvetleaf was ≤12 cm or ≤20 cm tall.

		Velvetleaf ≤12 cm tall[a]			Velvetleaf ≤20 cm tall[a]		
			Biomass reduction			Biomass reduction	
Herbicide treatment	Rate	Density	Observed	Expected[b]	Density	Observed	Expected[b]
	g ae/ai ha^{-1}	No. plants m^{-2}	%		No. plants m^{-2}	%	
Nontreated control	–	40 a	–	–	60 a	–	–
Dicamba	560	11 c	91 c	–	17 d	86 bc	–
Fluthiacet	7.2	0 d	100 a	–	1 g	99 a	–
Glyphosate	1,260	0 d	100 a	–	8 efg	94 ab	–
Dicamba + fluthiacet	560 + 7.2	0 d	100 a	100	3 fg	94 ab	99*[c]
Dicamba + glyphosate	560 + 1,260	0 d	99 ab	100	10 def	81 c	98*
Fluthiacet + glyphosate	7.2 + 1,260	1 d	100 a	100	0 g	100 a	99
Dicamba + fluthiacet + glyphosate	560 + 7.2 + 1,260	0 d	100 a	100	1 g	99 a	100
Dicamba	280	22 b	70 e	–	43 b	49 d	–
Fluthiacet	4.8	0 d	100 a	–	5f g	96 a	–
Glyphosate	630	1 d	97 ab	–	46 b	40 e	–
Dicamba + fluthiacet	280 + 4.8	3 d	93 bc	100	14 de	84 c	98*
Dicamba + glyphosate	280 + 630	12 c	82 d	99*	32 c	53 d	70*
Fluthiacet + glyphosate	4.8 + 630	0 d	100 a	100	5 fg	93 ab	98
Dicamba + fluthiacet + glyphosate	280 + 4.8 + 630	0 d	100 a	100	6 efg	93 ab	96

[a]Means presented within the same column and with no common letter(s) are significantly different according to Fisher's Protected LSD test.
[b]Expected values were determined by the Colby's equation (Colby 1967).
[c]Asterisks indicate significantly different from the observed value ($P < 0.05$) as determined by *t*-test, indicating antagonistic interactions of herbicides applied in a mixture.

Velvetleaf Density

Fluthiacet applied alone or in a mixture with dicamba and/or glyphosate applied to velvetleaf ≤12 cm tall reduced density to as few as ≤3 plants^{-2} at 14 DAT. Dicamba at 280 g ae ha^{-1} resulted in 22 plants m^{-2} compared to 11 plants m^{-2} when dicamba was applied at 560 g ae ha^{-1}. Thus, the application rate of dicamba can affect velvetleaf density and potentially seed production, because more plants survive the lower rate. Dicamba at 280 g ae ha^{-1} + glyphosate at 630 g ae ha^{-1} resulted in 12 velvetleaf plants m^{-2} compared with complete control and no plants with dicamba at 560 g ae ha^{-1} + glyphosate at 1,260 g ae ha^{-1} (Table 2).

Fluthiacet applied alone or in a mixture with dicamba and/or glyphosate to ≤20-cm-tall plants reduced velvetleaf density in the range of 1 to 14 plants m^{-2} at 14 DAT (Table 3). Dicamba at 280 g ae ha^{-1} or glyphosate at 630 g ae ha^{-1} resulted in 43 to 46 plants m^{-2} compared with 17 plants m^{-2} with dicamba at 560 g ae ha^{-1} and 8 plants m^{-2} with glyphosate at 1,260 g ae ha^{-1}. Dicamba + fluthiacet + glyphosate reduced velvetleaf density in the range of 1 to 6 plants m^{-2} regardless of the application rate (Table 3). Barnes et al. (2020) reported velvetleaf densities of 0 to 5 plants m^{-2} and 1 to 2 plants m^{-2} with dicamba at 560 g ae ha^{-1} and fluthiacet at 7.2 g ai ha^{-1}, respectively, compared with 82 plants m^{-2} in the nontreated control in a 2-yr study conducted for velvetleaf control in popcorn in Nebraska.

Velvetleaf Biomass Reduction

Dicamba at 560 g ae ha^{-1} applied to ≤12-cm-tall plants reduced 91% of velvetleaf biomass compared to 70% reduction with dicamba at 280 g ae ha^{-1} (Table 3). Creech et al. (2016) reported 24% to 33% velvetleaf biomass reduction with dicamba at 140 g ae ha^{-1} when plants were 15 cm tall. Thus, a higher rate of dicamba can improve velvetleaf control and subsequently reduce plant biomass. Dicamba at 280 g ae ha^{-1} + glyphosate at 630 g ae ha^{-1} reduced 82% of velvetleaf biomass compared to 99% reduction with dicamba at 560 g ae ha^{-1} + glyphosate at 1,260 g ae ha^{-1}. In addition, Colby's analysis suggested 99% expected velvetleaf biomass reduction with dicamba + glyphosate applied at lower rates (Table 3). Fluthiacet applied alone or in a mixture with glyphosate and/or dicamba provided 93% to 100% biomass reduction. Barnes et al. (2020) also reported 100% velvetleaf biomass reduction with fluthiacet applied alone at 7.2 g ai ha^{-1} or in mixture with mesotrione at 2.8 g ai ha^{-1} in popcorn.

Dicamba at 280 g ae ha^{-1} applied to ≤20-cm-tall velvetleaf reduced biomass 49% compared to 86% reduction with dicamba at 560 g ae ha^{-1} (Table 3). Furthermore, glyphosate at 630 g ae ha^{-1} reduced velvetleaf biomass 40% compared with 94% reduction at 1,260 g ae ha^{-1}. Waltz et al. (2004) reported 32% to 47% velvetleaf biomass reduction with glyphosate at 840 g ae ha^{-1} applied to 16-cm-tall plants. Furthermore, dicamba + glyphosate at the higher and lower rates resulted in 81% and 53% biomass reduction, respectively; however, expected biomass reduction was 98% and 70%, respectively (Table 3). Therefore, an antagonistic effect was observed in the dicamba + glyphosate mixture for velvetleaf biomass reduction. Recent studies have also reported antagonistic interactions of dicamba + glyphosate mixtures; for example, Huff (2010) reported an antagonistic effect of a dicamba + glyphosate mixture on a wide range of weed species, including prickly sida (*Sida spinosa* L.), pitted morningglory (*Ipomoea lacunosa* L.), large crabgrass [*Digitaria sanguinalis* (L.) Scop.], johnsongrass [*Sorghum halepense* (L.) Pers.], and hemp sesbania [*Sesbania herbacea* (Mill.) McVaugh]. In contrast, Spaunhorst and Bradley (2013) reported that glyphosate–resistant waterhemp (*Amaranthus rudis* J.D. Sauer) biomass reduction shifted from 52% with dicamba at 560 g ae ha^{-1} to 77% when dicamba was mixed with glyphosate at 860 g ae ha^{-1}, indicating that dicamba + glyphosate interaction might be specific to weed species. Fluthiacet reduced biomass 96% to 99% regardless of the application rate; however, dicamba + fluthiacet resulted in 94% to 84% biomass reduction compared with the expected 99% and 98% biomass reduction. In addition, fluthiacet + glyphosate, along with a three-way mixture of dicamba + fluthiacet + glyphosate, were both effective for control of velvetleaf throughout the study and

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Table 4. Herbicide treatment effects on dicamba/glyphosate–resistant (DGR) soybean yield in a field experiment conducted at South Central Agriculture Laboratory, near Clay Center, NE, in 2020. Herbicides were applied when velvetleaf was ≤12 cm or ≤20 cm tall.

Herbicide	Rate	DGR soybean yield	
		Velvetleaf ≤12 cm tall[a]	Velvetleaf ≤20 cm tall[a]
	g ae/ai ha^{-1}	kg ha^{-1}	
Nontreated control	–	1,470 g	1,470 d
Dicamba	560	3,050 b–f	2,920 abc
Fluthiacet	7.2	2,770 ef	2,660 c
Glyphosate	1,260	3,270 a–d	2,670 c
Dicamba + fluthiacet	560 + 7.2	3,530 a	3,480 a
Dicamba + glyphosate	560 + 1,260	3,280 abc	2,800 bc
Fluthiacet + glyphosate	7.2 + 1,260	2,900 c–f	2,790 bc
Dicamba + fluthiacet + glyphosate	560 + 7.2 + 1,260	3,380 ab	3,320 ab
Dicamba	280	2,840 ef	2,740 bc
Fluthiacet	4.8	2,740 ef	2,490 c
Glyphosate	630	2,850 def	2,480 c
Dicamba + fluthiacet	280 + 4.8	3,121 a–e	2,627 c
Dicamba + glyphosate	280 + 630	2,677 f	2,780 bc
Fluthiacet + glyphosate	4.8 + 630	2,631 f	2,515 c
Dicamba + fluthiacet + glyphosate	280 + 4.8 + 630	3,106 a–e	2,438 c

[a]Means presented within the same column with no common letter(s) are significantly different according to Fisher's protected LSD test.

resulted in >93% biomass reduction, slightly less than the expected control of ≥96% (Table 3).

Soybean Yield

No soybean injury was observed from dicamba or glyphosate, as DGR soybean has high-level resistance to both herbicides; however, fluthiacet resulted in 5% to 15% soybean injury 7 and 14 DAT, and no injury 28 DAT (data not shown). Velvetleaf interference with soybean throughout the growing season reduced soybean yield to as low as <1,475 kg ha^{-1} in the nontreated control in 2020 (Table 4). Higher soybean yields were obtained when herbicides were applied to ≤12-cm-tall velvetleaf plants compared to ≤20-cm-tall plants. For example, glyphosate at 1,260 g ae ha^{-1} applied to ≤12- and ≤20-cm-tall velvetleaf plants resulted in 3,267 and 2,671 kg ha^{-1} yield, respectively. Dicamba + fluthiacet at the higher labeled rate provided the highest soybean yields for both velvetleaf application heights and were comparable with several other herbicide programs applied at higher rates, mostly in two-way and/or three-way mixtures (Table 4). Literature about the effect of POST herbicides on soybean yield in competition with velvetleaf is limited. Terra et al. (2007) did not observe corn yield loss due to velvetleaf competition when dicamba was applied at variable rates from 32.8 to 318 g ae ha^{-1}, suggesting that despite velvetleaf's surviving herbicide applications, its competitiveness can be affected by the herbicide and crop grown. Barnes et al. (2020) reported that atrazine/*S*-metolachlor applied PRE provided partial control of velvetleaf and that a POST herbicide was needed to reduce velvetleaf seed production and popcorn yield loss.

Practical Implications

Weed management in no-till soybean production systems in the United States primarily depends on herbicides. The DGR soybean has been adopted rapidly by growers, and the use of dicamba is likely to increase in the future, particularly for management of glyphosate–resistant Palmer amaranth and waterhemp. The results of this study suggest that dicamba applied alone to ≤20-cm-tall velvetleaf provided less than 75% control 28 DAT compared to ≥90% control with dicamba at 560 g ae ha^{-1} + fluthiacet at 7.2 g ai ha^{-1} or glyphosate at 1,260 g ae ha^{-1}. It was evident that velvetleaf is very sensitive to fluthiacet, because it provided ≥94% control and ≥96% biomass reduction regardless of the application rate or velvetleaf height. The interaction of dicamba + fluthiacet + glyphosate mixture was additive for velvetleaf control and biomass reduction. To apply dicamba with fluthiacet, this mixture must be applied before July 1 in DGR soybean because of the dicamba label restriction (Anonymous 2020); however, fluthiacet can also be applied alone up to the full flowering soybean growth stage and is labeled for control of velvetleaf up to 90 cm tall (Anonymous 2011). It must be noted that a mixture of dicamba and fluthiacet would not control grass weeds; therefore, if grass weeds are present along with velvetleaf, glyphosate can be mixed for broad-spectrum weed control in DGR soybean, as the interaction of the three-way mixture was additive. The results of this study conclude that POST herbicides are available for effective control of velvetleaf in DGR soybean. As of 2020, only atrazine-resistant velvetleaf has been reported (Heap 2021); however, herbicides with multiple sites of action should be used to delay the evolution of herbicide-resistant velvetleaf.

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