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Influence of sulfentrazone and metribuzin applied preemergence on soybean development and yield

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Abstract

The use of photosystem II (PSII)-inhibitor and/or protoporphyrinogen oxidase (PPO)-inhibitor PRE herbicides in soybean may, under adverse environmental conditions, result in early season crop injury. A field study was conducted near Brule and North Platte, Nebraska, during the 2016 and 2017 growing seasons with the objective to evaluate the impact of PRE herbicides metribuzin (PSII-inhibitor) and sulfentrazone (PPO-inhibitor) on early season soybean development, final plant stand, and yield using 22 soybean varieties adapted to southwestern Nebraska. Herbicide treatments consisted of metribuzin (560 g ai ha^{-1}) and sulfentrazone (280 g ai ha^{-1}) applied within 3 d after planting and a nontreated control (NTC). Sulfentrazone reduced green canopy vegetation at the V2 growth stage by 22% and final plant stand at physiological maturity by 10% compared with the NTC. The number of pods per plant was 16% higher for sulfentrazone and the number of seeds per plant was 15% and 4% higher for sulfentrazone and metribuzin compared with the NTC, respectively. Sulfentrazone and metribuzin resulted in a slightly higher yield (3%) compared with the NTC, thus no yield reduction from PRE herbicides was observed in this study. These results support other findings that sulfentrazone and metribuzin have potential to cause early-season crop injury; however, when applied according to their label recommendations and following regional agronomic management practices, this impact may not translate into soybean yield reduction while such herbicides provide effective soil residual weed control.

Introduction

Synthetic herbicides represent the foundation for weed control in conventional (i.e., nonorganic) soybean production systems across the United States. Prior to the introduction of glyphosate-resistant (GR) soybean in 1996, growers utilized a variety of PRE and selective POST herbicides from multiple sites of action for weed control (Kniss 2018). The introduction of GR crops in the mid-1990s dramatically altered row-crop production in the United States allowing producers more flexibility for POST weed control with the use of the systemic and nonselective broad-spectrum herbicide glyphosate. This led to a reduction in labor and time requirements, reduced herbicide costs, and decreased reliance on tillage and other means of mechanical weed control (Bradley et al. 2004; Johnson et al. 2000a; Reddy and Whiting 2000). Conversely, adoption of GR soybean changed the herbicide use patterns (from 2000 to 2010) from PRE followed by POST programs to primarily POST application(s) of glyphosate alone (Duke 2015; Givens et al. 2009; Powles 2008), posing tremendous selection pressure for glyphosate resistance evolution.

Waterhemp (*Amaranthus tuberculatus* Moq.) and Palmer amaranth (*Amaranthus palmeri* S. Wats.) are troublesome weed species in Midwestern U.S. row crop production (Johnson 2000b; Norsworthy et al. 2014). The use of PRE herbicides is considered a foundation for management of such *Amaranthus* spp. and other problematic weeds such as kochia (*Kochia scoparia* L.; Kumar and Jha 2015; Whitaker et al. 2011). Due to overreliance on glyphosate and widespread occurrence of GR weeds, soybean producers are once again reintroducing PRE herbicides to their weed control programs. For instance, the total soybean planted area treated with metribuzin (photosystem II-inhibitor, PSII; Group 5) and sulfentrazone (protoporphyrinogen oxidase-inhibitor, PPO; Group 14), increased 18% and 22%, respectively, from 2006 to 2017 (USDA-NASS 2017). Hager et al. (2002) and Arneson et al. (2019) reported that these two herbicides were effective in controlling waterhemp 6 to 8 wk after planting. Sarangi et al. (2014) reported great control (>90%) of GR *Amaranthus* spp. 3 wk after planting when PRE PPO-inhibitor herbicides were used. Oliveira et al. (2017) reported benefits of using PRE herbicides to control several annual broadleaf and grass species. Furthermore, Norsworthy et al. (2014) indicated that the use of effective PRE herbicides is an important strategy for management of herbicide-resistant weeds. PRE herbicides control weeds that germinate in the first 3 to 4 wk after crop planting, which allow for more timely POST herbicide applications and protect crop yield loss in the early season when the crop is most vulnerable to weed competition (Butts et al. 2017; Knezevic et al. 2019; Tursun et al. 2016).

Although soil-applied PPO and PSII inhibitors are labeled and commonly recommended as PRE herbicides for soybean, there is a concern that these herbicides may cause early-season soybean injury and affect yield. Adequate soil moisture is necessary for PRE activation and subsequent availability in soil solution for effective weed control. However, when soil conditions are cool and wet for extended periods of time during crop emergence, the ability of soybean to metabolize PRE herbicides is reduced, which leads to increased plant injury (Moomaw and Martin 1978; Niekamp et al. 2000; Osborne et al. 1995). In addition, precipitation during the "soil cracking" stage of emergence can result in splashing of higher concentrations of PPO-inhibitor herbicides onto soybean hypocotyl, cotyledons, or growing points, which can lead to tissue necrosis (Hartzler 2004; Wise et al. 2015). Sulfentrazone is known to cause herbicide injury in the form of chlorosis, discoloration of veins, and shortening of internodes in less-tolerant soybean varieties and can reduce soybean stand by 17% and 35% in tolerant and less-tolerant varieties, respectively (Swantek et al. 1998). Other experiments reported that the range and variability in injury observed across varieties is likely due to varying tolerances to peroxidative stress caused by sulfentrazone application because no differences in uptake and translocation were observed (Dayan et al. 1997). Taylor-Lowell et al. (2001) observed early-season herbicide injury and reduction in plant stand when the PPO inhibitors flumioxazin and sulfentrazone were used; however, they observed no adverse effect on soybean yield. Interveinal chlorosis is the initial symptom of metribuzin injury, which becomes evident when the unifoliate and first trifoliate leaves are exposed, with greater risk of injury in soils with higher pH (>7) and/or low organic matter (Hartzler 2017). Rogers et al. (1971) observed that relative tolerance to metribuzin is partially related to the ability of soybean to degrade metribuzin more rapidly in tolerant varieties. Coble and Schrader (1973) reported that soybean tolerance to metribuzin was greatly influenced by application rate, soil organic matter, and amount of rainfall following herbicide treatment. Bollich et al. (1985) reported soybean injury and reduced nodule dry weight when metribuzin was applied at 0.3 kg ha^{-1} in a soil with coarse texture (57% sand, 37% silt, and 6% clay), high pH (7.8), and low organic matter content (0.6%).

Early-season herbicide injury and subsequent effect on yield is a concern of soybean producers who adopt metribuzin and/or sulfentrazone PRE in soybeans. Some seed companies provide information regarding soybean variety tolerance to soil-applied metribuzin and sulfentrazone; however, to our knowledge, information on their potential impact on soybean development and yield response under field conditions prone to PRE injury is not readily available. Thus, the objectives of this study were to 1) investigate the impact of soil-applied sulfentrazone and metribuzin on early-season growth and development of soybean using multiple varieties adapted to southwestern Nebraska and 2) determine whether potential early-season herbicide-induced injury could impact soybean yield. We hypothesized that PRE herbicides would impact early-season soybean development but have no adverse effect on yield.

Materials and Methods

Field experiments were conducted in 2016 and 2017 at the University of Nebraska West Central Water Resources Field Laboratory, near Brule, NE (41.1597°N, 102.02871°W; hereafter referred to as Brule) and the University of Nebraska West Central Research and Extension Center in North Platte, NE (41.0865°N, 100.7780°W; hereafter referred to as North Platte) for a total of 4 site-years. The previous crop at all field sites was no-till corn (*Zea mays* L.). Information regarding soil characteristics, soybean planting date, PRE herbicide application time, and harvest date at each site-year is presented in Table 1. Monthly rainfall and irrigation applied via center pivot, average air and soil temperature (10-cm depth), and 30-yr average air temperature and monthly rainfall for each site-year are presented in Table 2. Experimental sites were selected due to loam soil type, relatively low organic matter, and high pH, which are representative field conditions across southwestern Nebraska and also suitable for early-season crop injury from metribuzin and sulfentrazone (Grey et al. 1997).

The experiment was conducted as a 3 × 22 factorial with treatments consisting of two PRE herbicides applied at recommended label rates (metribuzin, 560 g ai ha^{-1}, Sencor® 75 DF Bayer AG, Leverkusen, Germany; and sulfentrazone, 280 g ai ha^{-1}, Spartan® 4F, FMC Corporation, Philadelphia, PA) plus a nontreated control (NTC), and 22 commercially available soybean varieties adapted to the region (Table 3). At all site-years, soybeans were planted at 360,000 seeds ha^{-1} (3.8 cm deep) and the PRE herbicide was applied within 3 d after planting (DAP; Table 1) using a CO_2-pressurized backpack sprayer equipped with a 3-m boom with six TeeJet XR11002 flat-fan nozzles (Spraying Systems Co., Wheaton, IL) on 50.8-cm spacing, calibrated to deliver 94 L of spray solution per hectare. Experimental units were 3 m wide (four rows on 76-cm spacing) and 9.1 m in length. Experimental units were maintained weed-free throughout the season by weekly hand weeding and/or hoeing to minimize the impact of weeds on soybean development and yield. The experiment was established in a strip-split-plot design employed in a randomized complete block design with four replications at each site-year. PRE herbicide treatments were considered as the strip-plot, whereas the soybean varieties were treated as the split-plot.

Soybean Canopy Development

Soybean canopy development was assessed when the crop reached the V2 (two open trifoliates) growth stage (Fehr and Caviness 1977), approximately 30 d after planting (DAP). The evaluation consisted of four photos of the center two soybean rows in each experimental unit (rows 2 and 3). Square frames (76 by 76 cm) were constructed from polyvinyl chloride pipe (1.25 cm diameter) and black fabric, and used to demark the areas designated for the photos (Figure 1). Two photos per row were taken at 1 m above the ground with an Apple iPhone 6s cellphone camera (Apple Inc., Cupertino CA) with the "square" setting. Black fabric fitted on squares was used to eliminate variability within photo area (e.g.,

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Table 1. Soil and crop management information for field experiments.

Site	Year	Soil pH	Organic matter	Soil texture[a]	Planting time	Herbicide application	Harvest
			—% —				
Brule	2016	6.7	2.2	Loam (19:44:37)	May 19	May 19	October 28
Brule	2017	6.8	2.1	Loam (20:42:38)	May 24	May 25	October 11
North Platte	2016	7.5	1.7	Loam (15:34:51)	May 10	May 11	October 13
North Platte	2017	7.4	1.7	Loam (20:32:48)	May 10	May 12	October 7

[a]In parentheses: (% clay:silt:sand) soil texture ratio.

Table 2. Monthly average air and soil temperature, and accumulated rainfall, irrigation, and total water.[a]

	Air temperature			Soil temperature[b]		Rainfall			Irrigation		Total water[c]	
	2016	2017	30 yr	2016	2017	2016	2017	30 yr	2016	2017	2016	2017
Brule	—C—					— mm —						
Apr	9	10	9	11	12	137	57	56	0	0	137	57
May	14	14	15	15	15	93	67	79	13	15	106	82
Jun	23	21	21	24	24	37	22	78	0	46	37	68
Jul	23	24	24	24	27	71	99	75	155	76	226	175
Aug	21	20	18	23	23	14	47	57	142	33	156	80
Sep	17	18	18	20	21	15	46	38	20	81	35	127
Oct	13	10	11	14	11	45	27	31	0	0	45	27
North Platte												
Apr	10	10	9	6	12	162	53	57	0	0	162	53
May	14	14	15	17	16	85	71	79	0	0	85	71
Jun	23	22	21	27	25	77	28	90	0	76	77	104
Jul	24	25	24	28	27	119	104	76	30	61	149	165
Aug	22	21	23	26	23	30	81	64	61	15	91	96
Sep	18	18	18	21	22	21	119	41	0	15	21	134
Oct	13	10	11	15	13	38	66	40	0	0	38	66

[a]Air and soil temperature and rainfall data were obtained from High Plains Regional Climate Center (https://hprcc.unl.edu) and irrigation amounts were recorded on site. The 30-yr average includes data from 1987 through 2017.
[b]Depth, 10 cm.
[c]Rainfall + irrigation.

emerging weeds, decaying plant residue). Photos were processed using the Canopeo cellphone application (Canopeo Software, Oklahoma State University, Division of Agricultural Sciences and Natural Resources Soil Physics program, Stillwater, OK; https://canopeoapp.com). The Canopeo app estimates fractional green canopy cover within each image (Liang et al. 2012; Paruelo et al. 2000; Patrignani and Ochsner, 2015), and was used in this study to estimate potential soybean growth reduction due to herbicide injury.

Final Soybean Plant Stand, Final Yield, and Yield Components

Harvest at all locations was conducted manually after soybeans reached physiological maturity (Table 1). Soybean plants from 2 m of row (1 m of row from each of the center two rows) of each experimental unit were enumerated to estimate final plant stand, cut at the base, and stored in canvas bags until threshing for estimation of yield. Six random soybean plants (three plants from each of the center two rows, separate of the 2 m of row harvested) were collected from each experimental unit and stored in canvas bags until assessment of yield components, which included number of pods per plant, number of seeds per pod, total seeds per plant, and 100 seed weight. Soybean samples were threshed with a stationary ALMACO thresher (LPT – Large Plot Thresher, Almaco, IA), and seeds were counted with an Old Mill Seed Counter (Model 900-2, Old Mill Equipment, San Antonio, TX). Soybean yield and the weight of 100 soybean seeds were adjusted to 13% moisture content.

Table 3. Soybean varieties evaluated.

Soybean variety	Maturity group	Seed treatment[a]	Former/current company[b]
CZ1845LL	1.8	Poncho/Votivo®	Bayer/BASF
CZ2312LL	2.3	Poncho/Votivo®	Bayer/BASF
CZ2510LL	2.5	Poncho/Votivo®	Bayer/BASF
CZ2810LL	2.8	Poncho/Votivo®	Bayer/BASF
CZ2915LL	2.9	Poncho/Votivo®	Bayer/BASF
CZ3233LL	3.2	Poncho/Votivo®	Bayer/BASF
CZ3443LL	3.4	Poncho/Votivo®	Bayer/BASF
5N207R2	2.0	Acceleron Standard®	Dow/Corteva
5N211R2	2.1	Acceleron Standard®	Dow/Corteva
5N224R2	2.2	Acceleron Standard®	Dow/Corteva
5N245R2	2.4	Acceleron Standard®	Dow/Corteva
5B241R2	2.4	Acceleron Standard®	Dow/Corteva
5N265R2	2.6	Acceleron Standard®	Dow/Corteva
5B264R2	2.6	Acceleron Standard®	Dow/Corteva
X56266NR2	2.6	Acceleron Standard®	Dow/Corteva
5N287R2	2.8	Acceleron Standard®	Dow/Corteva
5N286R2	2.8	Acceleron Standard®	Dow/Corteva
5N306R2	3.0	Acceleron Standard®	Dow/Corteva
P27T59R	2.7	ILeVo®	Pioneer/Corteva
P28T08R	2.8	ILeVo®	Pioneer/Corteva
P31T11R	3.1	ILeVo®	Pioneer/Corteva
P31T77R	3.1	ILeVo®	Pioneer/Corteva

[a]Poncho/Votivo® (clothianidin + *Bacillus firmus* I – 1582; 13 mg ai 100 seed^{-1}); Acceleron Standard® (metalaxyl +fluxapyroxad + pyraclostrobin + myclobutanil + imidacloprid; 50 mg ai 100 seed^{-1}); ILeVo® (fluopyram; 15 mg ai 100 seed^{-1}).
[b]Varieties from three seed companies were used in the field experiments: Bayer Crop Science (St. Louis, MO, USA), Dow AgroSciences (Wilmington, DE, USA), and Pioneer (Johnston, IA, USA). Due to mergers and acquisitions since the experiments were conducted, these varieties now represent two seed companies: BASF (Ludwigshafen, Germany) and Corteva Agriscience (Wilmington, DE, USA).

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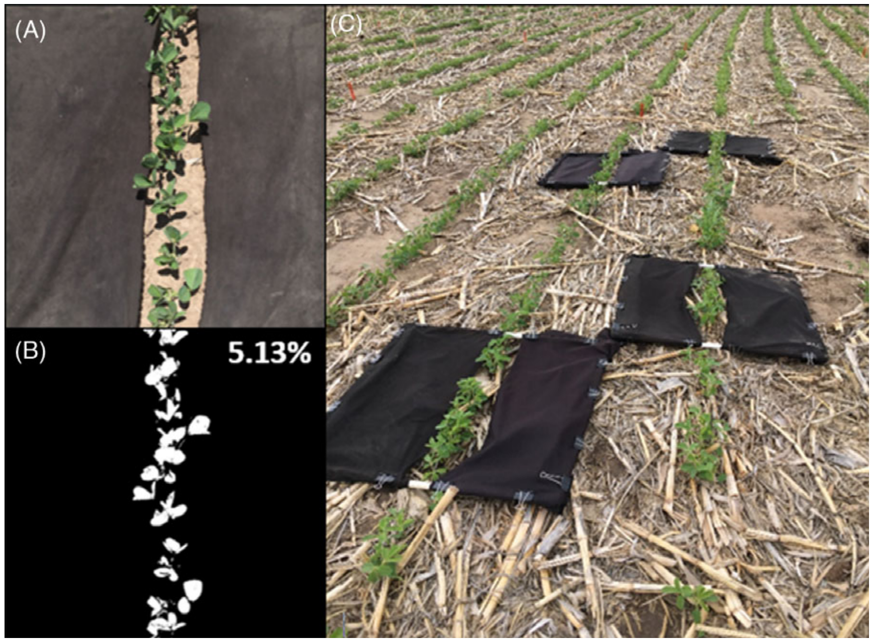

Figure 1. (A) Original, unprocessed photo of sulfentrazone treatment, (B) processed photo of sulfentrazone treatment for estimating soybean green canopy cover at V2 growth stage using the Canopeo phone application platform (www.canopeoapp.com). The photo at right, (C), shows where square frames were placed on the second and third soybean rows of an experimental plot so as to demarcate the photo area.

Statistical Analysis

Green canopy coverage (%), final plant stand (plants 2-m row^{-1}), final yield (g 2-m row^{-1}), and yield component data (number of pods per plant, total seeds per plant, number of seeds per pod, and 100 seed weight) were subjected to ANOVA using the PROC GLIMMIX procedure in SAS version 9.4 (SAS Institute Inc., Cary, NC). PRE herbicide treatments were treated as fixed effects, whereas replications nested within site-years and soybean varieties nested within site-years were treated as random effects. Site-years and soybean varieties were treated as random because the objective of this study was to evaluate the potential impact of PRE herbicide treatments assuming a random irrigated site in southwestern Nebraska (with similar environmental conditions as observed in this study) and random selection of locally adapted soybean variety. For each response variable, means were separated when PRE herbicide treatment effect was less than $P = 0.05$ using Fisher's protected least-significant difference. Canopy coverage, seeds per plant, and seeds per pod data were square root–transformed prior to analyses to satisfy Gaussian assumptions of normality and homogeneity of variance; back-transformed results are presented for ease of interpretation.

Results and Discussion

Soybean Canopy Development

Sulfentrazone reduced early season soybean growth by 22% (average canopy coverage across site-years and varieties was 5.4% at 30 DAP; Table 4). The early season sulfentrazone injury observed herein corroborates with the observations from an experiment conducted by Taylor–Lowell et al. (2001) who reported injury to 15 soybean varieties ranging from 4% to 61% when sulfentrazone was applied at three different rates (112, 224, and 446 g ai ha^{-1}) where the higher sulfentrazone rate led to higher injury particularly when wet and cool conditions persisted after soybean planting. Additionally, in a greenhouse experiment by Ribeiro et al. (2019) comparing 11 PRE herbicides using a silt loam soil, sulfentrazone was the most injurious herbicide to soybean at the VC growth stage, causing a 27% reduction in soybean green canopy coverage compared with the NTC.

Final Soybean Plant Stand and Yield

Compared with the NTC, sulfentrazone had an adverse impact on the final plant stand, resulting in a 10% average reduction (four fewer plants per 2 m of row), whereas metribuzin did not impact the final plant stand (Table 4). Although sulfentrazone application led to both reduced green canopy coverage during the early season (V2 growth stage; ~30 DAP) and the final plant stand at crop physiological maturity, these effects did not translate into a reduction in yield. Conversely, both PRE herbicides resulted in slightly higher average yield (by 3%) when compared with the NTC ($P = 0.0008$; Table 4). Although plots were hand weeded and hoed on a weekly basis, there was a higher opportunity for early-season weed competition in the NTC (no soil residual weed control from PRE herbicide treatment), which may partially explain the slightly higher yield in the metribuzin and sulfentrazone treatments. Nonetheless, our results support those previously reported by Taylor-Lowell et al. (2001) who observed no yield loss when soybeans were injured by sulfentrazone PRE. Additionally, despite observing sulfentrazone injury during the VC soybean growth stage, Ribeiro et al. (2019) reported no differences in total root and shoot biomass when the crop reached the R2 growth stage (45 DAP) in their greenhouse study. Soybean plants are known to compensate for reduced stands by producing additional branches (Cox and Cherney 2011). Weidenhammer et al. (1989) suggested that soybeans can compensate for herbicide injury when it occurs during early developmental stages, but the ability to

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Table 4. Green canopy cover (%; ~30 d after treatment [V2 growth stage]), final plant stand and yield at physiological maturity.[a]

Herbicide treatment[b]	Canopy cover	Final plant stand	Yield[c]
	——%——	——plants 2-m of row^{-1}——	——g 2-m of row^{-1}——
Control	6.9 a	42 a	588.0 b
Metribuzin	6.8 a	42 a	609.2 a
Sulfentrazone	5.4 b	38 b	608.5 a
P-value	<0.0001	<0.0001	0.0008

[a]Means within a column followed by the same letter are not different according to Fisher's least significant difference test (P = 0.05).
[b]PRE herbicide treatments were treated as fixed effects, whereas replications nested within site-years and soybean varieties nested within site-years were treated as random effects.
[c]Yield adjusted to 13% moisture content.

Table 5. Soybean yield components at crop physiological maturity.[a]

Herbicide treatment[b]	Pods per plant	Seeds per plant	Seeds per pod	100 seeds[c]
	——No.——	——No.——	——No.——	——g——
Control	43 b	99 c	2.3	15.0
Metribuzin	45 b	103 b	2.4	14.9
Sulfentrazone	50 a	114 b	2.4	14.9
P-value	<0.0001	<0.0001	0.7323	0.1460

[a]Means within a column followed by the same letter are not different according to Fisher's least significant difference test (P = 0.05).
[b]PRE herbicide treatments were treated as fixed effects, whereas replications nested within site-years and soybean varieties nested within site-years were treated as random effects.
[c]Adjusted to 13% of moisture.

compensate decreases as soybeans approach the blooming (R1) growth stage.

Soybean Yield Components

PRE herbicide treatments had a significant effect on the number of pods per plant and seeds per plant ($P < 0.0001$; Table 5). Sulfentrazone resulted in 16% more pods per plant (seven more pods per plant) than the NTC. This could be due to axillary bud growth by individual plants when additional space was available because of the reduction in plant stand. Sulfentrazone and metribuzin treatment resulted in 15% and 4% increases, respectively, in the number of seeds per plant (15 and 4 more seeds plant^{-1}) compared with the NTC. The number of seeds per pod and 100 seed weight were not influenced by PRE herbicide treatments ($P > 0.05$; Table 5). These results demonstrate that despite a reduction in early season green canopy and final plant stand due to sulfentrazone application, soybean plants that received this treatment were able to compensate yield via increases in the number of pods per plant and seeds per plant.

The findings from this experiment support previous research regarding the ability of soybean to compensate early-season PRE herbicide injury. These results should encourage soybean growers to continue including PRE herbicides as a part of an integrated weed management strategy in their production systems. The weed control benefits provided by PRE herbicides likely outweigh concerns regarding early-season injury, assuming that such herbicides are applied following their label requirements and the crop is established according to local best management practices. Soybean growers can opt to plant varieties with higher tolerance to PRE herbicides, when such information is provided by seed companies, as a means to reduce the likelihood of early-season crop injury (Belfry et al. 2015; Swantek et al. 1998; Taylor-Lowell et al. 2001). Further research should evaluate the tolerance of modern soybean varieties to PRE herbicide premixes containing multiple sites of action, which are becoming more commonly adopted by soybean growers because they provide extended and broader weed control and may potentially delay herbicide resistance (Arneson et al. 2019).

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