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Short title: Volunteer soybean in corn

Control of dicamba/glufosinate/glyphosate-resistant volunteer soybean in corn with preemergence and postemergence herbicides

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Abstract

The widespread adoption of multiple herbicide-resistant corn and soybean often causes the problem of volunteers in corn-soybean rotation, which necessitates alternative herbicides for effective management. The objective of this research was to evaluate preemergence (PRE) and postemergence (POST) herbicides labelled in corn for control of dicamba/glufosinate/glyphosate-resistant volunteer soybean. Field experiments were conducted from 2021 to 2023 near Clay Center, Nebraska. Two separate field experiments were conducted to evaluate 12 PRE and 14 POST herbicides to control volunteer soybean in Enlist corn. Soybean resistant to dicamba/glufosinate/glyphosate was planted perpendicular to corn rows to mimic volunteer soybean. Among PRE herbicides tested, acetochlor/clopyralid/flumetsulam (1,190; 1,050/106/34 g ai ha^{-1}) and acetochlor/clopyralid/mesotrione (2,304; 1,961/133/210 g ai/ae ha^{-1}) provided 97% and 99% control of volunteer soybean, respectively, in 2021, and 68% and 89% control, respectively, in 2023 at 42 d after PRE. Among POST herbicides tested, 2,4-D choline (1,064 g ae ha^{-1}), acetochlor/clopyralid/mesotrione (2,304; 1,961/133/210 g ai/ae ha^{-1}), atrazine/bicyclopyrone/mesotrione/*S*-metolachlor (2,409; 700/42/168/1,499 g ai ha^{-1}), clopyralid/flumetsulam (192; 146/46 g ai ha^{-1}), nicosulfuron + atrazine (34 + 1,120 g ai ha^{-1}), and thiencarbazone-methyl/tembotrione + atrazine (76; 12/63 + 896 g ai ha^{-1}) provided ≥ 97% volunteer soybean control, ≥ 94% density reduction, and ≥ 97% biomass reduction 28 d after POST herbicide application. Corn yield did not differ from the weed-free control in these treatments. The results of this study suggest that PRE and POST herbicides are available for control of dicamba/glufosinate/glyphosate-resistant volunteer soybean in Enlist corn, and careful selection of herbicide is required based on the herbicide-resistant soybean planted previous year.

Nomenclature: 2,4-D choline; acetochlor/clopyralid/flumetsulam; acetochlor/clopyralid/mesotrione; atrazine; atrazine/bicyclopyrone/mesotrione/*S*-metolachlor; clopyralid/flumetsulam; nicosulfuron; thiencarbazone-methyl/tembotrione; corn, *Zea mays* L.; soybean, *Glycine max* (L.) Merr.

Keywords: Crop volunteers; dicamba-resistant soybean; Enlist corn; herbicide-resistant; volunteer soybean.

Introduction

The United States is the leading producer and the second-largest exporter of soybean in the world (USDA-ERS 2024). Soybean accounts for over 90% of oilseed production in the United States (USDA-ERS 2024). In 2023, the United States produced 113.3 million MT of soybean from 33.3 million ha (USDA-NASS 2024). About 42% of soybean (i.e., 48 million MT) worth $27.7 billion was exported in 2023 (USDA-FAS 2023). Domestically, soybean is primarily used for animal feed, cooking oil, and biodiesel (USDA 2015).

Soybean grain harvests are a major operation for growers each year, covering over 2 million ha in Nebraska and Indiana, about 3 million ha in Minnesota, and exceeding 4 million ha in major soybean-producing states like Illinois and Iowa [USDA-NASS 2024b]. Volunteer soybean emerges from soybean seeds lost in the previous season. As per soybean harvest loss estimates, about 2% to 4% of potential soybean yield, equating to 67 to 134 kg ha^{-1}, is typically lost under good harvest conditions (Gliem et al. 1990; Huitink 2020; Staton 2023). Soybean harvest loss can exceed 134 kg ha^{-1} in certain situations such as green stems, lodged plants, harvest delays causing brittle pods, short plants with low-hanging pods, etc. (Staton 2023). Volunteer soybean is usually not a concern for growers in subsequent cropping seasons, but it may occur as scattered plants or substantial stands during occasional years when seed shattering or harvest losses are high, or when soybean is not harvested or partially harvested due to extreme weather events (Jhala et al. 2013). Though not always a concern for corn growers, season-long interference of volunteer soybean at a density of 3.5 plants m^{-2} (19.4 kg ha^{-1} seed loss, assuming 30% germination/survival and 6,000 seeds kg^{-1}) can reduce 10% of corn yield (Alms et al. 2016); therefore, control of volunteer soybean may be warranted depending on the level of infestation.

Growers can modify herbicide programs that are labelled in corn for control of volunteer soybean; however, multiple herbicide-resistant soybean have been developed and adopted, which makes it complex for growers to choose an effective herbicide for controlling volunteer soybean. For example, 2,4-D/glufosinate/glyphosate would not kill soybean volunteers possessing the Enlist E3 trait (2,4-D/glufosinate/glyphosate-resistant; Corteva Agriscience, Indianapolis, IN), and dicamba/glufosinate/glyphosate would not control volunteer soybean with the XtendFlex trait (dicamba/glufosinate/glyphosate-resistant; Bayer Crop Science, St. Louis, MO). Similarly, 4-hydroxyphenylpyruvate dioxygenase (HPPD)-inhibitor such as isoxaflutole (and glufosinate/glyphosate) would not be an effective option for managing LibertyLink GT 27 soybean (BASF Corporation, Florham Park, NJ) volunteers resistant to glufosinate/glyphosate/isoxaflutole. Thus, the widespread cultivation of soybean traits with resistance to one or more herbicides limits the available herbicide options for controlling multiple herbicide-resistant soybean volunteers.

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Growers use pre-emergence (PRE) and/or post-emergence (POST) herbicides to control weeds in corn. Sometimes, precipitation during early spring may wet the soil, delaying PRE herbicide application until after weeds have become established, or excessive rainfall can leach down PRE herbicide that was applied before rain events depending on the solubility of the herbicide (Jhala 2017). In contrast, a lack of moisture can also reduce the efficacy of residual herbicides. In such circumstances, POST herbicides might be the only option to control emerged weeds. Some extension publications (Cahoon et al. 2019; Currie and Geier 2018) and conference proceedings (Zollinger and Ries 2004) list PRE and/or POST herbicides for control of volunteer soybean in corn or other crops, such as cotton (*Gossypium hirsutum* L.) (York et al. 2005) and rice (*Oryza sativa* L.) (Bond and Walker 2009). Alms et al. (2016) evaluated five POST herbicides for control of glyphosate-resistant volunteer soybean in corn in South Dakota; however, there is limited scientific literature is available evaluating both PRE and POST corn herbicides for the control of multiple herbicide-resistant volunteer soybean in corn. In addition, several PRE herbicides with multiple active ingredients have been labelled in corn in the last few years. Many fields may contain dicamba-resistant soybean volunteers, as these varieties have been widely adopted in the United States since their commercialization in 2016 (Wechsler et al. 2019). Further, recent commercialization of corn resistant to 2,4-D/aryloxyphenoxypropionates/glufosinate/glyphosate (Enlist corn) enables the use of 2,4-D choline for controlling broadleaf weeds. The objectives of this study were to evaluate PRE and POST herbicides for control of dicamba/glufosinate/glyphosate-resistant volunteer soybean in Enlist corn and their effect on volunteer soybean density, biomass, and corn yield.

Materials and Methods

Site Description and Experimental Design

Field experiments were conducted at the University of Nebraska-Lincoln's South Central Ag Lab near Clay Center, NE (40.57°N, 98.13°W). The experimental site had silt loam soil (montmorillonitic, mesic, Pachic Argiustolls) with a sand:silt:clay percentage ratio of 17:58:25, a pH of 6.5, and 3.0% organic matter. The field was irrigated through a center-pivot irrigation system. Two separate field experiments were conducted from 2021 to 2023 to evaluate PRE (2021 & 2023) and POST (2021-22) herbicides for control of dicamba/glyphosate/glufosinate-resistant soybean volunteers in Enlist corn. Both experiments were conducted using a randomized complete block design with three replications. The plot size was 3 m × 9 m with four rows of Enlist corn (Hoegemeyer 8097 SXE™, NK29-Z4E3) planted at 76 cm row spacing. Volunteer soybean (Asgrow® AG27XF0, NK31-J9XF) was planted perpendicular to corn in 76 cm wide rows at about 4 cm depth. Dates of planting and the seeding rate of corn and volunteer soybean along with the timing of the PRE and POST herbicide applications are given in Table 1.

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The treatments and application rates used in the PRE and POST experiments are listed in Table 2 and Table 3, respectively. Additionally, nontreated and weed-free treatments were included in each experiment for comparison. Volunteer soybeans in weed-free plots were killed with hand-weeding and POST herbicide application. PRE herbicides were applied within one day of planting corn, and POST herbicides were applied when corn and volunteer soybean were around the V4 to V5 and V3 to V4 stage, respectively (Table 1). In 2021, the experimental sites received two additional POST applications of glyphosate (Roundup PowerMAX®, Bayer CropScience) at 1,260 g ae ha^{-1} on May 26 and June 9 for in-season weed control. Similarly, in 2022, pyroxasulfone (Zidua®SC, BASF Corporation, Research Triangle Park, NC) at 128 g ai ha^{-1} plus glufosinate (Liberty® 280 SL, BASF Corporation) at 655 g ai ha^{-1} was applied on June 24 to the POST herbicide experimental site. In 2023, pyroxasulfone at 147 g ai ha^{-1} plus glyphosate at 1,260 g ae ha^{-1} was applied on May 31 to the PRE herbicide experimental site. These herbicides labeled for use in soybean were applied to control non-target weeds naturally present in the study area. Weed-free plots received a PRE application of atrazine/bicyclopyrone/mesotrione/*S*-metolachlor (Acuron®, Syngenta Crop Protection, Greensboro, NC) at 2,900 g ai ha^{-1} and a POST application of acetochlor (Warrant Herbicide, Bayer CropScience, St. Louis, MO) at 1,260 g ai ha^{-1} plus dicamba (DiFlexx®, Bayer CropScience) at 420 g ae ha^{-1} for broad-spectrum weed control. Herbicides were applied using a CO_2-pressurized backpack sprayer, delivering a spray volume of 140 L ha^{-1} at 276 kPa. The sprayer was equipped with 11015 Turbo TeeJet Induction nozzles for PRE herbicides and 110015 AIXR flat-fan nozzles (TeeJet Spraying Systems Co., Wheaton, IL) for POST herbicides.

Data Collection and Statistical Analysis

Control of volunteer soybean was recorded at 28, 42, and 63 d after PRE (DAPRE) and 14 and 28 after POST (DAPOST) herbicide application using a scale of 0% to 100%, with 0% meaning no control and 100% meaning that plants were completely dead. Enlist corn injury was recorded on a similar scale of 0% to 100% at 14 and 28 DAPRE/POST herbicide application. Volunteer soybean density was recorded by counting the number of plants in a 1 m soybean row distance with three repetitions by randomly placing a 1 m scale in the middle two corn rows in each plot. After counting volunteer soybean plants, two 0.25 m^2 quadrats were randomly placed in each plot to collect aboveground volunteer soybean biomass, followed by oven-drying (70 C) to a constant weight to record dry biomass. Volunteer soybean density and biomass data were taken 63 DAPRE in 2021 and 28 DAPRE in 2023 for the PRE herbicide experiment, and 28 DAPOST for both years (2021 and 2022) of the POST herbicide experiment. Percent reduction (relative to the nontreated control) in volunteer soybean density and biomass were calculated using Equation 1 (Singh et al. 2023):

$$Y = \left[\frac{A-B}{A}\right] \times 100 \qquad [1]$$

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where *A* represents volunteer soybean density/biomass from the nontreated control plot and *B* represents volunteer soybean density/biomass from the herbicide-treated plot. At crop maturity, the grain yield of Enlist corn was recorded by harvesting the middle two rows of each plot with a small plot combine and adjusting to 15.5% moisture content.

Data were analyzed using R software ver. 4.2.2 (R Core Team 2024) for analysis. Data were checked for ANOVA assumptions of normality and homogeneity of variance using the *performance* package (Lüdecke et al. 2022). Data for corn grain yield met the ANOVA assumptions. A linear mixed-effects model was built using the *lme4* package (Bates et al. 2023) to analyze the normal data, whereas a generalized linear mixed (*glmer*) model with beta error distribution (link = ”logit”) was built using the *glmmTMB* package (Brooks et al. 2023; Stroup 2015) to analyze the non-normal data. For both models, year, herbicide, and their interaction were considered fixed factors, while replication nested within year was considered a random factor. Data were analyzed separately for each year if a year-by-herbicide interaction was significant. Data from the nontreated and weed-free controls were excluded from the analysis due to a lack of variance among replicates. If the ANOVA showed significant differences, treatment means were separated using Tukey’s method for P-value adjustments and Sidak confidence-level adjustments using the *emmeans* and *multcomp* packages (Hothorn et al. 2022; Lenth et al. 2022). For the *glmer* models, data were back transformed for presentation.

Results and Discussion

Volunteer Soybean Control with PRE Herbicides

Volunteer soybean control with PRE herbicides differed between years (Table 4). Control was relatively lower in 2023 than in 2021, probably because of less rainfall for fully activating the PRE herbicides (Figure 1). Cumulative rainfall during the first three weeks of May was 56 mm in 2021 compared to 15 mm in 2023 (Figure 1B). The PRE herbicides used in this study required at least 6 mm (Anonymous 2023, 2024) to 13 mm (Anonymous 2018, 2022) of activating rainfall (or sprinkler irrigation) within the first week of application and before the emergence of weeds. However, for optimal performance of soil-applied herbicides, approximately 51 mm of rainfall, evenly distributed over the two weeks following application, is beneficial (Johnson and Zimmer 2022). The experimental site was irrigated; however, the first irrigation in 2021 and 2023 was not applied until 41 d (June 17; 38 mm) and 20 d (May 23; 20 mm) after PRE herbicides were applied, respectively (data not shown). The crop was irrigated to meet seasonal water demand, as the growing seasons of 2021, 2022, and 2023 received 95, 118, and 50 mm less precipitation, respectively, than long-term (1990-2020) accumulated precipitation (453 mm; Figure 1 B). The average temperature during the growing seasons of 2021 to 2023 broadly followed the long-term temperature trend (Figure 1A).

Treatments containing clopyralid were the most effective, with acetochlor/clopyralid/flumetsulam (1,190; 1,050/106/34 g ai ha^{-1}) and acetochlor/clopyralid/mesotrione (2,304; 1,961/133/210 g ai/ae ha^{-1}) providing 83% and 97% control of volunteer soybean, respectively, 28 DAPRE in 2021 (Figure 2; Table 4). In 2023, acetochlor/clopyralid/flumetsulam and acetochlor/clopyralid/mesotrione provided 42% and 55% control, respectively, 28 DAPRE, which increased to 68% and 89%, respectively, by 42 DAPRE. By 63 DAPRE, control was ≥ 98% in both years in these treatments, which was greater than all other treatments in 2023. In a multi-state field experiment, Courtney (2016) found that acetochlor/clopyralid/flumetsulam (1,193; 1,053/106/34 g ha^{-1}) applied PRE reduced volunteer soybean stand by 56% in Mississippi (45 vs. 20 plants; 62 d after application, DAA), 72% in South Dakota (70 vs. 20 plants; 42 DAA), and 100% in North Carolina (55 vs 0 plants; 52 DAA).

Atrazine/bicyclopyrone/mesotrione/*S*-metolachlor (2,409; 700/42/168/1,499 g ai ha^{-1}) provided 75% control of volunteer soybean 28 DAPRE and 83% control 42 DAPRE in 2021, with almost half the efficacy in 2023. Other treatments containing HPPD-inhibitor such as acetochlor/mesotrione (2,696; 2,465/231 g ai ha^{-1}), isoxaflutole + atrazine (88 + 560 g ai ha^{-1}), and isoxaflutole/thiencarbazone-methyl + atrazine (129; 92/37 + 560 g ai ha^{-1}) provided similar control of 63% to 70% 28 DAPRE, 70% to 78% 42 DAPRE, and 75% to 89% 63 DAPRE in 2021 (Figure 3). However, in 2023, they provided 18% to 43% control 63 DAPRE. Acetochlor/atrazine (2,647/1,314 g ai ha^{-1}) provided 62% control of volunteer soybean 28 DAPRE and 45% control 42 DAPRE in 2021, whereas in 2023, it provided 48% control 28 DAPRE and 18% control 42 DAPRE. Atrazine (1,120 g ai ha^{-1}) mixed with pendimethalin (1,916 g ai ha^{-1}), pyroxasulfone (110 g ai ha^{-1}), or saflufenacil (62 g ai ha^{-1}) provided ≤ 27% control in 2021 and ≤ 32% control in 2023 28 DAPRE. Similarly, Courtney (2016) found that atrazine (1,120 g ha^{-1}) reduced volunteer soybean stand by 45% in South Dakota (70 vs. 39 plants; 42 DAA) and 51% in Mississippi (45 vs. 20 plants; 62 DAA). Dimethenamid-*P*/saflufenacil (731; 656/75 g ai ha^{-1}) and fluthiacet-methyl/pyroxasulfone (188; 5/183 g ai ha^{-1}) did not control volunteer soybean in 2021 (< 26% at 28 DAPRE) and 2023 (< 11% at 63 DAPRE), as both herbicides are labeled in soybean.

Volunteer Soybean Control with POST Herbicides

2,4-D choline (1,064 g ae ha^{-1}) provided 99% control of dicamba/glufosinate/glyphosate-resistant V3-V4 volunteer soybean 28 DAPOST in both years (Table 5; P = 0.03). Dan et al. (2011) also observed 95%-96% control of V3 volunteer soybean with 2,4-D (1,340 g ha^{-1}) 28 DAA in a greenhouse experiment. However, they observed only 64%-74% control when 2,4-D was applied at 1,005 g ha^{-1}. Zollinger and Ries (2004) observed 60% control of V4-V6 volunteer soybean with 2,4-D amine (280 g ha^{-1}) 28 DAPOST, while Theodoro et al. (2018) reported 75% control of V3 volunteer soybean 28 DAA with 2,4-D (806 g ha^{-1}) in a greenhouse experiment. Minor injury symptoms (≤ 4%)

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on Enlist corn were observed 28 DAPOST with some POST herbicides (data not shown); however, the injury was transient and was not visible later in the season. Treatments containing another synthetic auxin, i.e., clopyralid such as acetochlor/clopyralid/mesotrione (2,304; 1,961/133/210 g ai/ae ha^{-1}) and clopyralid/flumetsulam (192; 146/46 g ai ha^{-1}) provided ≥ 93% control 14 DAPOST and 99% control 28 DAPOST. Similarly, Zollinger et al. (2018) reported 90%-99% control of V2-V3 volunteer soybean with clopyralid/flumetsulam (48-96 g ha^{-1}) and clopyralid (79-105 g ha^{-1}). Zollinger and Ries (2004) also reported 95% and 75% control of V2-V3 and V4-V6 glyphosate-resistant volunteer soybean, respectively, 28 DAA with clopyralid/flumetsulam (56; 13/43 g ha^{-1}). In this study, the rate of clopyralid/flumetsulam was more than three times higher (192 vs. 56 g ha^{-1}) than Zollinger and Ries (2004), leading to better control of V3-V4 volunteer soybean (99%).

Atrazine/bicyclopyrone/mesotrione/*S*-metolachlor (2,409; 700/42/168/1,499 g ai ha^{-1}) was equally effective as herbicides containing synthetic auxins, providing similar control of 94%-98% 14 DAPOST and 98%-99% 28 DAPOST. Dan et al. (2011) reported 58% to 59% control of volunteer soybean with mesotrione (120 g ha^{-1}) 28 DAA. Theodoro et al. (2018) observed 39% control of V3 volunteer soybean with mesotrione (480 g ha^{-1}) 35 DAA. Dicamba/tembotrione (597; 521/76 g ai ha^{-1}) provided 80% to 95% control 28 DAPOST, similar to 2,4-D choline, atrazine/bicyclopyrone/mesotrione/S-metolachlor, and clopyralid-based treatments. Because the volunteer soybean used in this study was resistant to dicamba, the activity mostly came from the HPPD-inhibitor tembotrione. Volunteer soybean showed a mixed response to tembotrione in the literature, depending on the herbicide rate and growth stage. Dan et al. (2011) observed a 64%-72% control of volunteer soybean with tembotrione (100 g ha^{-1}) 28 DAA, while Alms et al. (2016) observed 87%-89% control of V3-V4 volunteer soybean with tembotrione (15 or 31 g ha^{-1}) in corn 28 DAA. However, in contrast, Theodoro et al. (2018) reported 46% control of V1 volunteer soybean and 12% control of V3 volunteer soybean with tembotrione (75 g ha^{-1}) 35 DAA. Similarly, Brighenti (2015) noted a 5%-13% control of V3 volunteer soybean in sunflower (*Helianthus annuus* L.) with tembotrione (21 g ha^{-1}) 7-21 DAA. Dimethenamid-*P*/topramezone (937; 919/18 g ai ha^{-1}) provided 47%-50% control of volunteer soybean 14 DAPOST and 85%-89% control 28 DAPOST. Currie and Geier (2018) noted 95% control of dicamba-resistant soybean 5 DAA and 100% control 82 DAA with dimethenamid-*P*/topramezone (736 g ha^{-1}) + atrazine (560 g ha^{-1}) and glyphosate (1,260 g ha^{-1}). Currie and Geier (2018) reported higher control of volunteer soybean (95%-100% vs. 85%-89%), despite applying a lower dose of dimethenamid-*P*/topramezone (736 vs. 937 g ha^{-1}), probably because atrazine (560 g ha^{-1}) was another effective herbicide in their treatment.

Atrazine (1,120 and 896 g ai ha^{-1}) mixed with nicosulfuron (34 g ai ha^{-1}) and thiencarbazone-methyl/tembotrione (75; 12/63 g ai ha^{-1}) provided ≥ 97% control of V3-V4 volunteer soybean 28 DAPOST. Zollinger et al. (2018) reported 80% to 90% control of V2-V3 and V4-V6 glyphosate-resistant volunteer soybean with atrazine + thiencarbazone-methyl/tembotrione (420 + 91 g ha^{-1}). The

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atrazine rate for the atrazine + thiencarbazone-methyl/tembotrione was more than double (896 vs. 420 g ha^{-1}) that used by Zollinger et al. (2018), although the thiencarbazone-methyl rate was 16 g ha^{-1} lower in this study (75 vs. 91 g ha^{-1}). With a lower rate of atrazine than this study, Theodoro et al. (2018) reported 100% control of V3 volunteer soybean 35 DAA with atrazine + nicosulfuron (500 + 40 g ha^{-1}) and atrazine + tembotrione (500 + 75 g ha^{-1}) in a greenhouse experiment. Nicosulfuron (40 g ha^{-1}) and tembotrione (75 g ha^{-1}) alone provided 42% and 12% control of volunteer soybean, respectively, in their study. Knezevic et al. (2014) observed that atrazine (560 g ha^{-1}) mixed with tembotrione (92 g ha^{-1}), or topramezone (25 g ha^{-1}), or mesotrione (105 g ha^{-1}) provided 90% to 100% control of V2-V3 glyphosate-resistant volunteer soybean and 66%-69% control of V4-V6 glyphosate-resistant volunteer soybean 14 DAA. Volunteer soybean control with glufosinate + atrazine (655 + 896 g ai ha^{-1}) varied by year, with 69% and 97% control 28 DAPOST in 2021 and 2022, respectively. Similarly, Alms et al. (2016) observed varying control with atrazine (1,120 g ha^{-1}); 98% control 56 DAA of V2 volunteer soybean in one year and 59% control 28 DAA of V3-V4 volunteer soybean in another year. Dan et al. (2011) observed 100% control of volunteer soybean with higher rate of atrazine (1,500 g ha^{-1}) 28 DAA. Zollinger and Ries (2004) reported 70% control of V4-V6 glyphosate-resistant volunteer soybean with atrazine (560 g ha^{-1}) 28 DAPOST. Carfentrazone-methyl (9 g ai ha^{-1}), fluthiacet-methyl (6 g ai ha^{-1}), fluthiacet-methyl/mesotrione (98; 5/93 g ai ha^{-1}), and tolpyralate (35 g ai ha^{-1}) provided < 50% control of volunteer soybean. Similarly, Brighenti et al. (2015) noted that carfentrazone (4 g ha^{-1}) did not provide effective control (23%; 7 DAA) of V3 volunteer soybean.

Among PRE herbicides, clopyralid-based herbicides (acetochlor/clopyralid/flumetsulam and acetochlor/clopyralid/mesotrione) controlled ≥ 98% of dicamba/glufosinate/glyphosate-resistant volunteer soybean by 63 DAPRE during both years. Similarly, clopyralid-based POST herbicides (acetochlor/clopyralid/mesotrione and clopyralid/flumetsulam) provided 99% volunteer soybean control by 28 DAPOST during both years. Atrazine-based POST treatments such as atrazine/bicyclopyrone/mesotrione/*S*-metolachlor, atrazine + nicosulfuron, and atrazine + thiencarbazone-methyl/tembotrione also controlled ≥ 97% of dicamba/glufosinate/glyphosate-resistant volunteer soybean by 28 DAPOST. These herbicide options can also be valuable for controlling soybean volunteers with Enlist E3 (2,4-D/glufosinate/glyphosate-resistance), LibertyLink GT 27 (glufosinate/glyphosate/isoxaflutole-resistance), or Roundup Ready 2 Xtend (dicamba/glyphosate-resistance) traits, as they lack resistance to clopyralid, atrazine, etc. Factors such as soil organic matter, pH, texture, clay content, amount of rainfall, and growth stage of volunteer soybeans are important to consider when determining herbicide rates and assessing carryover potential (Courtney 2016).

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Volunteer Soybean Density and Biomass with PRE and POST Herbicides

Clopyralid-based PRE herbicides, i.e., acetochlor/clopyralid/flumetsulam (1,190; 1,050/106/34 g ai ha^{-1}) and acetochlor/clopyralid/mesotrione (2,304; 1,961/133/210 g ai/ae ha^{-1}), provided ≥ 98% control of volunteer soybean that resulted in 100% reduction in density and biomass of volunteer soybean relative to the nontreated control 63 DAPRE in 2021 (Table 6). However, these treatments had only a 52%-55% reduction of volunteer soybean biomass 28 DAPRE in 2023. Herbicides containing HPPD-inhibitor such as acetochlor/mesotrione, atrazine/bicyclopyrone/mesotrione/*S*-metolachlor, and isoxaflutole + atrazine, isozaflutole/thiencarbazone-methyl + atrazine provided 85%-95% biomass reduction with 44%-85% volunteer soybean density reduction 63 DAPRE in 2021. In 2023, these treatments had a 37%-63% biomass reduction 28 DAPRE. Among POST herbicides, synthetic auxin or HPPD-inhibitor-containing treatments such as 2,4-D choline, acetochlor/clopyralid/mesotrione, clopyralid/flumetsulam, atrazine/bicyclopyrone/mesotrione/*S*-metolachlor, thiencarbazone-methyl/temborione + atrazine provided 98%-100% biomass reduction and 96%-100% density reduction of volunteer soybean relative to the nontreated control 28 DAPOST (Table 7). Courtney (2016) observed a 100% stand reduction of V3-V4 volunteer soybean with acetochlor/clopyralid/flumetsulam (1,193; 1,053/106/34 g ha^{-1}) in corn in North Carolina, and a 69% stand reduction in Mississippi (45 vs. 14 plants) and South Dakota (70 vs. 22 plants) 28 DAPOST.

Corn Yield

Averaged across 2021 and 2023, corn yield across PRE herbicides (15,017-17,413 kg ha^{-1}) was similar to the nontreated control (15,481 kg ha^{-1}; Table 6). Corn yield in the POST herbicide experiment varied by year (Table 7; P = 0.026). Corn yield did not differ among POST herbicides, except for the nontreated control in 2022 (7,412 kg ha^{-1}), when the volunteer soybean seeding rate was more than double compared to 2021 (32.5 vs. 12.5 plants m^{-2}). The nontreated control had 36% less yield than atrazine/bicyclopyrone/mesotrione/*S*-metolachlor in 2022. Similarly, Alms et al. (2016) estimated 37% corn yield loss with volunteer soybean at 33 plants m^{-2}. However, as an overall assessment combined across years, volunteer soybean did not cause significant yield loss, even when not controlled with PRE or POST herbicides. It must be noted that in each experiment, other weeds were mostly controlled using PRE and POST herbicides.

Practical Implications

Although volunteer soybean is not always a primary concern for corn growers implementing a corn-soybean rotation, it can become problematic in certain situations. The widespread adoption of multiple herbicide-resistant soybean traits can complicate the management of volunteer soybean because certain herbicides would not be effective, depending on the herbicide-resistant traits present in the soybean grown in the previous year. In this study, PRE and POST herbicides labeled in corn were evaluated for control of dicamba/glufosinate/glyphosate-resistant soybean volunteers. Among PRE herbicides, treatments containing clopyralid, such as acetochlor/clopyralid/flumetsulam (1,190 g ai ha^{-1}) and acetochlor/clopyralid/mesotrione (2,304 g ai/ae ha^{-1}) provided ≥ 98% control of volunteer soybean by 63 DAPRE in 2021 and 2023. The activating rainfall (or sprinkler irrigation) is crucial for PRE herbicides as they provided 83% to 97% control by 28 DAPRE in 2021; and 68% to 89% control by 42 DAPRE in 2023, likely due to more rainfall around the PRE application in 2021 than 2023. Atrazine/bicyclopyrone/mesotrione/*S*-metolachlor (2,409 g ai ha^{-1}) provided 87% control 63 DAPRE in 2021. In this study, volunteer soybean was planted at a depth of approximately 4 cm; however, soybean volunteers emerging from shallow or bare soil surfaces in no-till fields may not be effectively controlled by PRE herbicides, as these require contact with germinating seedlings. Among POST herbicides, 2,4-D choline (1,064 g ae ha^{-1}) and clopyralid-containing programs such as acetochlor/clopyralid/mesotrione (2,304 g ai/ae ha^{-1}) and clopyralid/flumetsulam (192 g ai ha^{-1}) provided 99% control of dicamba/glufosinate/glyphosate-resistant volunteer soybean in Enlist corn 28 DAPOST. Atrazine-based mixtures such as atrazine + nicosulfuron (1,120 + 34 g ai ha^{-1}) and atrazine + thiencarbazone-methyl/tembotrione (896 + 75 g ai ha^{-1}) provided ≥ 97% control of volunteer soybean 28 DAPOST. It is concluded that PRE and POST herbicide options are available that can control dicamba/glufosinate/glyphosate-resistant soybean volunteers in Enlist corn; however, herbicide should be carefully selected based on the herbicide-resistant soybean planted in the previous year. Due to the widespread adoption of dicamba/glufosinate/glyphosate-resistant soybean, these herbicides will not control volunteer soybean. Moreover, volunteer soybean should be targeted at an early vegetative stage for better control with POST herbicides (Alms et al. 2016; Knezevic et al. 2014; Zollinger and Ries 2004).

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Competing interests

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Table 1. Planting time and seeding rate of corn and volunteer soybean, and application timing of pre-emergence (PRE) and post-emergence (POST) herbicides for control of volunteer soybean in Enlist corn in field experiments conducted near Clay Center, NE from 2021 to 2023.

Year	Planting time		Seeding rate		Herbicide application time
	Enlist corn	Volunteer soybean	Enlist corn	Volunteer soybean[a]	
			--------------seeds ha^{-1}-------------		
	Pre-emergence herbicide study				
2021	May 7	May 5	87,500	125,000	May 7
2023	May 2	May 2	87,500	200,000	May 3
	Post-emergence herbicide study				
2021	May 7	May 5	87,500	125,000	June 15
2022	June 16	June 16	87,500	325,000	July 12

[a]Bin-run soybean seeds were planted to mimic volunteer soybean. The seeding rate was increased in 2022 and 2023 due to low germination of bin-run seeds.

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Table 2. List of pre-emergence herbicides, their common and trade names, sites of action, application rates, manufacturers, and adjuvants used with their application.

Common name	Trade name	SOA[a]	Rate[b]	Manufacturer[c]	Adjuvant[b]
			g ai or ae ha^{-1}		
Acetochlor/atrazine	Degree Xtra®	15,5	3,961 (2,647/1,314)	Bayer	-
Acetochlor/clopyralid/flumetsulam	Surestart® II	15,4,2	1,190 (1,050/106/34)	Corteva	-
Acetochlor/clopyralid/mesotrione	Resicore®	15,4,27	2,304 (1,961/133/210)	Corteva	0.25% v/v NIS
Acetochlor/mesotrione	Harness® MAX	15,27	2,696 (2,465/231)	Bayer	3.0% v/v AMS
Atrazine/bicyclopyrone/mesotrione/*S*-metolachlor	Acuron®	5,27,27,15	2,409 (700/42/168/1,499)	Syngenta	1.0% v/v COC
Dimethenamid-*P*/saflufenacil	Verdict®	15,14	731 (656/75)	BASF	1.0% v/v MSO
Fluthiacet-methyl/pyroxasulfone	Anthem® Maxx	14,15	188 (5/183)	FMC	0.25% v/v NIS
Isoxaflutole + atrazine	Balance® Flexx + AAtrex®4L	27 + 5	88 + 560	Bayer, Syngenta	1.0% v/v COC
Isoxaflutole/thiencarbazone-methyl + atrazine	Corvus® + AAtrex®4L	27,2 + 5	129 (92/37) + 560	Bayer, Syngenta	1.0% v/v COC + 3.0% v/v AMS
Pendimethalin + atrazine	Prowl® H2O + AAtrex®4L	3 + 5	1,916 + 1,120	BASF, Syngenta	-
Pyroxasulfone + atrazine	Zidua®SC + AAtrex®4L	15 + 5	110 + 1,120	BASF, Syngenta	1.0% v/v COC
Saflufenacil + atrazine	Sharpen® + AAtrex®4L	14 + 5	62 + 1,120	BASF, Syngenta	1.0% v/v MSO + 3.0% v/v AMS

[a]SOA: Herbicide Site of Action as per the classification list by the Weed Science Society of America.

[b]Abbreviations: ai, active ingredient; AMS, ammonium sulfate (N-Pak® AMS Liquid, Winfield United, LLC., St. Paul, MN 55164); COC, crop oil concentrate (Crop oil concentrate, KALO, Inc, Overland Park, KS 66213); MSO, methylated seed oil (Methylated seed oil surfactant, Loveland Products, INC., Greeley, CO 80632); NIS, non-ionic surfactant (Preference®, Nonionic surfactant and Antifoaming agent, Winfield United, LLC., St. Paul, MN 55164); % v/v, volume/volume percentage.

[c]BASF Corporation, Research Triangle Park, NC 27709; Bayer CropScience LP, St. Louis, MO 63167; Corteva Agriscience LLC, Indianapolis, IN 46268; FMC Corporation, Philadelphia, PA 19104; Syngenta Crop Protection, LLC, Greensboro, NC 27419.

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Table 3. List of postemergence herbicides, their common and trade names, sites of action, application rates, manufacturers, and adjuvants used with their application.

Common name	Trade name	SOA[a]	Rate[b]	Manufacturer	Adjuvant[b]
			g ai or ae ha^{-1}		
2,4-D choline	Enlist One®	4	1,064	Corteva	-
Acetochlor/clopyralid/mesotrione	Resicore®	15,4,27	2,304 (1,961/133/210)	Corteva	0.25% v/v NIS
Acetochlor/mesotrione	Harness® MAX	15,27	2,157 (1,972/185)	Bayer	0.25% v/v NIS + 3.0% v/v AMS
Atrazine/bicyclopyrone/mesotrione/S-metolachlor	Acuron®	5,27,27,15	2,409 (700/42/168/1,499)	Syngenta	1.0% v/v COC
Carfentrazone-methyl	Aim®EC	14	9	FMC	0.25% v/v NIS
Clopyralid/flumetsulam	Hornet®	4,2	192 (146/46)	AMVAC	0.25% v/v NIS
Dicamba/tembotrione	DiFlexx® DUO	4,27	597 (521/76)	Bayer	1.0% v/v COC
Dimethenamid-*P*/topramezone	Armezon® PRO	15,27	937 (919/18)	BASF	0.25% v/v NIS + 3.0% v/v AMS
Fluthiacet-methyl	Cadet™	14	6	FMC	0.25% v/v NIS + 3.0% v/v AMS
Fluthiacet-methyl/mesotrione	Solstice®	14,27	98 (5/93)	FMC	0.25% v/v NIS
Glufosinate + atrazine	Liberty® 280 SL + AAtrex®4L	10 + 5	655 + 896	BASF, Syngenta	3.0% v/v AMS
Nicosulfuron + atrazine	Accent® Q + AAtrex®4L	2 + 5	34 + 1,120	Corteva, Syngenta	1.0% v/v COC
Thiencarbazone-methyl/tembotrione + atrazine	Capreno® + AAtrex®4L	2 + 5	75 (12/63) + 896	Bayer, Syngenta	1.0% v/v COC + 3.0% v/v AMS
Tolpyralate	Shieldex®400SC	27	35	Summit Agro USA	0.25% v/v NIS + 2.5% v/v AMS

[a]SOA: Herbicide Site of Action as per the classification list by the Weed Science Society of America.

[b]Abbreviations: ai, active ingredient; ae, acid equivalent; AMS, ammonium sulfate (N-Pak® AMS Liquid, Winfield United, LLC., St. Paul, MN 55164); COC, crop oil concentrate (Crop oil concentrate, Kalo, Inc, Overland Park, KS 66213); MSO, methylated seed oil (Methylated seed oil surfactant, Loveland Products, INC., Greeley, CO 80632); NIS, non-ionic surfactant (Preference®, Nonionic surfactant and Antifoaming agent, Winfield United, LLC., St. Paul, MN 55164); % v/v, volume/volume percentage.

[c]AMVAC Chemical Corporation, Newport Beach, CA 92660; BASF Corporation, Research Triangle Park, NC 27709; Bayer CropScience LP, St. Louis, MO 63167; Corteva Agriscience LLC, Indianapolis, IN 46268; FMC Corporation, Philadelphia, PA 19104; Summit Agro USA, LLC, Durham NC 27707; Syngenta Crop Protection, LLC, Greensboro, NC 27419.

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Table 4. Control of dicamba/glyphosate/glufosinate-resistant soybean volunteers 28, 42, and 63 DAPRE with PRE herbicides evaluated in field experiments conducted near Clay Center, NE in 2021 and 2023.

Herbicide	Rate[a]	Volunteer soybean control[bc]											
		28 DAPRE[a]				42 DAPRE[a]				63 DAPRE[a]			
		2021		2023		2021		2023		2021		2023	
	g ai or ae ha^{-1}	---------------------------%---------------------------											
Nontreated control	-	0		0		0		0		0		0	
Weed-free control	-	100		100		100		100		100		100	
Acetochlor/atrazine	3,961 (2,647/1,314)	62	bcdef	48	cdefgh	45	bcdef	18	ef	48	bcd	13	de
Acetochlor/clopyralid/flumetsulam	1,190 (1,050/106/34)	83	ab	42	cdefgh	97	a	68	abcd	98	a	98	a
Acetochlor/clopyralid/mesotrione	2,304 (1,961/133/210)	97	a	55	bcdefg	99	a	89	ab	99	a	98	a
Acetochlor/mesotrione	2,696 (2,465/231)	70	abcd	52	bcdefgh	70	abc	50	cde	75	abc	43	bcde
Atrazine/bicyclopyrone/mesotrione/*S*-metolachlor	2,409 (700/42/168/1,499)	75	abc	40	defgh	83	abc	42	cdef	87	ab	43	bcde
Dimethenamid-*P*/saflufenacil	731 (656/75)	25	ghi	32	efghi	30	def	5	f	32	de	10	de
Fluthiacet-methyl/pyroxasulfone	188 (5/183)	5	i	37	defghi	7	ef	10	f	4	e	10	de
Isoxaflutole + atrazine	88 + 560	63	bcde	30	efghi	75	abc	23	ef	85	ab	27	de
Isoxaflutole/thiencarbazone-methyl + atrazine	129 (92/37) + 560	70	abcd	42	cdefgh	78	abc	23	ef	89	a	18	de
Pendimethalin + atrazine	1,916 + 1,120	27	ghi	32	efghi	25	def	41	cdef	20	de	39	cde
Pyroxasulfone + atrazine	110 + 1,120	18	hi	32	efghi	18	ef	12	ef	18	de	10	de
Saflufenacil + atrazine	62 + 1,120	23	ghi	28	fghi	25	def	8	f	22	de	12	de
P-value		0.003				< 0.001				< 0.001			

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

[b]Within a given evaluation timing, values with the same letter are not different according to estimated marginal means with Tukey P-value adjustments and Sidak confidence-level adjustments.

[c]Nontreated and weed-free controls were not included in the analysis.

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Table 5. Control of dicamba/glyphosate/glufosinate-resistant soybean volunteers 14, 28, and 56 DAPOST with POST herbicides evaluated in field experiments conducted near Clay Center, NE in 2021 and 2022.

Herbicide	Rate[a]	Volunteer soybean control[bc]							
		14 DAPOST[a]				28 DAPOST[a]			
		2021		2022		2021		2022	
	g ai or ae ha^{-1}	%							
Nontreated control	-	0		0		0		0	
Weed-free control	-	100		100		100		100	
2,4-D choline	1,064	99	abcd	99	a	99	abc	99	a
Acetochlor/clopyralid/mesotrione	2,304 (1,961/133/210)	99	a	99	a	99	a	99	a
Acetochlor/mesotrione	2,157 (1,972/185)	63	abcdef	75	abcde	78	abc	88	ab
Atrazine/bicyclopyrone/mesotrione/*S*-metolachlor	2,409 (700/42/168/1,499)	98	a	94	a	99	a	98	a
Carfentrazone-methyl	9	0	h	47	cdefg	23	def	48	bcdef
Clopyralid/flumetsulam	192 (146/46)	95	a	93	a	99	a	99	a
Dicamba/tembotrione	597 (521/76)	43	defg	63	abcdef	80	abc	95	a
Dimethenamid-*P*/topramezone	937 (919/18)	47	cdefg	50	bcdefg	85	ab	89	ab
Fluthiacet-methyl	6	0	h	17	gh	23	def	22	ef
Fluthiacet-methyl/mesotrione	98 (5/93)	32	fgh	37	efgh	38	cdef	12	f
Glufosinate + atrazine	655 + 896	66	abcdef	87	abc	69	abcd	97	a
Nicosulfuron + atrazine	34 + 1,120	97	a	92	ab	99	a	97	a
Thiencarbazone-methyl/tembotrione + atrazine	75 (12/63) + 896	98	a	99	a	99	a	99	a
Tolpyralate	35	35	efgh	18	gh	62	abcde	23	def
P-value		0.028				0.027			

[a]Abbreviations: ai, active ingredient; ae, acid equivalent; DAPOST, days after post-emergence.

[b]Within a given evaluation timing, values with the same letter are not different according to estimated marginal means with Tukey P-value adjustments and Sidak confidence-level adjustments.

[c]Nontreated and weed-free controls were not included in the analysis.

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Table 6. Density and biomass reduction of volunteer soybean and Enlist corn yield affected by pre-emergence herbicides evaluated for control of dicamba/glufosinate/glyphosate-resistant volunteer soybean in field experiments conducted near Clay Center, NE in 2021 and 2023.

Herbicide	Rate[a]	Density reduction[bc]		Biomass reduction[bc]		Density reduction[bc]	Biomass reduction[bc]	Corn yield[bcd]
		63 DAPRE[a]				28 DAPRE[a]		
		2021				2023		
	g ai or ae ha^{-1}	---%---						kg ha^{-1}
Nontreated control	-	0		0		0	0	15,481
Weed-free control	-	100		100		100	100	16,735
Acetochlor/atrazine	3,961 (2,647/1,314)	50	bcd	66	bcd	8	55	15,637
Acetochlor/clopyralid/flumetsulam	1,190 (1,050/106/34)	100	a	100	a	12	52	16,463
Acetochlor/clopyralid/mesotrione	2,304 (1,961/133/210)	100	a	100	a	14	56	16,862
Acetochlor/mesotrione	2,696 (2,465/231)	44	bcd	86	ab	15	63	17,258
Atrazine/bicycyclopyrone/mesotrione/*S*-metolachlor	2,409 (700/42/168/1,499)	69	abc	89	ab	5	42	15,017
Dimethenamid-*P*/saflufenacil	731 (656/75)	49	bcd	53	cd	11	52	16,141
Fluthiacet-methyl/pyroxasulfone	188 (5/183)	19	d	8	e	7	49	17,328
Isoxaflutole + atrazine	88 + 560	44	bcd	85	abc	13	38	16,404
Isoxaflutole/thiencarbazone-methyl + atrazine	129 (92/37) + 560	85	ab	95	ab	15	37	16,396
Pendimethalin + atrazine	1,916 + 1,120	30	cd	35	de	11	45	16,080
Pyroxasulfone + atrazine	110 + 1,120	46	bcd	15	e	6	43	17,413
Saflufenacil + atrazine	62 + 1,120	35	cd	36	de	18	43	16,645
P-value		< 0.001		< 0.001		0.969	0.883	0.294

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

[b]Within a given evaluation timing, values with the same letter are not different according to estimated marginal means with Tukey P-value adjustments and Sidak confidence-level adjustments.

[c]Nontreated and weed-free controls were not included in the analysis.

[d]Yield data were combined across years (2021 and 2023) as it did not differ between years.

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Table 7. Density and biomass reduction of volunteer soybean and Enlist corn yield influenced by POST herbicides evaluated for control of dicamba/glufosinate/glyphosate-resistant volunteer soybean in field experiments conducted near Clay Center, NE in 2021 and 2022.

Herbicide	Rate[a]	Density reduction[bc]		Biomass reduction[bc]		Corn yield[bc]			
		-------------28 DAPOST[a]--------------							
		2021-2022		2021-2022		2021		2022	
	g ai or ae ha^{-1}	------------------%--------------------				--------------------kg ha^{-1}--------------------			
Nontreated control	-	0		0		14,042	a	7,412	b
Weed-free control	-	100		100		14,486	a	9,261	ab
2,4-D choline	1,064	100	ab	100	a	13,982	a	10,633	a
Acetochlor/clopyralid/mesotrione	2,304 (1,961/133/210)	100	a	100	a	14,873	a	10,384	a
Acetochlor/mesotrione	2,157 (1,972/185)	47	bcd	78	ab	14,192	a	9,188	ab
Atrazine/bicyclopyrone/mesotrione/*S*-metolachlor	2,409 (700/42/168/1,499)	99	a	100	a	14,539	a	11,504	a
Carfentrazone-methyl	9	12	d	66	ab	13,314	ab	11,340	a
Clopyralid/flumetsulam	192 (146/46)	97	a	98	a	14,849	a	10,939	a
Dicamba/tembotrione	597 (521/76)	29	d	72	ab	14,538	a	11,263	a
Dimethenamid-*P*/topramezone	937 (919/18)	34	cd	78	ab	15,056	a	11,524	a
Fluthiacet-methyl	6	14	d	43	b	13,543	ab	10,255	ab
Fluthiacet-methyl/mesotrione	98 (5/93)	8	d	50	b	14,516	a	11,269	a
Glufosinate + atrazine	655 + 896	77	abc	82	ab	14,350	a	10,234	ab
Nicosulfuron + atrazine	34 + 1,120	94	a	99	a	14,259	a	9,554	ab
Thiencarbazone-methyl/tembotrione + atrazine	75 (12/63) + 896	96	a	100	a	14,855	a	10,436	a
Tolpyralate	35	21	d	50	b	14,049	a	10,138	ab
P-value		< 0.001		< 0.001		0.026			

[a]Abbreviations: ai, active ingredient; ae, acid equivalent; DAPOST, days after post-emergence.

[b]Within a given evaluation timing, values with the same letter are not different according to estimated marginal means with Tukey P-value adjustments and Sidak confidence-level adjustments.

[c]Nontreated and weed-free controls were not included in the analysis.

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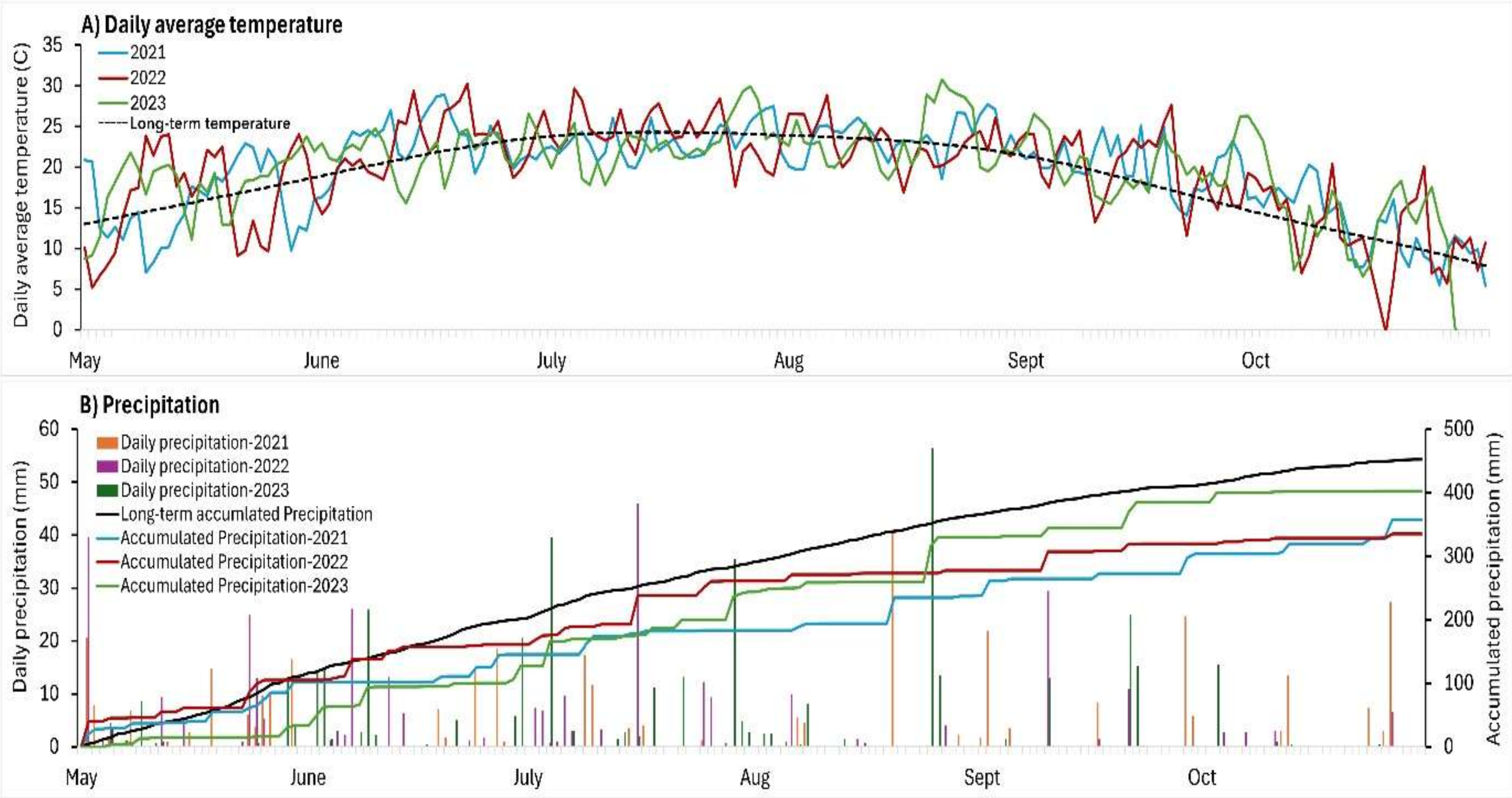

Figure 1. Daily average (A) temperature and (B) precipitation (mm) for the 2021, 2022, and 2023 growing seasons along with long-term (1990-2020) temperature and accumulated precipitation for South Central Ag Lab, near Clay Center, NE.

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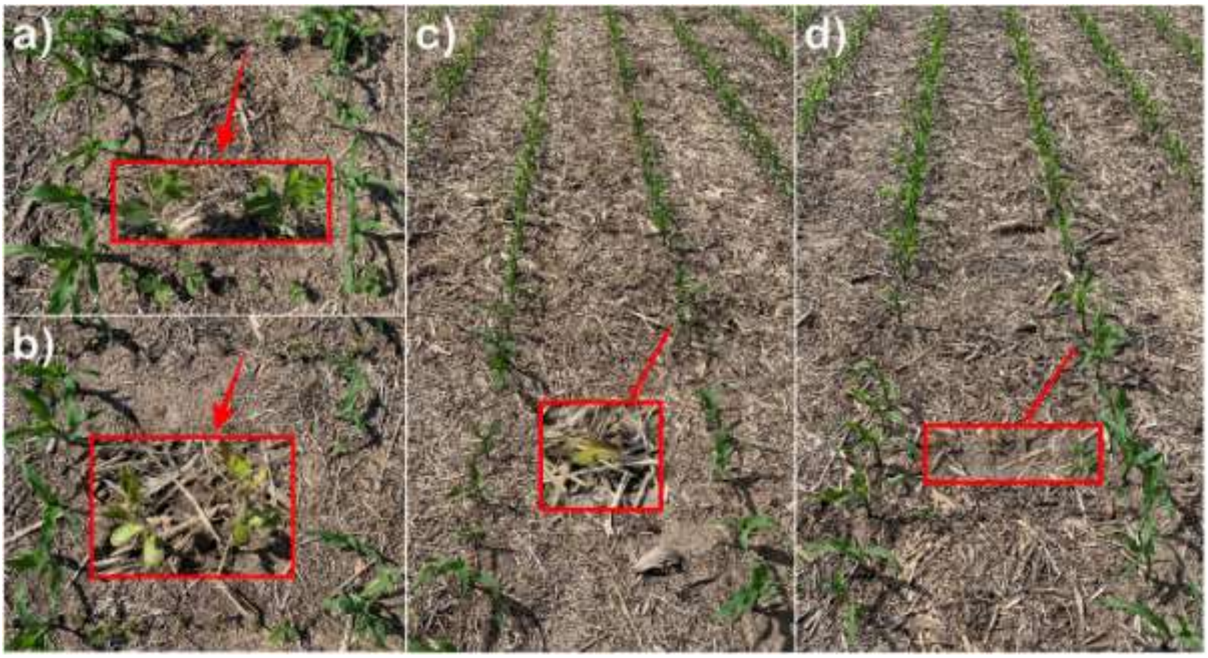

Figure 2. Dicamba/glufosinate/glyphosate-resistant volunteer soybean in a) nontreated control, b) atrazine/bicyclopyrone/mesotrione/*S*-metolachlor, c) acetochlor/clopyralid/mesotrione, and d) acetochlor/clopyralid/flumetsulam 28 d after preemergence applied in a field experiment conducted near Clay Center, NE in 2021.

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Figure 3. Injury symptoms on dicamba/glufosinate/glyphosate-resistant volunteer soybean 34 d after PRE application of isoxaflutole/thiencarbazone-methyl + atrazine (129 + 560 g ai ha^{-1}) in a field experiment conducted near Clay Center, NE in 2021.

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