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Control of velvetleaf (*Abutilon theophrasti*) at two heights with POST herbicides in Nebraska popcorn

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Abstract

Velvetleaf is an economically important weed in popcorn production fields in Nebraska. Many PRE herbicides in popcorn have limited residual activity or provide partial velvetleaf control. There are a limited number of herbicides applied POST in popcorn compared with field corn, necessitating the evaluation of POST herbicides for control of velvetleaf. The objectives of this study were to (1) evaluate the efficacy and crop safety of labeled POST herbicides for controlling velvetleaf that survived *S*-metolachlor/atrazine applied PRE and (2) determine the effect of velvetleaf height on POST herbicide efficacy, popcorn injury, and yield. Field experiments were conducted in 2018 and 2019 near Clay Center, Nebraska. The experiments were arranged in a split-plot design with four replications. The main plot treatments were velvetleaf height (≤15 cm and ≤30 cm) and subplot treatments included a no-POST herbicide control, and 11 POST herbicide programs. Fluthiacet-methyl, fluthiacet-methyl/mesotrione, carfentrazone-ethyl, dicamba, and dicamba/diflufenzopyr provided greater than 96% velvetleaf control 28 d after treatment (DAT), reduced velvetleaf density to fewer than 7 plants m^{-2}, achieved 99% to 100% biomass reduction, and had no effect on popcorn yield. Herbicide programs tested in this study provided greater than 98% control of velvetleaf 28 DAT in 2019. Most POST herbicide programs in this study provided greater than 90% control of up to 15 cm and up to 30 cm velvetleaf and no differences between velvetleaf heights in density, biomass reduction, or popcorn yield were observed, except with topramezone and nicosulfuron/mesotrione 28 DAT in 2018. On the basis of contrast analysis, herbicide programs with fluthiacet-methyl or dicamba provided better control than herbicide programs without them at 28 DAT in 2018. It is concluded that POST herbicides are available for control of velvetleaf up to 30-cm tall in popcorn production fields.

Introduction

Popcorn is grown on nearly 90,000 ha in the United States every year (USDA NASS 2018). States that produce more than 500 ha of popcorn annually include Illinois, Indiana, Iowa, Kansas, Kentucky, Michigan, Nebraska, and Ohio (USDA NASS 2018). Global popcorn sales have increased by an average of 4 million kg each year from 1970 to 2017, with sales of more than 540 million kg in 2017 (Popcorn Board 2019). Nebraska produces the most popcorn of any state in the United States; popcorn is grown on approximately 26,000 ha in Nebraska, producing 167 million kg, which represents 34% of U.S. popcorn production in 2017 (USDA NASS 2018). Popcorn production is normally contracted by the popcorn processor and the farmer (D'Croz-Mason and Waldren 1978; Ziegler 2001). Popcorn growth and development varies from field corn in several ways: Popcorn has shorter and thinner stalks, narrower and more upright leaves, and slower emergence than field corn (Ziegler 2001). Because of these characteristics, popcorn is less competitive with weeds than is field corn (Ziegler 2001).

The majority of popcorn production in the United States is under conservation tillage systems and herbicides are the primary method of weed control (Pike et al. 2002). Weed control is a challenge for popcorn producers because there are fewer herbicide options compared with field corn. For example, herbicide premixes such as isoxaflutole/thiencarbazone (Anonymous 2016a), tembotrione/thiencarbazone (Anonymous 2012), rimsulfuron/mesotrione (Anonymous 2016b), and acetochlor/flumetsulam/clopyralid (Anonymous 2014b, 2014c) are labeled in field corn but not in popcorn. Commercially available popcorn hybrids are not genetically modified, so commonly used POST herbicides in herbicide-resistant field corn, such as glyphosate and/or glufosinate, cannot be used for weed control in popcorn (Fernandez-Cornejo et al. 2014; Ziegler 2001).

Velvetleaf is a large-seeded annual broadleaf weed (Bazzaz et al. 1989) native to China, where it was cultivated as a fiber crop (Sattin et al. 1992). It was introduced to North America in the 17th century for fiber production (DeFelice et al. 1988, Spencer 1984). Velvetleaf is now a major agricultural weed in corn, cotton (*Gossypium hirsutum* L.), soybean [*Glycine max* (L.) Merr.], and sorghum [*Sorghum bicolor* (L.) Moench] production fields in North America (Spencer 1984). A statewide survey conducted in 2015 reported velvetleaf as the fourth most difficult to control weed in Nebraska (Sarangi and Jhala 2018a). Widespread occurrence and seed-bank persistence of velvetleaf contributes to its longevity and long-term success (Warwick and Black 1988). For example, Toole and Brown (1946) reported that velvetleaf buried for 39 yr in Virginian soil had 43% seed viability. A similar study in Nebraska reported 25% and 35% viability in eastern and western Nebraska, respectively, after 17 yr of velvetleaf seed burial (Burnside et al. 1996). Its growth potential and canopy architecture enable velvetleaf to compete for light with most agronomic crops (Bazzaz et al. 1989).

Velvetleaf interference in field corn has been attributed primarily to light competition (Lindquist et al. 1998). Velvetleaf competition in field corn has been reported to result in substantial yield losses. Campbell and Hartwig (1982) reported 70% yield reduction in field corn after 6 weeks of competition. Lindquist et al. (1996) reported yield loss from velvetleaf ranged from 0% to 80%, depending on the year, in Nebraska. Terra et al. (2007) reported variable field corn yield loss due to velvetleaf competition, ranging from 0% to 72% at 20 velvetleaf plants m^{-1} row. Liphadzi and Dille (2006) reported maximum field corn yield losses from velvetleaf competition ranged from 41% to 100%. Werner et al. (2004) reported 37% field corn yield loss from 21 velvetleaf plants m^{-2} in Pennsylvania. Similarly, Scholes et al. (1995) reported 37% yield loss from 24 velvetleaf plants m^{-2} in South Dakota. Soil water level affects competition between velvetleaf with field corn (Vaughn et al. 2007, 2016). Increased field corn populations and velvetleaf that emerge after field corn emergence have resulted in less velvetleaf seed production (Teasdale et al. 1998). Field corn yield loss due to velvetleaf interference has been reported to be greater with higher levels of nitrogen fertilizer (Barker et al. 2006; Bonifas et al. 2005).

Herbicides applied PRE, such as atrazine/fluthiacet-methyl/pyroxasulfone (1,260 g ai ha^{-1}) and acetochlor/clopyralid/flumetsulam (1,190 g ai ha^{-1}), controlled velvetleaf 78% to 90% and 74% to 79%, respectively at 28 d after treatment (DAT) in field corn in Nebraska (Sarangi and Jhala 2018b). Liphadzi and Dille (2006) showed that the competitiveness of surviving velvetleaf in field corn was reduced after isoxaflutole and flumetsulam was applied PRE. Similarly, velvetleaf that survived dicamba, halosulfuron-methyl, or flumiclorac applied POST was less competitive with field corn than velvetleaf in plots not treated with a POST herbicide (Terra et al. 2007). Although velvetleaf plants that survive PRE or POST herbicide applications are likely to be less competitive, seed production from survivors is a concern because they contribute to soil seed bank (Liphadzi and Dille 2006; Murphy and Lindquist 2002; Terra et al. 2007).

Weed height at the time of herbicide application can influence herbicide efficacy (Wiles et al. 1992; Wilkerson et al. 1991). King and Oliver (1992) reported reduced herbicide efficacy as time after weed emergence increased for a number of weed species. Herbicide application to weeds at the proper weed height is a tactic used to delay the evolution of herbicide resistance (Norsworthy et al. 2012). Fluthiacet-methyl (4.8 to 7.2 g ai ha^{-1}) can be applied to velvetleaf until the plants are up to 91 cm tall (Anonymous 2011). The recommended height for broadleaf summer annual weeds is 3 to 8 cm when applying dicamba at rates ranging from 210 to 1,120 g ai ha^{-1} (Anonymous 2018a). There is no information in the scientific literature, to our knowledge, on effect of velvetleaf height on labeled POST herbicide efficacy in popcorn.

Atrazine and *S*-metolachlor are commonly applied in mixture because of their crop safety in yellow and white popcorn (Barnes et al. 2019b). For instance, it was estimated that 99% and 11% of popcorn fields were treated PRE and/or POST with atrazine and *S*-metolachlor, respectively, in 1999 in the United States (Bertalmio et al. 2003). Sarangi and Jhala (2018a) reported in a statewide survey that *S*-metolachlor/atrazine was the third most commonly used PRE herbicide in field corn in eastern Nebraska. *S*-metolachlor/atrazine, applied PRE, is a commonly used herbicide in popcorn production; one concern with its use is that it provides only partial control of velvetleaf (Anonymous 2014a; Taylor-Lovell and Wax 2001). Barnes et al. (2019a) reported that *S*-metolachlor/atrazine (2,470 g ai ha^{-1}) applied PRE reduced velvetleaf density 24% to 0% in 2017 and 2018, respectively. Because of rain and other unexpected events, it can be difficult for growers to apply PRE herbicides. For example, in the 2019 growing season in Nebraska and several other popcorn-producing states, spring was extremely wet. Several growers were able to plant popcorn but were not able to apply PRE herbicide; therefore, they had to rely on POST herbicides for weed control. Herbicide-resistant popcorn has not been developed, so nonselective herbicides that can be used in glyphosate/glufosinate-resistant field corn cannot be used in popcorn. In addition, relatively new premixture herbicides such as atrazine/bicyclopyrone/*S*-metolachlor/ (Anonymous 2017a) and acetochlor/clopyralid/mesotrione (Anonymous 2017b) are labeled to apply PRE in popcorn, but not POST. Often, popcorn growers have to rely on POST herbicides for weed control.

To our knowledge, scientific literature is not available for velvetleaf control in popcorn with POST herbicides. The objectives of our research were (1) to evaluate the efficacy and crop safety of labeled POST herbicides for controlling velvetleaf that survived *S*-metolachlor/atrazine applied PRE in Nebraska popcorn and (2) to determine the effect of velvetleaf height on POST herbicide efficacy, popcorn injury, and yield. We hypothesized the efficacy of POST herbicides available for control of velvetleaf may be reduced when applied to velvetleaf up to 30-cm tall compared with plants up to 15-cm tall.

Materials and Methods

Site Description

Field experiments were conducted at the University of Nebraska-Lincoln, South Central Agricultural Laboratory near Clay Center, NE (40.5752°N, 98.1428°W; 552 m above mean sea level) in 2018 and 2019. The soil type 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. In early spring, the site was disked with a tandem disk at a depth of 10 cm and fertilized with 202 kg ha^{-1} nitrogen in the form of anhydrous ammonia (82-0-0) applied with an anhydrous ammonia coulter on 96-cm spacing.

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Table 1. Herbicide programs for POST control of velvetleaf in popcorn in field experiments conducted at the University of Nebraska, South Central Agricultural Laboratory near Clay Center, NE, in 2018 and 2019.

Herbicide program[a]	Rate	Trade name	Manufacturer	Adjuvant[b]
	g ai ha^{-1}			vol/vol
No-POST herbicide[a]	NA			
Carfentrazone-ethyl	17.5	Aim EC	FMC	NIS 0.25%
Fluthiacet-methyl	7.2	Cadet	FMC	NIS 0.25% + AMS 2.86 kg ai ha^{-1}
Topramezone	24.5	Impact	Amvac	MSO 1.5%
Tembotrione	98	Laudis	Bayer	MSO 1%
Halosulfuron-methyl	52.5	Permit	Gowan	0.5%
Dicamba	560	DiFlexx	Bayer	NIS 0.25% + AMS 2.86 kg ai ha^{-1}
Dicamba/diflufenzopyr	392	Status	BASF	NIS 0.25% + AMS 2.86 kg ai ha^{-1}
Dicamba/tembotrione	597	DiFlexx DUO	Bayer	COC 1%
Fluthiacet-methyl/mesotrione	2.8	Solstice	FMC	NIS 0.25%
Nicosulfuron/mesotrione	118	Revulin Q	Corteva	NIS 0.25%
Dicamba/halosulfuron-methyl	190	Yukon	Gowan	NIS 0.25%

[a]The experimental site was treated with *S*-metolachlor/atrazine at 2,470 g ai ha^{-1} applied PRE, including the no-POST herbicide control plots.
[b]Abbreviations: AMS, ammonium sulfate; COC, crop oil concentrate; MSO, methylated seed oil; NA, not applicable; NIS, nonionic surfactant.

Starter fertilizer ammonium polyphosphate (APP; 10-34-0) was applied in-furrow at 6 kg ha^{-1} during planting.

Treatments and Experimental Design

The treatments were arranged in a split-plot design with four replications. The main plot treatments consisted of two velvetleaf heights (≤15 cm and ≤30 cm tall) and 11 subplot POST herbicide programs (Table 1). A no-POST herbicide control was included for comparison. Plot dimensions were 9-m long by 3-m wide. A yellow popcorn hybrid (VYP 321; Conagra Brands, Chicago, IL 60654) was planted on April 30, 2018, and May 1, 2019, with a row spacing of 76 cm at a depth of 4 cm and a planting density of 89,000 seeds ha^{-1}. *S*-metolachlor/atrazine (Bicep II Magnum; Syngenta Crop Protection, Greensboro, NC 27419) was applied at 2,470 g ai ha^{-1} on May 2, 2018, and May 2, 2019, using a tractor sprayer to treat the entire research site to achieve early-season control of small-seeded weeds (Geier et al. 2009; Grichar et al. 2003; Steele et al. 2005). This PRE herbicide resulted in high survival rate of velvetleaf and low survival rate of other weed species (Anonymous 2014a; Taylor-Lovell and Wax 2001). Except for *S*-metolachlor/atrazine applied PRE, POST herbicides were applied with a CO_2-pressurized backpack sprayer and a boom equipped with five TTI 110015 flat-fan nozzles for treatments included dicamba (TeeJet, Spraying Systems, Wheaton, IL 60189) or five AIXR 110015 flat-fan nozzles spaced 51-cm apart for other herbicide treatments. POST herbicides were applied to velvetleaf plants up to 15 cm tall on June 8 and June 10 in 2018 and 2019, respectively, and to velvetleaf plants up to 30 cm tall on June 22 and June 17 in 2018 and 2019, respectively. Popcorn growth stages when velvetleaf reached up to 15 and up to 30 cm were V6 and V9, respectively, in 2018, and V5 and V8, respectively, in 2019.

Data Collection

Velvetleaf control was assessed visually on a scale of 0% to 100%, with 0% representing no control and 100% representing complete control at 14 and 28 DAT. Popcorn injury was assessed on a scale of 0% to 100%, with 0% representing no injury and 100% representing plant death at 14 and 28 DAT. Velvetleaf densities were assessed from two randomly placed 0.5-m^2 quadrats in each plot at 14 and 28 DAT. Velvetleaf aboveground biomass was assessed from two randomly placed 0.5-m^2 quadrats in each plot at 45 d after POST herbicides were applied. Surviving velvetleaf plants were cut near the soil surface, dried in paper bags at 65 C for 10 d, and dry weight was recorded. Percent biomass reduction compared with that of the no-POST herbicide control was calculated using Equation 1 (Wortman 2014):

$$\%\ \text{Biomass reduction} = [(C - B)/C] \times 100 \qquad [1]$$

where *C* represents the velvetleaf biomass from the no-POST herbicide control plot in the corresponding replication block and *B* represents the biomass of the treatment plots. At popcorn harvest, five velvetleaf plants (if present) from each plot were collected and the number of seed capsules per plant were counted. Popcorn was harvested from the middle two rows with a plot combine and the yields were adjusted to 14% grain moisture content.

Statistical Analysis

Data were subjected to ANOVA in R, version 3.5.1 (R Core Team, 2019), using the base packages and the Agricolae: Statistical Procedures for Agricultural Research Package (Mendiburu 2017). ANOVA was performed using the *sp.plot* (split plot) function where velvetleaf height (≤15 cm or ≤30 cm) was treated as the main plot and POST herbicides were considered the subplot effect. Replications nested within years were considered random effects in the model. ANOVA assumptions of normality and homogeneity of variance were tested (Kniss and Streibig 2018). Improvements in normality were gained for density and biomass data with a logit transformation. Back-transformed data are presented in tables for interpretation. If the random effect of year was significant, data were analyzed with years separated. Treatment means were separated at $P \leq 0.05$ using Fisher protected LSD test. Orthogonal contrast analysis was conducted to compare velvetleaf control between herbicide programs that included fluthiacet-methyl or dicamba, and programs that did not include fluthiacet-methyl or dicamba.

Results and Discussion

Average daily temperatures and precipitation for the 2018 and 2019 growing seasons were similar to the 30-yr average for the experimental site (Figure 1). Year was significant for all measured variables except velvetleaf seed capsules; therefore, data were analyzed separately.

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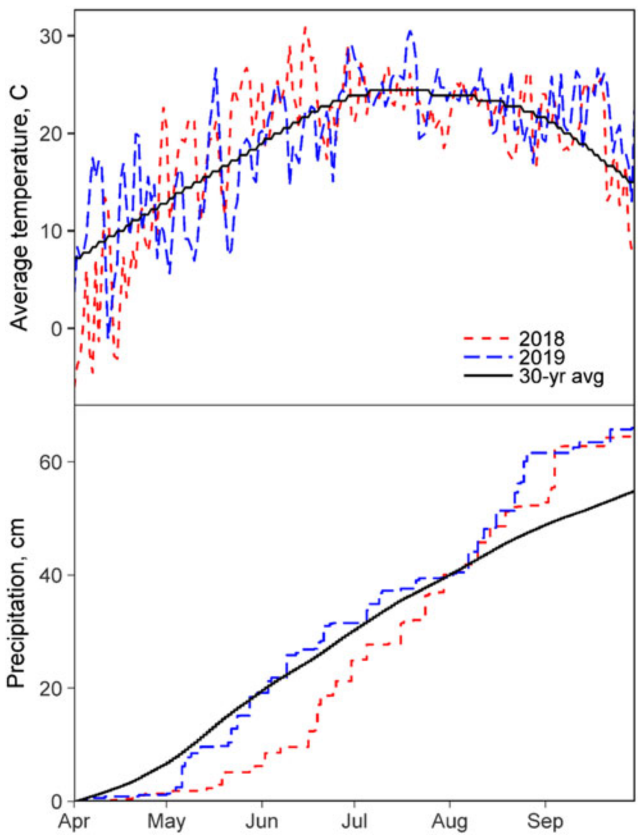

Figure 1. Average daily air temperature and total precipitation during 2018 and 2019 growing seasons compared with the 30-yr average (avg) at the University of Nebraska–Lincoln, South Central Agricultural Laboratory near Clay Center, NE.

Velvetleaf Control

Velvetleaf control 14 DAT varied across years and an interaction between velvetleaf height and herbicide program occurred in both years of the study; however, at 28 DAT in 2019, velvetleaf height did not affect herbicide efficacy (Table 2). Most POST herbicide programs controlled velvetleaf 95% or greater at 14 and 28 DAT regardless of velvetleaf height at application. Cafentrazone, fluthiacet-methyl, dicamba, dicamba/diflufenzophr, and fluthiacet-methyl/mesotrione resulted in 95% or greater control 14 DAT regardless of velvetleaf height at the time of application in 2018 and 2019. Similarly, Barnes et al. (2019b) reported velvetleaf that survived a PRE herbicide was controlled 99% with dicamba/diflufenzopyr, 98% with dicamba/tembotrione, and 95% with fluthiacet-methyl/mesotrione 21 DAT in popcorn. Sarangi and Jhala (2018c) reported velvetleaf that survived flumioxazin/pyroxasulfone applied PRE was controlled 98% 14 DAT with 5 g ai ha^{-1} fluthiacet-methyl applied when velvetleaf was 12-cm tall. Bussan et al. (2001) reported 0% to 7% survival of 5-cm velvetleaf treated with dicamba at 560 g ai ha^{-1} plus 28% nitrogen at 1.25% vol/vol.

Topramezone provided 91% control of up to 15-cm–tall velvetleaf but only 64% control of velvetleaf up to 30-cm tall at 14 DAT in 2018. Topramezone is labeled for control of velvetleaf less than 20-cm tall (Anonymous 2019); therefore, relatively less control of up to 30-cm velvetleaf was expected. In contrast, topramezone resulted in 98% or greater control in 2019 regardless of velvetleaf height. The lower level of velvetleaf control with topramezone in 2018 might have been due to lower-than-average precipitation and higher-than-average maximum daily temperatures in June 2018 compared with June 2019 (Figure 2). When weeds are under stress, herbicide efficacy is reduced. For example, Godar et al. (2015) reported greater control, shorter plants, and higher mortality rate in Palmer amaranth [*Amaranthus palmeri* (S.) Watson] treated with mesotrione at low temperatures (25/15 C day/night) compared with high temperatures (40/30 C day/night) with 85% control obtained with concentrations of 14.9 and 80.8 g ai ha^{-1} at low and high temperatures, respectively. Tembotrione resulted in 80% to 81% control of 12- to 30-cm–tall velvetleaf 14 DAT in 2018.

In 2019, control of velvetleaf up to 15-cm tall was 99% with tembotrione compared with 81% control of velvetleaf up to 30-cm tall. In 2018, application of halosulfuron-methyl resulted in 84% and 90% control of velvetleaf up to 15- and up to 30-cm tall, respectively, 14 DAT. In 2019, halosulfuron provided 99% and 95% control of velvetleaf up to 15- and up to 30-cm tall, respectively, 14 DAT.

In 2018, 88% to 94% control of velvetleaf was achieved with dicamba/tembotrione and 99% in 2019. Similarly, control of velvetleaf at 14 DAT with nicosulfuron/mesotrione (99%) and dicamba/halosulfuron-methyl (96% to 99%) in 2019 was greater than control with nicosulfuron/mesotrione (84% to 92%) and dicamba/halosulfuron-methyl (86% to 90%) in 2018. Orthogonal contrasts indicated that POST herbicide programs with fluthiacet-methyl or dicamba resulted in greater control of velvetleaf than herbicide programs without fluthiacet-methyl or dicamba in 2018 (data not shown). In 2019, herbicide programs with or without fluthiacet-methyl or dicamba resulted in similar control of velvetleaf at 28 DAT.

New dicamba products labeled for use in dicamba-resistant soybean do not allow for ammonium sulfate because it increases dicamba volatility (Zollinger et al. 2016). However, ammonium sulfate is commonly used as a water conditioner and the ammonium increases herbicide absorption and translocation (Zollinger et al. 2016). Mixing ammonium sulfate with dicamba increases dicamba efficacy in redroot pigweed (*Amaranthus retroflexus* L.) and common lambsquarters (*Chenopodium album* L.) (Roskamp et al. 2013). Nebraska Extension recommends that ammonium sulfate not be added to dicamba, to reduce dicamba volatility and subsequent off-target injury (Klein et al. 2018). Ammonium sulfate was added in this study to dicamba and dicamba/diflufenzopyr as recommended on the product labels; therefore, if recommendations to exclude ammonium sulfate from dicamba applications are followed, relatively less control of velvetleaf is expected or warrants investigation.

Velvetleaf control at 28 DAT varied across years. Velvetleaf (≤15 cm tall) control ranging from 80% to 89% was achieved with dicamba/halosulfuron-methyl, halosulfuron-methyl, and tembotrione 28 DAT in 2018. More than 94% control of velvetleaf up to 15-cm tall was achieved with the rest of the herbicide treatments 28 DAT in 2018. Carfentrazone-ethyl applied at 35 g ai ha^{-1} has been reported to provide 98% control of velvetleaf 30 DAT, but it was applied when velvetleaf was not more than 10-cm tall (Durgan et al. 1997). Sarangi and Jhala (2018c) reported 95% control of velvetleaf 28 DAT with 5 g ai ha^{-1} fluthiacet-methyl applied to 12-cm velvetleaf that survived flumioxazin/pyroxasulfone applied PRE.

Dicamba/halosulfuron-methyl, halosulfuron-methyl alone, and nicosulfuron/mesotrione provided 90% to 92% control of velvetleaf up to 30-cm tall 28 DAT in 2018. Schuster et al. (2008) reported 91% to 93% control of 5- to 8-cm–tall velvetleaf with

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Table 2. Comparison of POST herbicide programs for control of velvetleaf up to 15- and up to 30-cm tall in popcorn at 14 and 28 DAT in field experiments conducted at the University of Nebraska, South Central Agricultural Laboratory near Clay Center, NE, in 2018 and 2019.

		Velvetleaf control 14 DAT				Velvetleaf control 28 DAT		
		2018		2019		2018		2019
		Velvetleaf height (cm)[c]						
Herbicide program[a]	Rate[b]	≤15	≤30	≤15	≤30	≤15	≤30	≤15 and ≤30
	g ai ha^{-1}	%						
No-POST herbicide	NA	0 e	0 g	0 b	0 c	0 e	0 f	0 b
Carfentrazone-ethyl	17.5	98 a	98 ab	99 a	99 a	98 a	98 ab	99 a
Fluthiacet-methyl	7.2	99 a	99 a	99 a	99 a	98 a	99 a	99 a
Topramezone	24.5	91 abc	64 f	99 a	98 a	94 ab	69 e	99 a
Tembotrione	98	81 d	80 e	99 a	81 b	80 d	86 d	99 a
Halosulfuron-methyl	52.5	84 cd	90 bcd	99 a	95 a	85 cd	91 bcd	99 a
Dicamba	560	96 a	95 abc	97 a	97 a	98 a	98 ab	99 a
Dicamba/diflufenzopyr	392	98 a	97 ab	99 a	99 a	97 a	99 a	99 a
Dicamba/tembotrione	597	94 ab	88 cde	99 a	99 a	97 a	95 abc	99 a
Fluthiacet-methyl/mesotrione	2.8	99 a	98 ab	99 a	99 a	99 a	98 ab	99 a
Nicosulfuron/mesotrione	118	92 abc	84 de	99 a	99 a	96 a	90 cd	99 a
Dicamba/halosulfuron-methyl	190	86 bcd	90 bcd	99 a	96 a	89 bc	92 bcd	99 a
P value		<0.001		<0.001		<0.001		<0.001

[a]The experimental site was treated with *S*-metolachlor/atrazine 2,470 g ai ha^{-1} applied PRE, including the no-POST control plots.
[b]Abbreviations: DAT, days after treatment; NA, not applicable.
[c]Means presented within the same column with no common letter(s) are significantly different according to Fisher protected LSD (α = 0.05).

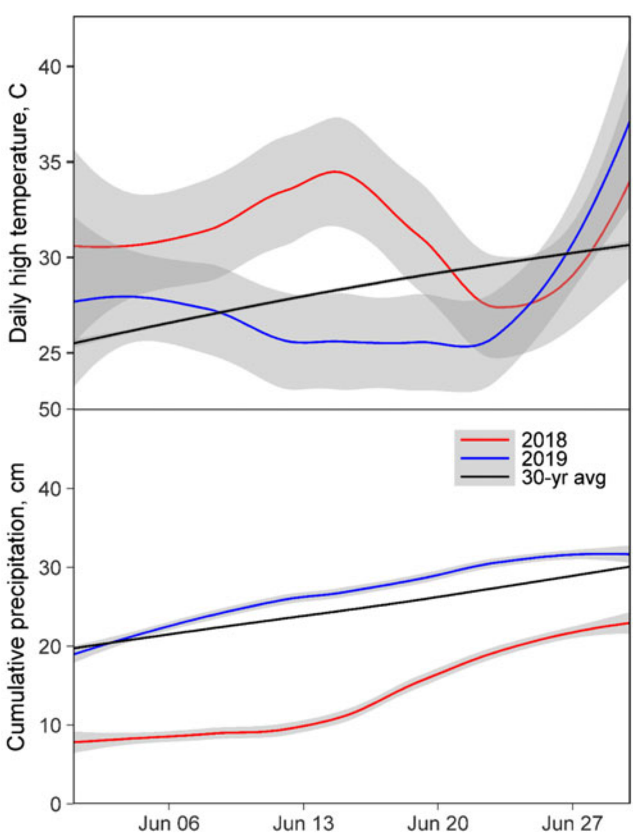

Figure 2. Maximum daily air temperature and total cumulative precipitation during June 2018 and 2019 compared with the 30-yr average (avg) at the University of Nebraska–Lincoln, South Central Agricultural Laboratory near Clay Center, NE.

105 to 140 g ai ha^{-1} nicosulfuron/mesotrione 21 DAT. Tembotrione and topramezone controlled velvetleaf up to 30-cm tall 85% and 69%, respectively, at 28 DAT in 2018. Bollman et al. (2008) reported 95% to 98% control of 5- to 10-cm velvetleaf 35 DAT with 12 g ai ha^{-1} topramezone and 96% to 100% control with tembotrione at 92 g ai ha^{-1} in plots treated with *S*-metolachlor applied PRE. All other herbicide programs achieved greater than 95% control of velvetleaf up to 30 cm 28 DAT in 2018. Velvetleaf control was not affected by plant height in 2019 (Table 2). All herbicide programs controlled velvetleaf up to 15- and up to 30-cm tall 99% 28 DAT in 2019.

Results of herbicide programs with fluthiacet-methyl or dicamba did not differ from other herbicide programs 28 DAT in 2019. These herbicides are not necessarily labeled for control of velvetleaf at this height. For example, dicamba is labeled to provide effective control of 3- to 8-cm–tall velvetleaf, fluthiacet-methyl/mesotrione for velvetleaf less than 13-cm tall, and tembotrione for velvetleaf less than 15-cm tall. In contrast, few herbicides evaluated in this research are labeled for velvetleaf height within the tested height range, including topramezone (≤20 cm), dicamba/halosulfuron-methyl (≤23 cm), nicosulfuron/mesotrione (≤25 cm), halosulfuron-methyl (≤30 cm), carfentrazone-ethyl (≤61 cm), and fluthiacet-methyl (≤91 cm). Fluthiacet-methyl/mesotrione and nicosulfuron/mesotrione are labeled only in yellow popcorn and should not be applied in white popcorn. Velvetleaf control with herbicide programs including fluthiacet-methyl or dicamba provided greater control than herbicide programs without them 28 DAT in 2018 but not in 2019.

Velvetleaf Density

Velvetleaf density at 28 DAT varied by year. Herbicide application by velvetleaf height did not influence velvetleaf density in either year of the study (Table 3). Velvetleaf density in no-POST herbicide plots was 83 plants m^{-2} in 2018 compared with 113 plants m^{-2} in 2019. Velvetleaf density in herbicide programs ranged from 2 to 58 plants m^{-2} in 2018. Velvetleaf density after application of carfentrazone-ethyl, fluthiacet-methyl, dicamba, dicamba/diflufenzopyr, dicamba/tembotrione, and fluthiacet-methyl/mesotrione was not more than 9 plants m^{-2} in 2018. Topramezone, halosulfuron-methyl, and tembotrione, applied POST, resulted in velvetleaf densities that were similar to the no-POST control in

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Table 3. Comparison of velvetleaf density and biomass 28 and 45 DAT, respectively, of plants ≤30-cm tall, and 2019 velvetleaf capsule yield in herbicide programs for control of velvetleaf ≤15- and ≤30-cm tall in popcorn in field experiments conducted at the University of Nebraska, South Central Agricultural Laboratory near Clay Center, NE in 2018 and 2019.

		Density 28 DAT[b,c]		Biomass reduction[d]		Capsules[e]
Herbicide program[a]	Rate	2018	2019	2018	2019	2018/2019
	g ai ha^{-1}	—— m^{-2} ——		—— % ——		plant^{-1}
No-POST herbicide	NA	83 a	113 a	0	0	9 a
Carfentrazone-ethyl	17.5	4 ef	0 b	100 ab	100	0 b
Fluthiacet-methyl	7.2	2 fg	1 b	100 a		0 b
Topramezone	24.5	52 ab	1 b	78 e		2 ab
Tembotrione	98	58 ab	0 b	84 de		0 b
Halosulfuron-methyl	52.5	53 ab	1 b	83 de		0 b
Dicamba	560	5 def	0 b	100 a		0 b
Dicamba/diflufenzopyr	392	6 cde	1 b	99 a		1 ab
Dicamba/tembotrione	597	9 cde	0 b	97 bc		0 b
Fluthiacet-methyl/mesotrione	2.8	2 fg	0 b	100 a		0 b
Nicosulfuron/mesotrione	118	17 cd	1 b	99 ab		3 ab
Dicamba/halosulfuron-methyl	190	30 bc	0 b	94 cd		0 b
P value		<0.001	<0.001	<0.001	NS	<0.001

[a]The experimental site was treated with *S*-metolachlor/atrazine 2,470 g ai ha^{-1} applied PRE, including the no-POST control plots.
[b]Abbreviations: DAT, days after treatment; NA, not applicable; NS, not significant.
[c]Means presented within the same column with no common letter(s) are significantly different according to Fisher protected LSD ($\alpha = 0.05$).
[d]No-POST herbicide control was excluded from biomass reduction analysis to meet assumptions of ANOVA.
[e]There was no significant difference between the number of velvetleaf seed capsules; therefore, data of both years were combined.

2018. As expected, based on control ratings 28 DAT, velvetleaf density ranged from 0 to 1 plants m^{-2} for all herbicide programs in 2019. Orthogonal contrasts indicated that herbicide programs with fluthiacet-methyl or dicamba reduced velvetleaf density more than herbicide programs without fluthiacet-methyl or dicamba in 2018 (data not shown). Treatments with fluthiacet-methyl resulted in less velvetleaf than treatments with dicamba in 2018. Sarangi and Jhala (2018c) reported velvetleaf density of 3 m^{-2} at 28 DAT with 5 g ai ha^{-1} fluthiacet-methyl applied to 12-cm velvetleaf that survived flumioxazin/pyroxasulfone applied PRE compared with 16 plants m^{-2} when only the PRE herbicide was applied.

Biomass Reduction

Velvetleaf biomass reduction varied by year. Velvetleaf plant height at the time of POST herbicide application did not affect velvetleaf biomass reduction. In 2018, 78% to 100% biomass reduction was observed across POST herbicide programs (Table 3). Carfentrazone-ethyl, fluthiacet-methyl, dicamba, dicamba/diflufenzopyr, dicamba/tembotrione, and fluthiacet-methyl/mesotrione reduced velvetleaf biomass 99% to 100%. Topramezone, halosulfuron-methyl, and tembotrione reduced velvetleaf biomass the least at 78%, 83%, and 84%, respectively. In 2019, there was no difference in velvetleaf biomass reduction among the herbicide programs evaluated. Zhang et al. (2013) reported 90% velvetleaf biomass reduction with topramezone at 15.84 g ai ha^{-1} plus 0.3% methylated seed oil. Hart (1997) reported halosulfuron-methyl at 9 g ai ha^{-1} plus dicamba at 140 g ai ha^{-1} plus crop oil concentrate or methylated seed oil 1% vol/vol resulted in 87% velvetleaf biomass reduction.

Velvetleaf Seed Capsules

The no-POST herbicide plots resulted in an average of 9 velvetleaf seed capsules plant^{-1} (Table 3). Lindquist et al. (1995) report that each velvetleaf capsule contains approximately 40 seeds. Dicamba/diflufenzopyr, topramezone, and nicosulfuron/mesotrione treatments resulted in 1, 2, and 3 capsules plant^{-1}, respectively, which was similar to the no-POST control. Velvetleaf seed production was reduced with all other herbicide programs. Schmenk and Kells (1998) reported 50% less seed production in velvetleaf that escaped atrazine compared with nontreated plants. Murphy and Lindquist (2002) reported that velvetleaf that survived halosulfuron, dicamba, or flumiclorac applied POST produced the same number of capsules plant^{-1} as the no-POST herbicide; however, velvetleaf density was reduced, resulting in significantly less seed production. Terra et al. (2007) reported velvetleaf treated with dicamba, halosulfuron, or flumiclorac produced fewer capsules and seeds than did nontreated velvetleaf. Bussan et al. (2001) reported velvetleaf seed production is correlated with velvetleaf biomass in corn and soybean production systems.

Popcorn Injury and Yield

Popcorn injury was not observed in any of herbicide programs tested in this study during both years. Yield varied by year; however, there was no effect of herbicide program or velvetleaf height on yield. Popcorn yield averaged 5,060 kg ha^{-1} across all treatments in 2018. Popcorn yield in 2019 was poor due to rain events in May that resulted in poor crop stand and hail and wind damage in August that resulted in lodging averaging 1,052 kg ha^{-1} across all treatments. It has to be noted that the no-POST herbicide plots in this study also received atrazine/*S*-metolachlor applied PRE that provided partial control of velvetleaf. In addition, the majority of velvetleaf in no-POST herbicide plots emerged after popcorn emerged; therefore, the velvetleaf was not very competitive.

Practical Implications

Weed management in no-till popcorn depends primarily on herbicides. Selecting a POST herbicide in popcorn is more challenging than in field corn because there a fewer registered herbicides. There are fewer control options for weeds that escape PRE herbicides and reach height above most label recommendations. Velvetleaf was effectively controlled by a number of POST herbicides tested in this study at heights ranging from 12 to 30 cm. Fluthiacet-methyl and carfentrazone-ethyl provided 98% to 99% control and are labeled for velvetleaf up to 91- and up to 62-cm tall, respectively. With the addition of ammonium sulfate, dicamba and dicamba/diflufenzopyr provided 95% or greater velvetleaf control.

From the results of this study, we conclude that effective POST herbicides are available for control of 12- to 30-cm velvetleaf in popcorn production. Velvetleaf interference did not reduce popcorn yield relative to the no-POST herbicide control. This is not unexpected, based on information known about the reduced competitiveness of weeds that survive a soil-applied herbicide. The reduction in velvetleaf seed production is an important weed management principle, especially considering the longevity of velvetleaf in the seedbank. As of 2019, only atrazine-resistant velvetleaf has been reported (Heap 2019); however, herbicide with multiple sites of action should be used to delay the evolution of herbicide-resistant velvetleaf.

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