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ARTICLE

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# Weed control and response of yellow and white popcorn hybrids to herbicides

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**Abstract**

Popcorn (*Zea mays* L. var. everta) is an important crop to Midwestern US producers. While there is considerable research on field corn and sweet corn sensitivity to herbicides, there is a lack of information on popcorn sensitivity to herbicides. Field experiments were conducted in 2017 and 2018 to evaluate herbicides labeled for yellow popcorn in commercially available popcorn hybrids for weed control and crop response in Nebraska. The experiments were arranged in a split-plot design. The main plot treatments consisted of two white and six yellow popcorn hybrids. Ten sub-plot treatments consisted of nontreated control, weed-free control, and four pre-emergence (PRE) followed by postemergence herbicide treatments applied at labeled rates (1X) and double the labeled rates (2X). Across hybrids, PRE herbicide treatments resulted in 4–8% injury. Across all PRE herbicide treatments, a yellow hybrid, R265, displayed the greatest average plant injury (11%). At labeled rates, broadleaf weed control in both years, and foxtail control in 2017, ranged from 95–99% with all treatments; however, foxtail control was limited (72–86%) for most treatments in 2018. Weed biomass reduction in all herbicide treatments ranged from 90–98% and 68–97% control in 2017 and 2018, respectively. Yield losses ranged from 0–7% in herbicide treatments, with a 42% yield loss in the untreated control. Although slight hybrid differences in herbicide sensitivity were detected, the differences were not linked to popcorn color. Information reported in this research are the first that determined popcorn sensitivity to herbicides.

## 1 | INTRODUCTION

Popcorn (*Zea mays* L. var. everta) is an important field crop for many producers in the US Midwest. Popcorn is grown on nearly 90,000 ha of land annually in the United States (USDA NASS, 2018). Illinois, Indiana, Iowa, Kansas, Kentucky, Michigan, Nebraska, and Ohio are eight major contributing states for popcorn production in the United States (USDA NASS, 2018). Nebraska is the leading producer of popcorn in the United States, producing 160 million kg of the total 356 million kg popcorn produced overall (45% of the national production) on over 28,000 ha in 2012 (USDA NASS, 2018). The next three top popcorn producing states combined (Indiana, Illinois, and Ohio) produced 42% of the nation's harvest in 2012 (USDA NASS, 2018). Popcorn is usually produced under contracts, which specify the hybrids and area to be planted (D'Croz-Mason & Waldren, 1978; Ziegler, 2001). The majority of popcorn is produced under conservation tillage systems (Pike et al., 2002). Popcorn emerges slower, produces narrower and more upright leaves,

**Abbreviations:** DA POST, days after postemergence application; DA PRE, days after pre-emergence application; DAT, days after treatment; fb, followed by; PRE, PRE, pre-emergence; POST, postemergence.

and tends to have shorter and thinner stalks than field corn (*Zea mays* L. var. indentata; Ziegler, 2001). For these reasons, growers depend on herbicides for weed control in popcorn production (Pike et al., 2002). However, popcorn is generally more susceptible to yield loss than field corn due to weed competition and herbicide injury. Additionally, white popcorn is generally more sensitive to herbicides than yellow popcorn (Loux et al., 2017).

A pest-management strategic plan was created by a group of popcorn growers, agronomists, university scientists, and agricultural specialists to communicate current pest-management practices in popcorn production and to identify the challenges associated with pest management (Pike et al., 2002). This strategic plan was based on the information gathered in the crop profile for popcorn (Bertalmio et al., 2003). The top regulatory priority outlined in the plan was to identify and expand the number of herbicides with distinct sites of action for weed control and crop safety. Pike et al. (2002) suggested that if popcorn was included in the registration package to the US Environmental Protection Agency (USEPA), the market opportunity gained by herbicide manufacturers was not enough to warrant field testing and subsequent inclusion of popcorn onto the herbicide label. Many herbicides labeled for field corn are not labeled for popcorn, such as premixes of isoxaflutole/thiencarbazone (Corvus; Bayer CropScience, 2016), and tembotrione/thiencarbazone (Capreno; Bayer CropScience, 2012; Table 1). A premix of acetochlor/clopyralid/flumetsulam (Surestart II; Corteva Agriscience, 2014) is labeled for field corn but not for popcorn. Additionally, certain premixtures such as acetochlor/clopyralid/mesotrione (Resicore; Corteva Agriscience, 2017) and atrazine/bicyclopyrone/mesotrione/*S*-metolachlor (Acuron; Syngenta Crop Protection, 2017) are labeled for PRE and POST application for field corn, but are not labeled for POST application for popcorn. Lack of inclusion could be due to sensitivity of popcorn, or lack of research and interest by the herbicide industry to register these herbicides in a minor crop. For example, mesotrione (Callisto; Syngenta Crop Protection, 2001) was first labeled for field corn in 2001, however yellow popcorn was added to the label in 2004 (Syngenta Crop Protection, 2004).

The top research priority outlined in the Popcorn Pest Management Strategic Plan for the North Central Region is to determine hybrid sensitivity to herbicides (Pike et al., 2002). Some herbicides that are labeled for field corn, sweet corn (*Zea mays* L. var. saccharata), and yellow popcorn specifically exclude white popcorn from the label, including atrazine/mesotrione/*S*-metolachlor (Lumax; Syngenta Crop Protection, 2009) and atrazine/bicyclopyrone/mesotrione/*S*-metolachlor (Acuron; Syngenta Crop Protection, 2017). A different formulation of a premix of atrazine/mesotrione/*S*-metolachlor (Lexar; Syngenta Crop Protection, 2012) than previously mentioned (Lumax) is labeled for field corn, seed corn, sweet corn, and even in grain sorghum (*Sorghum bicolor* [L.] Moench ssp. Bicolor), but is not labeled for white popcorn. Herbicide labels often have statements indicating that the selectivity of the herbicide on popcorn is unknown, and to test in a small area or contact supplier or university specialist to verify sensitivity. Research has been conducted to determine the sensitivity of sweet corn to a number of herbicides labeled for field corn (Bollman, Boerboom, Becker, & Fritz, 2008; Meyer, Pataky, & Williams, 2010; Nordby, Williams, Pataky, Riechers, & Lutz, 2008; Williams & Pataky, 2010; Williams, Wax, Pataky, & Meyer, 2008); however, scientific literature does not exist regarding weed control and response of commercially-grown yellow and white popcorn hybrids to herbicides. The objectives of this research were to evaluate weed control, crop growth, and yield response in Nebraska commercially available yellow and white popcorn hybrids treated with pre- (PRE) and postemergence (POST) herbicides labeled in yellow popcorn.

**Core Ideas**

- White and yellow popcorn sensitively to herbicides was not dependent on popcorn color.
- Effective weed control was achieved with the herbicide programs tested.
- No popcorn yield loss was observed from herbicides even at double the labeled rate.

# 2 | MATERIALS AND METHODS

## 2.1 | Site description

Field experiments were conducted at the University of Nebraska-Lincoln, South Central Agricultural Laboratory near Clay Center, NE (40.5752, –98.1428, 552 m elevation above mean sea level) in 2017 and 2018. 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 2.5–3% 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$^{-1}$ of nitrogen in the form of anhydrous ammonia (82–0-0) applied with an anhydrous ammonia coulter on 96-cm spacing. Starter fertilizer ammonium polyphosphate (APP; 10–34–0) was applied in-furrow at 6 kg ha$^{-1}$ during planting. The predominant broadleaf weed species were velvetleaf (*Abutilon theophrasti* Medik.), common lambsquarters (*Chenopodium album* L.), common waterhemp (*Amaranthus tuberculatus* [Moq.] J. D. Sauer), and Palmer amaranth (*Amaranthus palmeri* S. Watson). Grass weed species consisted of green foxtail (*Setaria viridis* [L.] P.

**TABLE 1** Common and chemical names of herbicides

| Common name | Chemical name |
|---|---|
| Acetochlor | 2-chloro-*N*-(ethoxymethyl)-*N*-(2-ethyl-6-methylphenyl)acetamide |
| Atrazine | 6-chloro-4-*N*-ethyl-2-*N*-propan-2-yl-1,3,5-triazine-2,4-diamine |
| Bentazon | 2,2-dioxo-3-propan-2-yl-1*H*-2$\lambda^6$,1,3-benzothiadiazin-4-one |
| Bicyclopyrone | (1*R*,5*S*)-3-[hydroxy-[2-(2-methoxyethoxymethyl)-6-(trifluoromethyl)pyridin-3-yl]methylidene]bicyclo[3.2.1]octane-2,4-dione |
| Carfentrazone | 2-chloro-3-[2-chloro-5-[4-(difluoromethyl)-3-methyl-5-oxo-1,2,4-triazol-1-yl]-4-fluorophenyl]propanoic acid |
| Clopyralid | 3,6-dichloropyridine-2-carboxylic acid |
| Dicamba | 3,6-dichloro-2-methoxybenzoic acid |
| Diflufenzopyr | 2-[(*E*)-*N*-[(3,5-difluorophenyl)carbamoylamino]-*C*-methylcarbonimidoyl]pyridine-3-carboxylic acid |
| Dimethenamid-P | 2-chloro-*N*-(2,4-dimethylthiophen-3-yl)-*N*-[(2*S*)-1-methoxypropan-2-yl]acetamide |
| Flumetsulam | *N*-(2,6-difluorophenyl)-5-methyl-[1,2,4]triazolo[1,5-a]pyrimidine-2-sulfonamide |
| Fluthiacet | 2-[2-chloro-4-fluoro-5-[(3-oxo-5,6,7,8-tetrahydro-[1,3,4]thiadiazolo[3,4-a]pyridazin-1-ylidene)amino]phenyl]sulfanylacetic acid |
| Foramsulfuron | 2-[(4,6-dimethoxypyrimidin-2-yl)carbamoylsulfamoyl]-4-formamido-*N*,*N*-dimethylbenzamide |
| Halosulfuron | 3-chloro-5-[(4,6-dimethoxypyrimidin-2-yl)carbamoylsulfamoyl]-1-methylpyrazole-4-carboxylic acid |
| Isoxaflutole | (5-cyclopropyl-1,2-oxazol-4-yl)-[2-methylsulfonyl-4-(trifluoromethyl)phenyl]methanone |
| Mesotrione | 2-(4-methanesulfonyl-2-nitrobenzoyl)cyclohexane-1,3-dione |
| Nicosulfuron | 2-[(4,6-dimethoxypyrimidin-2-yl)carbamoylsulfamoyl]-*N*,*N*-dimethylpyridine-3-carboxamide |
| Primisulfuron | 2-[[4,6-bis(difluoromethoxy)pyrimidin-2-yl]carbamoylsulfamoyl]benzoic acid |
| Pyroxasulfone | 3-[[5-(difluoromethoxy)-1-methyl-3-(trifluoromethyl)pyrazol-4-yl]methylsulfonyl]-5,5-dimethyl-4*H*-1,2-oxazole |
| Saflufenacil | 2-chloro-4-fluoro-5-[3-methyl-2,6-dioxo-4-(trifluoromethyl)pyrimidin-1-yl]-*N*-[methyl(propan-2-yl)sulfamoyl]benzamide |
| *S*-metolachlor | mixture of 80–100% 2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-[(2*S*)-1-methoxypropan-2-yl]acetamide and 20–0% 2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-[(2*R*)-1-methoxypropan-2-yl]acetamide |
| Tembotrione | 2-[2-chloro-4-methylsulfonyl-3-(2,2,2-trifluoroethoxymethyl)benzoyl]cyclohexane-1,3-dione |
| Thiencarbazone | 4-[(3-methoxy-4-methyl-5-oxo-1,2,4-triazole-1-carbonyl)sulfamoyl]-5-methylthiophene-3-carboxylic acid |
| Topramezone | 4-[3-(4,5-dihydro-1,2-oxazol-3-yl)-2-methyl-4-methylsulfonylbenzoyl]-2-methyl-1*H*-pyrazol-3-one |

Beauv.) and yellow foxtail (*Setaria pumila* [Poir.] Roem. & Schult.), which have been grouped and referred to as "foxtails."

## 2.2 | Treatments and experimental design

The treatments were arranged in a split-plot design with three replications. The main plot treatments consisted of eight commercially available hybrids (Table 2). Ten sub-plot treatments consisted of a nontreated control, weed-free control, and four PRE followed by (fb) POST herbicide treatments (Table 3). The herbicide treatments were applied at the labeled PRE and POST rates (1X) and double the labeled PRE and POST rates (2X). PRE herbicide treatments consisted of one of five commercially available premix combinations and represented ten different herbicides (Table 3). Postemergence herbicide treatments consisted of one of five commercially available premix combinations with an additional five chemicals represented (Table 3).

**TABLE 2** Commercially available white and yellow popcorn hybrids tested in field experiments conducted at the University of Nebraska-Lincoln, South Central Agricultural Laboratory near Clay Center, NE, in 2017 and 2018

| Hybrid | Kernel type | Supplier |
|---|---|---|
| M2101 | Yellow | Conagra Brands, Chicago, IL |
| VYP315 | Yellow | Conagra Brands, Chicago, IL |
| VYP220 | Yellow | Conagra Brands, Chicago, IL |
| VWP111 | White | Conagra Brands, Chicago, IL |
| N1H820 | Yellow | Zangger Popcorn Hybrids, North Loup, NE |
| R265 | Yellow | Crookham Company, Caldwell, ID |
| SH3707W | White | Schlessman Seed Company, Milan, OH |
| AP2507 | Yellow | Agricultural Alumni Seed Improvement Association, Romney, IN |

**TABLE 3** Herbicide treatments tested in a commercial popcorn hybrid field experiment at the University of Nebraska-Lincoln South Central Agricultural Laboratory near Clay Center, NE, in 2017 and 2018

| Herbicide treatment | Timing[a] | Rate g ai ha$^{-1}$ | Relative rate | Trade name | Manufacturer[b] | Adjuvant[c] | Label stipulations[d] |
|---|---|---|---|---|---|---|---|
| Nontreated control | | 0 | NA | | | | |
| Weed-free control | | | | | | | |
| *S*-metolachlor/atrazine | PRE | 2470 | 1X | Bicep II Magnum | Syngenta | | None |
| *S*-metolachlor/atrazine | POST | 3240 | 1X | Bicep II Magnum | Syngenta | | None |
| Pyroxasulfone/fluthiacet | PRE | 188 | 1X | Anthem MAXX | FMC | | None |
| Dicamba/tembotrione | POST | 597 | 1X | Diflexx DUO | Bayer | COC | Contact seed provider or test in small area first. |
| Pyroxasulfone/fluthiacet | PRE | 376 | 2X | Anthem MAXX | FMC | | |
| Dicamba/tembotrione | POST | 1194 | 2X | Diflexx DUO | Bayer | COC | |
| Acetochlor/atrazine | PRE | 4200 | 1X | Degree Xtra | Bayer | | None |
| Mesotrione/fluthiacet | POST | 110 | 1X | Solstice | FMC | NIS | Yellow popcorn only; No UAN or AMS, use NIS; contact seed company, field man, or university specialist. |
| Acetochlor/atrazine | PRE | 8400 | 2X | Degree Xtra | Bayer | | |
| Mesotrione/fluthiacet | POST | 220 | 2X | Solstice | FMC | NIS | |
| Clopyralid/acetochlor/mesotrione | PRE | 2300 | 1X | Resicore | Corteva | | Yellow popcorn only; PRE only |
| Topramezone/dimethenamid-P | POST | 940 | 1X | Armezon PRO | BASF | MSO | Refer to seed company recommendations; 951 g ai ha$^{-1}$ maximum |
| Clopyralid/acetochlor/mesotrione | PRE | 4600 | 2X | Resicore | Corteva | | |
| Topramezone/dimethenamid-P | POST | 1880 | 2X | Armezon PRO | BASF | MSO | |
| Saflufenacil/dimethamid-P | PRE | 730 | 1X | Verdict | BASF | | verify with supplier |
| Diflufenzopyr/dicamba | POST | 392 | 1X | Status | BASF | NIS+AMS | verify with supplier |
| Saflufenacil/dimethamid-P | PRE | 1460 | 2X | Verdict | BASF | | |
| Diflufenzopyr/dicamba | POST | 784 | 2X | Status | BASF | NIS+AMS | |

[a]Abbreviations: AMS, ammonium sulfate (DSM Chemicals North America, Augusta, GA); COC, crop oil concentrate (Agridex, Helena Chemical, Collierville, TN); PRE, pre-emergence; POST, postemergence; MSO, methylated seed oil (Southern Ag, Suwanee, GA); NIS, nonionic surfactant (Induce, Helena Chemical, Collierville, TN).
[b]Bayer CropScience, Research Triangle Park, NC; Corteva Agriscience, Indianapolis, IN; FMC Corporation, Philadelphia, PA; BASF Corporation, Research Triangle Park, NC; Syngenta Crop Protection, Greensboro, NC.
[c]AMS at 5% (v/v), COC or MSO at 1% (v/v), and NIS at 0.25% (v/v) were mixed with herbicides.
[d]Summary of language used in product labels. Product labels can be found at https://cdms.net.

Plot dimensions were 9-m long by 3-m wide. On 8 May 2017 and 30 April 2018, popcorn hybrids (Table 2) were planted with a row spacing of 76 cm at a depth of 4 cm and a planting density of 89,000 seeds ha$^{-1}$. Pre-emergence herbicides were applied on 9 May 2017 and 2 May 2018, and POST herbicides were applied on 19 June 2017 and 12 June 2018 using a handheld $CO_2$–pressurized backpack sprayer equipped with four AIXR 110015 flat-fan nozzles (TeeJet Technologies, Spraying Systems, Wheaton, IL) spaced 60 cm apart. The sprayer was calibrated to deliver 140 L ha$^{-1}$ at 276 kPa at a constant speed of 4.8 km h$^{-1}$. Weed-free control plots were kept weed-free using PRE and POST herbicide treatments of *S*-metolachlor/atrazine as well as by hoeing as needed (Table 3).

## 2.3 | Data collection

Air temperature and rainfall data throughout the growing season were obtained from the High Plains Regional Climate Center automated weather station, which was located only about 350 m from the experimental field. Weed control was assessed visually on a scale of 0–100%, with 0% representing no injury and 100% representing plant death, at 28 d after PRE (DA PRE) and 21 d after POST (DA POST) herbicide application. Weed density was assessed from two randomly placed 0.5-m$^2$ quadrats in the middle two popcorn rows from each plot at 21 DA PRE (30 May 2017, 28 May 2018) and 21 DA POST (10 July 2017, 1 July 2018). Popcorn injury was assessed on a scale of 0–100%, with 0% representing no injury and 100% representing plant death, at 21 DA PRE and 21 DA POST. Popcorn stand counts were measured 21 DA PRE in 2 m of the middle two rows. Popcorn plant height was measured from 6 plants per plot from the soil surface to the top leaf collar at 35 DA PRE and 21 DA POST. Popcorn lodging (%) was assessed 60 DA POST from the entire length of the middle two rows. Above-ground weed biomass was assessed from two randomly placed 0.5-m$^2$ quadrats in the middle two rows from each plot at 45 DA POST. Surviving weeds were cut near the soil surface, placed in paper bags, dried in an oven at 50 C for 10 d, and dry biomass weight was recorded. Popcorn was harvested from the middle two rows with a plot combine and the yields were adjusted to 14% grain moisture content. Percent stand reduction, percent biomass reduction, percent height reduction, and percent yield loss were calculated using the equation (Wortman, 2014):

$$Y = \left[(C - B)/C\right]100 \qquad (1)$$

where *C* represents the popcorn stand from the nontreated control, weed biomass from the nontreated control, popcorn height in the weed-free control, or yield in the weed-free control in the corresponding replication block; *B* represents the popcorn stand, weed biomass, popcorn height, or yield of the treated plot.

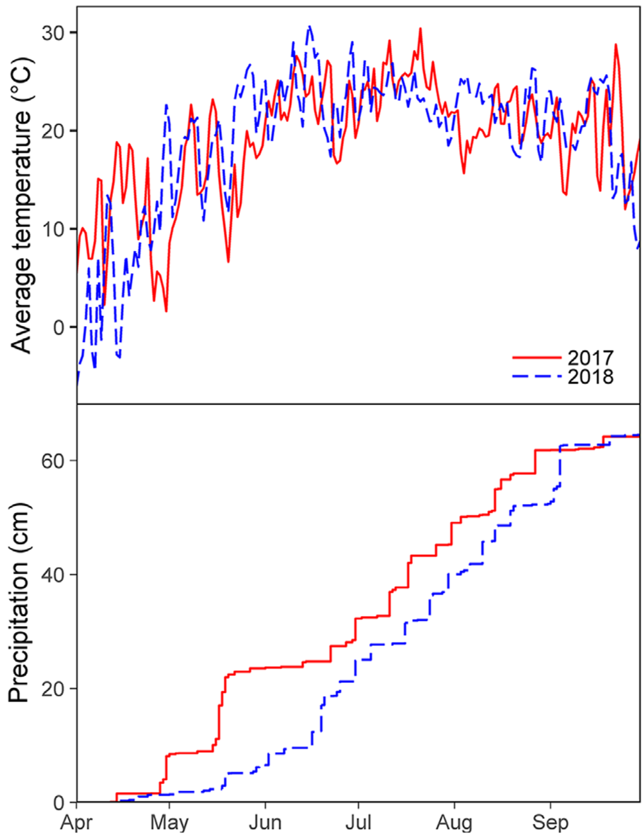


**FIGURE 1** Average daily air temperature, total precipitation (rainfall + irrigation) during 2017 and 2018 growing seasons at the University of Nebraska–Lincoln, South Central Agricultural Laboratory near Clay Center, NE

## 2.4 | Statistical analysis

Statistical analyses were subjected to analysis of variance (ANOVA) in R version 3.5.1 utilizing the base packages (R Core Team, 2019) and the Agricolae: Statistical Procedures for Agricultural Research Package (Mendiburu, 2017). The ANOVA was performed using the *sp.plot* (split plot) function, where hybrid was treated as the main plot and herbicide treatment was considered as the subplot effect. Replications nested within years were considered random effects in the model. The ANOVA assumptions of normality and homogeneity of variance were tested (Kniss & Streibig, 2018). Improvement in normality was not gained through transformation of data; therefore, data were analyzed without transformation. If the random effect of year was significant, data was analyzed with years separated. Treatment means were separated at $P \leq .05$ using Fisher's protected least significant difference test.

# 3 | RESULTS

Average air temperatures were similar both years (Figure 1). Total precipitation (rainfall plus supplemental irrigation)

**TABLE 4** Irrigation amounts in field experiments conducted at the University of Nebraska-Lincoln, South Central Agricultural Laboratory near Clay Center, NE, in 2017 and 2018

| 2017 | | 2018 | |
|---|---|---|---|
| | cm | | cm |
| June 22 | 2.7 | June 16 | 2.8 |
| June 30 | 3.8 | July 16 | 3.6 |
| July 11 | 4.2 | July 24 | 3.9 |
| July 17 | 3.7 | Aug. 10 | 3.9 |
| July 31 | 3.8 | | |
| Aug. 14 | 3.8 | | |

totaled about 60 cm for each year (Figure 1). Irrigation amounts were 22 cm in 2017 and 14.2 cm in 2018 (Figure 1; Table 4). The growing degree day totals were 1032 and 1135 for 2017 and 2018, respectively.

## 3.1 | Popcorn herbicide sensitivity

There were no interactions between popcorn hybrids and herbicide treatments with popcorn injury. Averaged among popcorn hybrids, PRE herbicides resulted in 4–8% popcorn injury 21 DA PRE (Table 5). Although statistically similar in several treatments, labeled herbicide rates (1X rates) resulted in 4–6% injury as compared with 6–8% injury at 2X rates. Popcorn hybrid injury ranged from 3–11%, with the two white hybrids resulting in 3–6% injury from PRE herbicide treatments. Popcorn hybrid response to PRE herbicides varied among hybrids with the most sensitive hybrid, R265, a yellow popcorn, resulting in 11% injury among the treatments (Table 5). Stand reductions were not observed compared to the nontreated control 21 DA PRE (data not shown). There was an interaction between popcorn hybrids and herbicide treatments with popcorn height 35 DA PRE only in 2017. Popcorn height reduction compared with the weed-free control was reduced by saflufenacil/dimethamid-P at 2X rate in VYP220 (28%), VWP111 (14%), AP2507 (13%), and R265 (13%) and from pyroxasulfone/fluthiacet at 2X rate in N1H820 (17%) and VYP220 (16%; Table 6).

Popcorn injury 21 DA POST was only observed in 2018 and no interaction between popcorn hybrids and herbicide treatments occurred (Table 5). Saflufenacil/dimethamid-P fb diflufenzopyr/dicamba at 2X rate resulted in 5% crop injury 21 DA POST in 2018. No interaction occurred for popcorn lodging between popcorn hybrids and herbicide treatments. No interaction between popcorn hybrids and herbicide treatments occurred for popcorn height reduction 21 DA POST. Height reduction among herbicide treatments was minimal (1–5%) as compared to the weed-free control; however, the nontreated control resulted in a 15% reduction in height compared with the weed-free control (data not shown). Lodging 60 DA POST was similar to nontreated and weed-free controls, and was not influenced by hybrid or herbicide treatment (data not shown). No interaction between popcorn hybrids and herbicide treatments occurred for popcorn yield loss, with losses due to herbicide treatments resulting in only 1–7% compared to the weed-free control (Table 5). Yield losses were not greater at 2X rates compared to labeled rates (Table 5).

## 3.2 | Weed control

At labeled rates, clopyralid/acetochlor/mesotrione provided greatest control of velvetleaf (98%) 28 DA PRE (Table 7). Saflufenacil/dimethamid-P resulted in 93% control of velvetleaf and pyroxasulfone/fluthiacet and acetochlor/atrazine resulted in 87 and 86% control of velvetleaf 28 DA PRE, respectively. All PRE herbicides at labeled rates (1X) provided 95–98% control of common lambsquarters 28 DA PRE, except pyroxasulfone/fluthiacet (87%). Common waterhemp and Palmer amaranth were controlled 94–99% and 98–99% with all herbicides at labeled rates 28 DA PRE, respectively. Foxtails in 2017 were controlled 95 and 98% with labeled rates of pyroxasulfone/fluthiacet and clopyralid/acetochlor/mesotrione, respectively, whereas acetochlor/atrazine and saflufenacil/dimethamid-P resulted in 90–91% control. Control of foxtails in 2018 ranged from 87–90% 28 DA PRE with all herbicides, except pyroxasulfone/fluthiacet (78%).

Broadleaf weed control ranged from 95–99% from all herbicide treatments at labeled rates 21 DA POST (Table 7). Foxtail control ranged from 91–99% and 72–96% in 2017 and 2018, respectively. The greatest foxtail control 21 DA POST was achieved with acetochlor/atrazine fb mesotrione/fluthiacet (95%), clopyralid/acetochlor/mesotrione fb topramezone/dimethenamid-P resulting in 99% in 2017, and 96% control in 2018.

Weed density 21 DA PRE was reduced from 172 plants $m^{-2}$ to 0–13 plants $m^{-2}$ when PRE herbicides were applied at labeled rates in 2017 (Table 8). In 2018, saflufenacil/dimethamid-P and clopyralid/acetochlor/mesotrione at labeled rates resulted in the lowest weed densities 21 DA PRE (103–123 plants $m^{-2}$) compared with the nontreated control (259 plants $m^{-2}$). Foxtail density 21 DA PRE in the nontreated control in 2017 was 71 plants $m^{-2}$ and was reduced to 0–1 $m^{-2}$ by herbicide treatments. In 2018, foxtail density was 158 plants $m^{-2}$ in the nontreated control, and was reduced to 88 plants $m^{-2}$ by labeled rates of saflufenacil/dimethamid-P (data not shown). Weed density 21 DA POST was reduced from 83 plants $m^{-2}$ to 1–9 plants $m^{-2}$ from all herbicide treatments at labeled rates in 2017. In 2018, herbicide treatments at labeled rates reduced weed density from 171 plants $m^{-2}$ to 42–67 plants $m^{-2}$. Weed densities at labeled

**TABLE 5** Popcorn 2017 and 2018 PRE injury, 2018 POST injury, and 2017 and 2018 yield loss from herbicide treatments and 2017 and 2018 PRE injury by hybrid in field experiments conducted at the University of Nebraska-Lincoln, South Central Agricultural Laboratory near Clay Center, NE, in 2017 and 2018

| Herbicide treatment[a] | Relative rate[a] | Injury 21 DA PRE[b] | 2018 injury 21 DA POST[bc] | Yield loss[b] |
|---|---|---|---|---|
| | | % | | |
| Nontreated control | – | 0 d | 0 c | 42 a |
| Pyroxasulfone/fluthiacet fb | 1X | 4 c | 1 bc | 4 b |
| Dicamba/tembotrione | 2X | 6 abc | 2 b | 1 b |
| Acetochlor/atrazine fb | 1X | 6 bc | 1 bc | 2 b |
| Mesotrione/fluthiacet | 2X | 7 ab | 1 bc | 1 b |
| Clopyralid/acetochlor/mesotrione fb | 1X | 6 abc | 0 c | 7 b |
| Topramezone/dimethenamid-P | 2X | 6 ab | 1 bc | 4 b |
| Saflufenacil/dimethamid-P fb | 1X | 5 bc | 2 b | 3 b |
| Diflufenzopyr/dicamba | 2X | 8 a | 5 a | 1 b |
| Weed-free control | 1X | 5 bc | 1 bc | 0 b |
| **Hybrid** | | | | |
| VWP111 – white | | 3 e | ns | ns |
| VYP315 – yellow | | 8 b | ns | ns |
| VYP220 – yellow | | 4 de | ns | ns |
| M2101 – yellow | | 4 cde | ns | ns |
| SH3707W – white | | 6 bc | ns | ns |
| AP2507 – yellow | | 5 bcd | ns | ns |
| N1H820 – yellow | | 3 e | ns | ns |
| R265 – yellow | | 11 a | ns | ns |

[a]Abbreviations: DA PRE, days after pre-emergence application; DA POST, days after postemergence application; fb, followed by; X, labeled rate reported in Table 3; ns, nonsignificant.

[b]Means presented within the same column with no common letter(s) are significantly different according to Fisher's Protected Least Significant Difference, where α = .05.

[c]Popcorn POST injury for 2018 only; there was no observable POST injury in 2017.

**TABLE 6** Popcorn height reduction from herbicide treatments 35 DA PRE in field experiments conducted at the University of Nebraska-Lincoln, South Central Agricultural Laboratory near Clay Center, NE, in 2017

| Herbicide treatment[a] | Relative rate[b] | Height reduction VWP111 white | VYP315 yellow | VYP220 yellow | M2101 yellow | SH3707W white | AP2507 yellow | N1H820 yellow | R265 yellow |
|---|---|---|---|---|---|---|---|---|---|
| | | % | | | | | | | |
| Nontreated control | – | 6 abc | 12 a | 4 c | 11 a | 4 a | 0 b | 6 ab | 13 a |
| Pyroxasulfone/fluthiacet | 1X | 9 abc | 3 ab | 0 c | 5 a | 5 a | 0 b | 8 ab | 1 b |
| | 2X | 10 abc | 8 ab | 16 b | 8 a | 5 a | 5 ab | 17 a | 3 b |
| Acetochlor/atrazine | 1X | 5 bc | 3 ab | 2 c | 7 a | 3 a | 0 b | 5 ab | 4 ab |
| | 2X | 6 abc | 4 ab | 3 c | 12 a | 4 a | 3 b | 3 ab | 7 ab |
| Clopyralid/acetochlor/mesotrione | 1X | 6 abc | 1 b | 4 c | 3 a | 3 a | 0 b | 8 ab | 0 b |
| | 2X | 9 abc | 9 ab | 6 c | 9 a | 4 a | 0 b | 9 ab | 1 b |
| Saflufenacil/dimethamid-P | 1X | 7 abc | 1 b | 7 bc | 5 a | 2 a | 4 b | 4 ab | 1 b |
| | 2X | 14 a | 10 ab | 28 a | 6 a | 3 a | 13 a | 5 ab | 13 a |
| Weed-free control | 1X | 0 c | 0 b | 0 c | 0 a | 0 a | 0 b | 0 b | 0 b |

[a]Abbreviations: DA PRE, days after pre-emergence application; X, labeled rate reported in Table 3.

[b]Means presented within the same column with no common letter(s) are significantly different according to Fisher's Protected Least Significant Difference where α = .05.

**TABLE 7** Weed control in popcorn from herbicide treatments 28 DA PRE and 21 DA POST by species in field experiments conducted at the University of Nebraska-Lincoln, South Central Agricultural Laboratory near Clay Center, NE, in 2017 and 2018

| | | Weed species | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Velvetleaf[b] | | Common lambsquarters[b] | | Common waterhemp[b] | | 2018 Palmer amaranth[b,c] | | 2017 grasses[b] | | 2018 grasses[b] | |
| Herbicide treatment[a] | Relative rate[a] | 28 DA PRE | 21 DA POST | 28 DA PRE | 21 DA POST | 28 DA PRE | 21 DA POST | 28 DA PRE | 21 DA POST | 28 DA PRE | 21 DA POST | 28 DA PRE | 21 DA POST |
| | | % | | | | | | | | | | | |
| Nontreated control | – | 0 d | 0 c | 0 d | 0 c | 0 c | 0 c | 0 c | 0 c | 0 e | 0 d | 0 e | 0 d |
| Pyroxasulfone/fluthiacet fb dicamba/tembotrione | 1X | 87 c | 98 a | 87 c | 98 ab | 95 ab | 99 a | 98 ab | 99 a | 95 a-d | 93 bc | 78 d | 72 c |
| | 2X | 92 b | 98 a | 90 bc | 98 ab | 99 ab | 99 a | 99 a | 98 ab | 98 abc | 97 ab | 86 bc | 86 b |
| Acetochlor/atrazine fb mesotrione/fluthiacet | 1X | 86 c | 95 b | 95 ab | 97 b | 94 b | 97 b | 99 a | 97 b | 90 cd | 95 abc | 90 bc | 86 b |
| | 2X | 93 b | 98 a | 96 a | 99 a | 97 ab | 99 a | 94 b | 99 a | 99 ab | 98 a | 85 cd | 83 b |
| Clopyralid/acetochlor/mesotrione fb topramezone/dimethenamid-P | 1X | 98 a | 99 a | 99 a | 99 a | 99 a | 99 a | 99 a | 99 a | 98 ab | 99 a | 87 bc | 96 a |
| | 2X | 98 a | 99 a | 99 a | 99 a | 99 a | 99 a | 99 a | 99 a | 99 a | 99 a | 92 abc | 97 a |
| Saflufenacil/dimethamid-P fb diflufenzopyr/dicamba | 1X | 93 b | 99 a | 96 ab | 99 a | 95 ab | 98 ab | 99 a | 99 a | 91 bcd | 91 c | 90 bc | 85 b |
| | 2X | 96 ab | 99 a | 97 a | 99 a | 96 ab | 99 a | 99 a | 99 a | 90 d | 98 ab | 93 ab | 87 b |
| Weed-free control | 1X | 99 a | 99 a | 99 a | 99 a | 99 a | 99 a | 99 a | 99 a | 99 a | 99 a | 99 a | 99 a |

[a] Abbreviations: DA PRE, days after pre-emergence application; DA POST, days after postemergence application; fb, followed by; X, rate reported as g ai $ha^{-1}$ in Table 3.

[b] Means presented within the same column with no common letter(s) are significantly different according to Fisher's Protected Least Significant Difference where $\alpha = .05$.

[c] Popcorn POST injury for 2018 only; there was no observable POST injury in 2017.

**TABLE 8** Weed density, biomass, and biomass reduction in popcorn from herbicide treatments in field experiments conducted at the University of Nebraska-Lincoln, South Central Agricultural Laboratory near Clay Center, NE, in 2017 and 2018

| Herbicide treatment[a] | Relative rate[b] | Weed density[b] | | | | Weed biomass[b] | | Biomass reduction[b] | |
|---|---|---|---|---|---|---|---|---|---|
| | | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 |
| | | 21 DA PRE | | 21 DA POST | | 45 DA POST | | 45 DA POST | |
| | | plants m$^{-2}$ | | | | g m$^{-2}$ | | % | |
| Nontreated control | – | 172 a | 259 a | 83 a | 171 a | 1534 a | 1250 a | 0 d | 0 e |
| Pyroxasulfone/fluthiacet fb dicamba/tembotrione | 1X | 13 b | 229 ab | 9 b | 67 b | 151 b | 407 b | 90 c | 68 d |
| | 2X | 3 b | 188 abc | 4 bcd | 46 bcde | 33 c | 370 bc | 98 ab | 70 d |
| Acetochlor/atrazine fb mesotrione/fluthiacet | 1X | 1 b | 196 abc | 3 cd | 47 bcd | 29 c | 367 bc | 98 ab | 71 d |
| | 2X | 1 b | 169 bcd | 3 cd | 37 cde | 19 c | 217 d | 99 a | 84 b |
| Clopyralid/acetochlor/mesotrione fb topramezone/dimethenamid-P | 1X | 0 b | 123 cde | 1 cd | 42 cde | 43 c | 36 e | 97 ab | 97 a |
| | 2X | 0 b | 105 de | 1 d | 27 de | 0 c | 13 e | 100 a | 99 a |
| Saflufenacil/dimethamid-P fb diflufenzopyr/dicamba | 1X | 10 b | 103 de | 7 bc | 49 bc | 85 bc | 320 bcd | 95 b | 74 cd |
| | 2X | 0 b | 55 ef | 1 cd | 25 e | 0 c | 239 cd | 100 a | 80 bc |
| Weed-free control | 1X | 0 b | 0 f | 0 d | 0 f | 0 c | 0 e | 100 a | 100 a |

[a]Abbreviations: DA PRE, days after PRE-emergence application; DA POST, days after POST-emergence application; fb, followed by; X, rate reported as g ai ha$^{-1}$ in Table 3.

[b]Means presented within the same column with no common letter(s) are significantly different according to Fisher's Protected Least Significant Difference where α = .05.

rates were similar to 2X rates at 21 DA PRE and 21 DA POST.

Weed biomass 45 DA POST in the nontreated control averaged 1534 and 1250 g m$^{-2}$ in 2017 and 2018, respectively (Table 8). Weed biomass reductions from 95–98% were achieved from all herbicide treatments in 2017, except pyroxasulfone/fluthiacet fb dicamba/tembotrione (90%). In 2018, 97% biomass reduction was achieved with clopyralid/acetochlor/mesotrione fb topramezone/dimethenamid-P. All other herbicide treatments at labeled rates in 2018 resulted in weed biomass reductions from 68–74%. Biomass reduction was similar in 1X rate herbicide treatments to 2X rates.

### 3.3 | Popcorn yield loss

Averaged among popcorn hybrids, yield loss ranged from 1–7% and did not differ among herbicide treatments and weed-free control (Table 5). The nontreated control resulted in 42% yield loss compared with the weed-free control. Yield loss was similar among 1X and 2X rates. Yield loss did not vary by hybrid.

## 4 | DISCUSSION

The two white popcorn hybrids tested, VWP111 and SH3707W, did not result in more herbicide injury than the six yellow popcorn hybrids tested in this research. These findings are inconsistent with the assumption that white popcorn hybrids are inherently more sensitive to herbicides than yellow hybrids (Loux et al., 2017); however, the few hybrids tested are not enough to make a generalized conclusion about the effect of hybrid color. Height reduction due to PRE herbicides was observed only in 2017 at 2X rates and was dependent on hybrid. Clopyralid/acetochlor/mesotrione (Resicore) is not labeled for white popcorn (Corteva Agriscience, 2017). However, this herbicide did not result in a high level of injury, even at the 2X rate, suggesting that there may not be a strong reason or justification for keeping white popcorn off of the label, but more white popcorn hybrid screening may be warranted prior to labeling herbicides for use in white popcorn. Mesotrione/fluthiacet (Solstice) is also only labeled for yellow popcorn; however, when following label instructions for yellow popcorn (Not to add urea ammonium nitrate [UAN] or ammonium sulfate [AMS] and to use nonionic surfactant [NIS]; FMC Corporation, 2013), minimal injury occurred, regardless of the application rate or hybrid color. 4-Hydroxyphenylpyruvate dioxygenase-(HPPD) inhibiting herbicide tolerance in sweet corn hybrids has been reported to be hybrid dependent (Bollman et al., 2008; O'Sullivan, Zandstra, & Sikkema, 2002). Further investigation into sensitivity of sweet corn to HPPD-inhibiting herbicides concluded that hybrid sensitivity was linked to a mutation of the P450 allele, and that hybrids that are homozygous for the nonmutated allele are rarely injured at labeled rates (Williams & Pataky, 2008, 2010). This allele in sweet corn confers tolerance to other P450-metabolized herbicides such as bentazon, carfentrazone, dicamba/diflufenzopyr, foramsulfuron, halosulfuron, and primisulfuron (Nordby et al., 2008; Williams et al., 2008). Although greater injury was observed from saflufenacil/dimethamid-P fb diflufenzopyr/dicamba at a 2X rate, popcorn yield loss was not influenced.

Broadleaf weed control was achieved with all herbicide treatments; however, grass weed control was poor for all treatments, except clopyralid/acetochlor/mesotrione fb topramezone/dimethenamid-P. The high foxtail density and the subsequent lack of control provided by most herbicide treatments was a major contributor to increased total weed density and biomass in 2018 compared with 2017. The efficacy of topramezone on grass weeds is an advantage for popcorn production fields with a history of high grass weed densities, as it has shown to be effective on a number of grass weed species (Grossmann & Ehrhardt, 2007). Additionally, growers have been using nicosulfuron (Accent Q, Corteva Agriscience, 2009) and nicosulfuron/mesotrine (Revulin Q; Corteva Agriscience, 2015) herbicides for grass weed control in yellow popcorn production. Sarangi and Jhala (2018) reported 95, 91, and 82% control of velvetleaf, Palmer amaranth, and foxtails, respectively, 28 d after treatment (DAT) with saflufenacil/dimethenamid; and reported velvetleaf, Palmer amaranth, and foxtail densities 42 DAT of 6, 17, and 16 plants $m^{-2}$, respectively, which is consistent with the control achieved in this study. In a dose response study with 10-cm-tall common waterhemp, mesotrione/fluthiacet resulted in >90% control and biomass reduction 21 DAT, similar to the results obtain in this study (Ganie, Stratman, & Jhala, 2015). Similar Palmer amaranth control (95–100%) with acetochlor/atrazine has been reported in the literature (Janak & Grichar, 2016). Chahal et al. (2018) reported 90% Palmer amaranth control and 82% biomass reduction 28 DA POST from saflufenacil/dimethamid-P fb diflufenzopyr/dicamba. Hauver, Chahal, Watteyne, and Jhala (2017) reported 93% control of Palmer amaranth with clopyralid/acetochlor/mesotrione. Parks, Curran, Roth, Hartwig, and Calvin (1995) reported 96% common lambsquarters control 56 DAT with rates of dicamba similar to the ones used in this study.

### 4.1 | Recommendations and practical implications

Weed control in popcorn is important and challenging due to limited herbicide options compared with field corn. The research was designed to determine the response of commonly grown yellow and white popcorn hybrids in Nebraska to PRE and POST herbicides. Selected yellow and white popcorn hybrids were not sensitive to herbicides tested in this research, with low observed injury and minimal yield loss, even at higher than labeled rates. Although a few hybrid differences to herbicide tolerance were detected, the differences did not appear to be linked to hybrid kernel color and did not translate into detectable yield losses. The tested herbicide treatments provided adequate control of broadleaf weeds and, if labeled, can be recommended to popcorn growers. Additional measures for grass weed control may be necessary, depending on field history and herbicide treatment. The tested herbicide treatments combine PRE fb POST herbicide application and herbicides with multiple sites of action, which are key to delay the evolution of herbicide-resistant weeds (Norsworthy et al., 2012). Not all herbicide treatments are labeled in white popcorn and producers should refer to label instructions. Results from this research are the first to determine popcorn sensitivity to herbicides, and can be of immediate use in practical applications to popcorn producers, crop consultants, popcorn companies, and herbicide manufacturers, and can contribute to enhance popcorn production efficiency.

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