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Sulfentrazone crop safety and efficacy in cabbage and broccoli

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Abstract

In 2021 and 2022, research was initiated at two locations to evaluate the efficacy and safety of sulfentrazone in transplanted cabbage and broccoli. Treatments included oxyfluorfen at 560 g ha^{-1} applied pretransplant (PRE-T), sulfentrazone applied at 116 or 233 g ha^{-1} PRE-T, and *S*-metolachlor applied at 715 g ha^{-1} immediately after transplanting (POST-T) followed by (fb) oxyfluorfen applied at 210 g ha^{-1} postemergence (POST) 14 d after planting (DAP). The weedy cover of nontreated plots averaged between 6% (14 DAP) and 72% (42 DAP); all herbicide-treated plots averaged less than 30% cover at 42 DAP. At 14 and 28 DAP, oxyfluorfen, *S*–metolachlor fb oxyfluorfen, and the high rate of sulfentrazone reduced total monocotyledonous and dicotyledonous weed densities by 62% and 100%, respectively, relative to the nontreated control. The density of hairy galinsoga (in New Jersey) and combined ladysthumb and prostrate knotweed (in New York) were reduced by 71% to 99%. Except for the low rate of sulfentrazone, all herbicide treatments reduced weed biomass at harvest by ≥88%. Crop injury varied in response to herbicide treatments or weed competition but was also affected by crop and location. Between 14 and 28 DAP, the greatest amount of stunting (22%) was noted in the *S*-metolachlor fb oxyfluorfen treatments at both locations. Averaged over treatments, greater stunting was observed in broccoli than in cabbage in New York, whereas stunting estimates were higher for cabbage in New Jersey. All treatments in New Jersey resulted in significantly increased cabbage yield and broccoli and cabbage head sizes relative to the nontreated controls. No yield difference was noted between herbicide treatments and the nontreated check in New York. Data derived from these studies will be used to enhance crop safety recommendations in northeastern U.S. production environments for sulfentrazone used PRE in transplanted cabbage and support a potential label for broccoli.

Introduction

Cole crops such as cabbage and broccoli are important horticultural commodities in the United States. In 2022, cabbage was grown on 23,000 ha nationwide, with an estimated value of US$613 million (USDA-NASS 2023). In 2022, New York ranked second behind California in cabbage area harvested (4,300 ha), yield (192 million kg), and value of utilized production (US$74 million; USDA-NASS 2023). Vegetable production in New Jersey, where annual sales were US$184 million in 2021, includes multiple cole crops, including cabbage, which was valued at US $8 million (USDA-NASS 2022). Broccoli is valued at US$815 million in the United States, with most of the production located in California and Arizona (USDA-NASS 2023). The advancement of the broccoli industry in New York and other eastern states has been supported by breeding efforts to develop cultivars that are more tolerant of regional growing conditions (Farnham and Björkman 2011; USDA-NASS 2019; Wyenandt et al. 2023).

Additional factors, such as effective weed management, are also required to maximize yields of cole crops. Cole crops are short in stature, with relatively shallow root systems, making them poor competitors with weeds for limited resources (Sikkema et al. 2007; Yu et al. 2018). Direct interference for water, nutrients, and light can reduce both head numbers and size. For example, Bellinder (2012) reported that the combined interference of hairy galinsoga, common lambsquarters, pigweed species (*Amaranthus* spp.), and large crabgrass (*Digitaria sanguinalis* L.) in cabbage fields could reduce yields by approximately 55%. In an economic threshold study conducted by Bell (1995), an Italian ryegrass (*Lolium perenne* L.) density of 4.9 plants m^{-2} reduced broccoli yields by 3.6%, resulting in an economic loss equal to the cost of POST weed control (US$221 ha^{-1}). Averaged over 44 studies (mostly conducted in Michigan, New Jersey, New York, Wisconsin, and Ontario) across 20 yr, cabbage yield loss was estimated at 54% when weeds were not controlled, despite the use of other best crop production practices (M. VanGessel, personal communication). Weeds can also impede and delay harvest operations (Bell 1995; Fennimore et al. 2010; Smart et al. 2001). Additionally, some weed seeds can physically contaminate cabbage heads, whereas common ragweed (*Ambrosia artemisiifolia* L.)

seeds have the potential to spread the pathogen responsible for Sclerotinia rot [*Sclerotinia sclerotiorum* (Lib.) de Bary] (Dillard and Hunter 1986). Furthermore, weeds of the mustard family, such as shepherd's purse (*Capsella bursa-pastoris* L.) and field pennycress (*Thlaspi arvense* L.), can serve as alternate hosts for the pathogens that cause Alternaria leaf spot [*Alternaria brassicicola* (Schwein.) Wiltshire], bacterial black rot [*Xanthomonas campestris* (Pammel) Dowson], and club root (*Plasmodiophora brassicae* Woronin) diseases (Chen et al. 2011; Guerena 2020). Seed contamination and disease stress can reduce cabbage and broccoli head quality, potentially decreasing yields and increasing the labor required to achieve industry standards for fresh or processing markets.

Herbicides are important tools for the management of weeds in cabbage and broccoli production systems, although the effectiveness of chemical weed control is limited by the relatively few numbers of registered products and their narrow spectrums of control (Sikkema et al. 2007; Wyenandt et al. 2023). Sulfentrazone (classified by the Weed Science Society of America as a Group 14 herbicide) is an aryl triazinone herbicide that inhibits the protoporphyrinogen oxidase (PPO) enzyme and for which use in cole crops is limited to transplanted cabbage in some states (including New Jersey but not New York). In soybean [*Glycine max* (L.) Merr.] crops, sulfentrazone can be used preemergence (PRE), early preplant, or preplant incorporated (PPI) with targeted activity against many annual broadleaf weed species including pigweeds, common lambsquarters, some morningglory species (*Ipomoea* spp.), and some annual grasses, such as foxtails (*Setaria* spp.) and witchgrass (*Panicum capillare* L.) (Hartzler 2017; Niekamp et al. 1999; Senseman 2007; Taylor-Lovell et al. 2001). Yellow nutsedge remains a troublesome weed species of specialty crops (Van Wychem 2022) but can be controlled by >90% with sulfentrazone applied POST at 260 g ha^{-1} (Krausz et al. 1998). Several states obtained a Special Local Need registration under §24c of the Federal Insecticide Fungicide Rodenticide Act (FIFRA) to use sulfentrazone to control broadleaf weeds and sedges in various specialty crops and to control haircap moss (*Polytrichum commune* Hedw.) within cranberry (*Vaccinium macrocarpon* Aiton) crops.

Sulfentrazone applied PRE can produce inconsistent crop damage incidence and severity, largely due to underlying edaphic conditions (Niekamp et al. 1999; Vencill 2002). For example, Ferrell et al. (2003) concluded that variability in soil pH within a site could differentially affect sulfentrazone uptake and result in injury patterns. Especially in soils with pH near 6.5, sulfentrazone-soil dynamics are particularly variable, with organic matter and soil type also playing a major role (Anonymous 2022a; Grey et al. 1997). The northeastern and mid-Atlantic regions of the United States with a high average rainfall could cause sulfentrazone crop uptake by moving the herbicide into the root, leaching below root level, and thus increasing microbial degradation, all of which can influence weed control efficacy and crop injury potential (Mueller et al. 2014; Senseman 2007). These regions are also home to a diversity of agricultural soil types, all with different properties such as pH and organic matter content, which have implications on crop-herbicide dynamics.

As consumer demand for local foods increases, the need for effective weed control options in vegetable production near eastern U.S. population centers is imperative (Atallah et al. 2014). Few studies have evaluated weed control and cabbage and broccoli tolerance to sulfentrazone applied PRE-T, particularly in the northeastern United States. Sulfentrazone is also a valuable tool for improved control of troublesome sedge species compared to PPO-inhibiting oxyfluorfen, which is already labeled for use on cabbage and broccoli. Therefore, the objectives of this research were to evaluate weed control and cabbage and broccoli tolerance to sulfentrazone to support recommendations regarding the safe and effective use of this active ingredient.

Materials and Methods

Site Description

In 2021 and 2022, experiments were conducted to evaluate weed control efficacy and crop safety of sulfentrazone on cabbage and broccoli crops at Cornell AgriTech in Geneva, NY (42.87032°N, 77.02728°W), and the Rutgers Agricultural Research and Extension Center in Bridgeton, NJ (39.523611°N, 75.201944°W). The soil in Geneva was a Honeoye loam (fine-loamy, mixed, semiactive, mesic Glossic Hapludalfs) with 38% sand, 44% silt, 18% clay, and 2.5% organic matter, pH 6.3. The Bridgeton site was a Chillum silt loam soil (fine-silty, mixed, semiactive, mesic Typic Hapludults) with 54% sand, 28% silt, 18% clay, and 2.4% organic matter, pH 5.7.

Plot Size and Plant Material

All fields were disked before transplanting to eliminate emerged weeds. In Geneva, plots were 7.6 m long and 3.1 m wide. Each plot had two rows of broccoli next to two rows of cabbage on 76.2-cm spacing; individual plant spacing within rows was 50.8 cm. Using a water wheel transplanter, cabbage 'Padoc' and broccoli 'Emerald Crown' cultivars were manually transplanted into bareground flat beds on May 20, 2021, and May 10, 2022. In Bridgeton, plots were 9.1 m long and 3.1 m wide. Each plot had two rows of broccoli next to two rows of cabbage on 76.2-cm spacing; individual plant spacing within rows was 30.5 cm. Cabbage 'Botran' and broccoli 'Avenger' cultivars were manually transplanted on August 17, 2021, and cabbage Padoc and broccoli Emerald Crown were transplanted on August 4, 2022. All transplants had three to four leaves at planting; root balls were placed at least 5 cm deep at both locations. Both sites received 1.5 cm supplemental irrigation on the same day as planting to set transplants and incorporate soil-applied herbicides. Additional irrigation was supplied as needed in New Jersey, whereas the New York site was rainfed. Both sites followed local pest and crop management guidelines with respect to fertilization and insect and disease control.

Treatments

The experiment was arranged as a split-plot design with four replications; herbicide treatments were considered the main plot, and cole crop species as the subplot. Oxyfluorfen is considered the standard PRE-T herbicide treatment for cole crops but was also granted a Special Local Need registration exemption under FIFRA §24(c) for POST application of the herbicide (Anonymous 2021, 2022b). Thus, PRE-T treatments consisted of oxyfluorfen (GoalTender®; Nufarm Inc., Alsip, IL) at 560 g ha^{-1} and sulfentrazone (Spartan Charge® in New York and Zeus® XC in New Jersey; FMC Corp., Philadelphia, PA) at 116 or 233 g ha^{-1}. Because the potential for cole crop injury may increase when mixing oxyfluorfen and *S*-metolachlor or when applying *S*-metolachlor PRE-T (Wyenandt et al. 2023), a treatment

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Table 1. Average monthly rainfall.

Month	Geneva			Bridgeton		
	2021	2022	30-yr average	2021	2022	30-yr average
	mm					
May	49	42	83	82	127	89
June	64	117	92	74	71	106
July	135	18	95	216	51	113
August	120	23	89	101	55	124
September	31	27	83	109	101	112
October	205	5	97	96	150	96
November	30	39	65	18	91	80
Total	634	271	604	695	646	720

including *S*–metolachlor (Dual Magnum®; Syngenta Crop Protection, Greensboro, NC) at 715 g ha^{-1} applied POST-T fb oxyfluorfen at 210 g ha^{-1} 14 DAP was also included. A nontreated weedy control was also added for comparison. Selected rates reflect label recommendations regarding soil texture and organic matter content.

In New York, herbicide treatments were applied using a CO_2-pressurized backpack sprayer and a two-nozzle boom equipped with TeeJet XR11002VS nozzles (Spraying Systems Co., Glendale Heights, IL) set 48 cm apart, and calibrated to deliver 187 L ha^{-1} at a pressure of 276 kPa. In New Jersey, herbicides were applied using a CO_2-pressurized backpack sprayer and a four-nozzle boom equipped with TeeJet XR8004VS nozzles (Spraying Systems Co.), each set 46 cm apart and calibrated to deliver 187 L ha^{-1} at a pressure of 207 kPa.

Data Collection

Crop injury was visually estimated using a scale ranging from 0% (no visible injury) to 100% (total plant death). Across years, sites, and crops, the predominant injury response was stunting, although minor chlorosis and necrosis were also observed and included in the overall crop injury rating. Visible injury for both cabbage and broccoli was assessed at 14, 21, 28, and 42 DAP. Weed cover, a visual estimate of the percentage of plot area covered with weeds, was evaluated both years in New York and in 2022 in New Jersey at 14, 21, 28, and 42 DAP using a scale of ranging from 0% (no weed cover) to 100% (soil completely covered by weeds). At 14 and 28 DAP, individual weed plants were separated by species and counted in a 0.25-m^2 quadrat positioned in the direct center of each cabbage and broccoli subplot in each herbicide treatment whole plot. Aboveground weed biomass was collected from two 0.25-m^2 quadrats placed in the center of each crop subplot at crop harvest.

In 2021, New York cabbage and broccoli harvests occurred ahead of schedule on July 21 (63 DAP) due to significant rainfall and soil waterlogging, which resulted in crop vigor loss and disease development (Table 1). In 2022, exceptionally dry conditions occurred during head development, necessitating an early harvest on July 13 (65 DAP). Both years, mean head weight per plot was determined by averaging the data from 10 heads harvested from adjacent rows of cabbage and broccoli in each plot. In New Jersey, broccoli and cabbage harvest occurred on October 28, 2021 (72 DAP) and October 6, 2022 (63 DAP). In addition to mean head weight, head circumference was computed by averaging the equatorial circumference of 10 heads collected from two rows in the center of each plot.

Statistical Analysis

Because of unequal variances, weed cover, and crop injury data were arcsine square root–transformed before analysis and back-transformed for presentation of the data (Grafen and Hails 2002). Data were subjected to ANOVA using the GLIMMIX procedure with SAS software (version 9.4; SAS Institute Inc., Cary, NC) to evaluate the impacts of residual herbicide applications, cole crop species, and their interaction on visual estimate of weed cover and crop injury, weed count and aboveground biomass, and crop yield and head circumference. Location, cole crop species, and herbicide treatments were considered fixed effects, whereas year and replications nested within year were treated as random effects. When an interaction including location was significant, data were separately analyzed by location. In the absence of significant residual herbicide treatment by crop species interactions, data were combined over fixed effects and mean comparisons between treatments were performed using Tukey's honestly significant difference test at ($\alpha = 0.05$).

Results and Discussion

Weed Cover

Both trial locations were planted in fields with substantial weed pressure that averaged 101 and 122 weeds m^{-2} in the weedy control 14 and 28 DAP, respectively, across locations. Dominant species at the Geneva site included common ragweed, ladysthumb, prostrate knotweed, shepherd's purse, field pennycress, common lambsquarters, and annual grasses including foxtails and barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.]. Dominant species at the Bridgeton site included hairy galinsoga, yellow nutsedge, common lambsquarters, oakleaf goosefoot (*Chenopodium glaucum* L.), carpetweed (*Mollugo verticillata* L.), redroot pigweed (*Amaranthus retroflexus* L.), and annual grasses including stinkgrass [*Eragrostis cilianensis* (All.) Vignolo ex Janch.] and goosegrass [*Eleusine indica* (L.) Gaertn.].

Results from ANOVA indicated significant effects of crop (21 and 42 DAP) and the interaction between crop and herbicide (42 DAP) with respect to total weed cover (Table 2). However, herbicide was the predominant factor that influenced the amounts of weedy vegetation observed in the trials (Table 2). All herbicide treatments were averaged across locations and reduced mean total weed cover, relative to the nontreated check, for each observation date. Furthermore, the oxyfluorfen, *S*-metolachlor fb oxyfluorfen, and sulfentrazone high-rate treatments did not differ at 14, 21, or 28 DAP. At 42 DAP,

Table 2. Visual evaluation of weed cover as affected by residual herbicides at Geneva, NY, in 2021 and 2022, and at Bridgeton, NJ, in 2022.[a,b,c]

Treatment	Rate	14 DAP	21 DAP[d]	28 DAP	42 DAP
Herbicide	g ha^{-1}	%			
Nontreated weedy control	–	6 a	26 a	52 a	72 a
Oxyfluorfen	560	0 c	0 c	0 c	2 c
Sulfentrazone	116	1 b	7 b	13 b	27 b
Sulfentrazone	233	0 bc	2 bc	4 bc	21 b
S-metolachlor fb oxyfluorfen	715 fb 210	0 bc	0 c	0 c	1 c
Fixed source of variation		P > *F*			
Herbicide		<0.0001	<0.0001	<0.0001	<0.0001
Crop		0.7551	0.0074	0.1428	0.0042
Herbicide × crop		0.2768	0.5580	0.8562	0.0479
Location		0.0701	–	0.0896	0.0805
Location × herbicide		0.1544	–	0.1008	0.0914
Location × crop		0.1110	–	0.1202	0.0505
Location × herbicide × crop		0.0602	–	0.7067	0.0569

[a]Abbreviations: DAP, days after planting; fb, followed by.
[b]Data represent experiments that were carried out in Geneva, NY, in 2021 and 2022, and Bridgeton, NJ, in 2022.
[c]Main effect means within a column followed by the same letters are not significantly different from each other according to Tukey's honestly significance test ($P \leq 0.05$).
[d]Data from 21 DAP are from New York only; weed cover data were not collected from the study location in New Jersey.

Table 3. Hairy galinsoga, common ragweed, and smartweed density 14 and 28 DAP as affected by residual herbicides in 2021 and 2022.[a,b,c]

		GASCI		AMBEL		POLXX	
Treatment	Rate	14 DAP	28 DAP	14 DAP	28 DAP	14 DAP	28 DAP
Herbicide	g ha^{-1}	m^{-2}					
Nontreated weedy control	–	70 a	29 a	2 a	9 a	7 a	21 a
Oxyfluorfen	560	1 c	1 c	1 ab	1 bc	1 b	1 b
Sulfentrazone	116	23 ab	28 a	2 a	3 a	8 a	14 a
Sulfentrazone	233	7 bc	11 b	0 ab	2 ab	2 ab	2 b
S-metolachlor fb oxyfluorfen	715 fb 210	3 c	1 c	0 b	0 c	0 b	0 b
Fixed source of variation		P > *F*					
Herbicide		<0.0001	<0.0001	0.0029	<0.0001	<0.0001	<0.0001
Crop		0.4137	0.7567	0.0803	0.1007	0.2582	0.0518
Herbicide × crop		0.2456	0.6937	0.7166	0.3117	0.9508	0.7866

[a]Abbreviations: AMBEL, common ragweed; DAP, days after planting; fb, followed by; GASCI, hairy galinsoga; POLXX, ladysthumb and prostrate knotweed combined.
[b]The main effect means within a column followed by the same letters are not significantly different from each other according to Tukey's honestly significance test ($P \leq 0.05$).
[c]GASCI density was determined at the Bridgeton, NJ, location; the densities of AMBEL and GPOLXX were determined at the Geneva, NY, location.

the sulfentrazone low-rate (27%) and high-rate (21%) treatments had higher weed cover estimates than oxyfluorfen (2%) or *S*-metolachlor fb oxyfluorfen (1%), and lower weed cover estimates relative to the nontreated check (72%).

Weed Density

Hairy galinsoga in New Jersey and smartweeds and common ragweed in New York were selected for individual analyses because they were recurrent across treatments and years within their respective locations (Table 3). In New Jersey, hairy galinsoga densities were affected by herbicide treatment. At 14 DAP, hairy galinsoga density was just 1 plant m^{-2} with oxyfluorfen and just 3 plants m^{-2} with *S*-metolachlor fb oxyfluorfen compared with 70 plants m^{-2} in the nontreated controls. At 28 DAP, hairy galinsoga density was 1 plant m^{-2} after the oxyfluorfen and *S*-metolachlor fb oxyfluorfen treatments, whereas it was 29 plants m^{-2} in the nontreated controls. Hairy galinsoga density was 7 plants m^{-2} at 14 DAP and 11 plants m^{-2} at 28 DAP relative to the nontreated check. Hairy galinsoga suppression was not significant with the low rate of sulfentrazone.

In New York, smartweed and common ragweed was also affected by herbicide treatment. At 14 DAP, smartweed density was 7 plants m^{-2} in the nontreated control, 1 plant m^{-2} after oxyfluorfen was applied, and 0 plants m^{-2} after *S*-metolachlor fb oxyfluorfen. At 28 DAP, smartweed densities remained at 1 and 0 plants m^{-2} in the oxyfluorfen and *S*-metolachlor fb oxyfluorfen treatment groups, respectively, compared with the nontreated check, in which 21 plants m^{-2} were counted. Sulfentrazone high rate also reduced hairy galinsoga to just 2 plants m^{-2} at 14 and 28 DAP relative to the nontreated check. The sulfentrazone low rate did not suppress smartweed. Common ragweed density was lower than that of hairy galinsoga and smartweed and was not affected by any herbicide treatment, except for *S*-metolachlor fb oxyfluorfen, at 14 DAP. At 28 DAP, common ragweed density was 1 plant m^{-2} with oxyfluorfen and 0 plant m^{-2} with *S*-metolachlor fb oxyfluorfen. Those were the only treatments that reduced common ragweed numbers relative to the nontreated control at 9 plants m^{-2}.

All treatments reduced total monocotyledonous and dicotyledonous weed densities by 73% to 100% compared to the nontreated control at both 14 and 28 DAP (Table 4), except for the density of dicotyledonous weeds at28 DAP following application of low-rate sulfentrazone. Hairy galinsoga was the most abundant broadleaf weed species and was not controlled at 28 DAP with the low rate of sulfentrazone, which may explain the lack of significant dicotyledonous weed density 28 DAP for this treatment compared to the control. The density of monocotyledonous species was greater 28 DAP when sulfentrazone had been applied regardless of

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Table 4. Total dicotyledonous and monocotyledonous weed densities 14 DAP and 28 DAP and total weed biomass at harvest as affected by residual herbicides.[a,b]

		Dicotyledonous		Monocotyledonous		
Treatment	Rate	14 DAP	28 DAP	14 DAP	28 DAP	Weed DW
Herbicide	g ha^{-1}	m^{-2}				g m^{-2}
Nontreated weedy control	–	74 a	65 a	27 a	57 a	575 a
Oxyfluorfen	560	2 c	6 bc	0 c	1 d	9 c
Sulfentrazone	116	20 b	37 ab	3 b	14 b	232 ab
Sulfentrazone	233	6 bc	14 b	0 c	3 c	67 b
S-metolachlor fb oxyfluorfen	715 fb 210	3 c	3 c	0 c	0 d	4 c
Site						
Geneva, NY		4 b	6 b	2	3 b	33
Bridgeton, NJ		22 a	43 a	2	8 a	66
Fixed source of variation		*P* > *F*				
Herbicide		<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Crop		0.4932	0.0710	0.2937	0.3554	0.7024
Herbicide × crop		0.5676	0.9071	0.7767	0.8820	0.9708
Location		0.0018	0.0104	0.6918	0.0092	0.1295
Location × herbicide		0.0784	0.4531	0.0604	0.0301	0.1678
Location × crop		0.7685	0.5452	0.2204	0.4523	0.2488
Location × herbicide × crop		0.4966	0.7012	0.3604	0.9096	0.1020

[a]Abbreviations: DAP, days after planting; DW, dry weight; fb, followed by.
[b]The main effect means within a column followed by the same letters are not significantly different from each other according to Tukey's honestly significance test ($P \leq 0.05$).

rate, than it was when oxyfluorfen or S-metolachlor fb oxyfluorfen were applied. Except for monocotyledonous species at 14 DAP, differences in total monocotyledonous and dicotyledonous weed densities were also detected between locations; weed counts were consistently higher across treatments than they were in New York.

Weed Biomass

At harvest, the oxyfluorfen and *S*–metolachlor fb oxyfluorfen treatments resulted in the lowest weed biomass, at 9 g and 4 g m^{-2}, respectively (Table 4). The sulfentrazone high-rate treatment was less effective than the oxyfluorfen or *S*-metolachlor fb oxyfluorfen treatments at reducing weed biomass (67 g m^{-2}) but they performed better than the nontreated control (575 g m^{-2}). Sulfentrazone low rate (232 g m^{-2}) did not result in lower weed biomass accumulation. Weed biomass was double in New Jersey than it was in New York. This was most likely due to environmental conditions during both trial years. For example, in 2022, the New York trial site had lower than average rainfall, which could have suppressed weed emergence and growth (Table 1).

Cole crops are not competitive against weeds due to their stature, shallow root systems, and slow canopy closure (Sikkema et al. 2007; Yu et al. 2018). Thus, early-season control of weeds in transplanted cabbage (21 to 35 DAP) and broccoli (15 to 30 DAP) is critical for the crop to maintain vigor and achieve yield (Latif et al. 2021; Weaver 1984). Other researchers also reported reduced control of monocotyledonous weeds with sulfentrazone applied PRE. Hutchinson et al. (2005) noted less than 25% season-long control of volunteer oat (*Avena sativa* L.) with sulfentrazone applied PRE at 105 g ha^{-1} to potato (*Solanum tuberosum* L.) crops, whereas Reddy et al. (2012) reported less than 80% control of green foxtail [*Setaria viridis* (L.) Beauv.] with sulfentrazone applied PRE at 90 to 140 g ha^{-1} to sunflower (*Helianthus annuus* L.) crops. Walsh et al. (2015) found 90% dry weight reduction in soybean 9 wk after treatment due to redroot pigweed, common ragweed, common lambsquarters, and green foxtail weeds calculated from dose-response curves at rates of 214, 514, 133, and 721 g ai ha^{-1}, respectively. Our results were similar and reflected differences in sulfentrazone weed control between broadleaf weed species with hairy galinsoga and smartweeds being not controlled 28 DAP with sulfentrazone at 116 g ha^{-1}. An important factor that may have played a part in the biomass differences between sites is the biology of hairy galinsoga. The plant has no seed dormancy, which allows it to germinate continuously throughout the growing season (Brown et al. 2022). As such, hairy galinsoga contributed to a disproportionately high amount of the total weed biomass in New Jersey and doubled the biomass between sites in combination with the environmental and irrigation differences. The variations in weed spectra between the two sites and their emergence peaks may have also compounded the effects described above. For example, both Palmer amaranth and hairy galinsoga have a delayed emergence peak compared with other summer annuals (Brown et al. 2022). When combined with the effects of differing residual activity between herbicides, also impacted by environmental and edaphic conditions, we observed weed biomass differences between the sulfentrazone treatments and the non-sulfentrazone treatments across sites.

Crop Injury

The crop injury data have been separated by state because site-by-herbicide and site-by-crop interactions were significant for each rating date. In New York, significant differences were observed among herbicide treatments for crop stunting at 14, 21, and 28 DAP (Table 5). The greatest injury at 14, 21, and 28 DAP occurred in the sulfentrazone high rate (9 to 15%) and *S*-metolachlor fb oxyfluorfen (4 to 22%) treatment groups. The sulfentrazone low rate and oxyfluorfen treatments had injury rating estimates of 5% or less at all observation dates. The injury was transient and almost unobservable by 42 DAP. No injury was observed in the nontreated checks at any time. There was a difference in the amount of stunting observed between crops in New York in the 3 wk after transplanting; broccoli experienced four and two times the crop injury observed in cabbage at 14 and 21 DAP, respectively (Table 5).

In New Jersey, there were no significant differences among herbicide treatments for crop injury at 14 and 28 DAP (Table 6).

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Table 5. Visual evaluation of crop injury at 14, 21, 28, and 42 DAP as affected by residual herbicides and crop species at the Geneva, NY, location in 2021 and 2022.[a,b]

Treatment	Rate	14 DAP	21 DAP	28 DAP	42 DAP
Herbicide	g ha^{-1}		——— m^{-2} ———		
Nontreated weedy control	–	0 b	0 d	0 c	0
Oxyfluorfen	560	1 ab	2 cd	4 b	0
Sulfentrazone	116	2 ab	5 bc	4 b	0
Sulfentrazone	233	9 a	13 ab	15 a	2
S-metolachlor fb oxyfluorfen	715 fb 210	4 a	21 a	22 a	1
Crop					
Broccoli	–	4 a	8 a	6	0
Cabbage	–	1 b	4 b	7	1
Fixed source of variation			——— P > *F* ———		
Herbicide		0.0012	<0.0001	<0.0001	0.0519
Crop		<0.0001	0.0003	0.6840	0.7207
Herbicide × crop		0.0876	0.2508	0.2632	0.9824

[a]Abbreviations: DAP, d after planting; fb, followed by.
[b]Data were pooled across crop species or herbicides when the herbicide × crop interaction was not significant. Main effect means within a column followed by the same letters are not significantly different from each other according to Tukey's honestly significance test (P ≤ 0.05).

Table 6. Visual evaluation of crop injury 14, 21, 28, and 42 DAP as affected by residual herbicides and crop species at the Bridgeton, NJ, location in 2021 and 2022.[a,b]

					42 DAP			
Treatment	Rate	14 DAP	21 DAP	28 DAP	Broccoli		Cabbage	
Herbicide	g ha^{-1}			——— m^{-2} ———				
Nontreated weedy control	–	0	1 b	0	61 a	Y	70 a	X
Oxyfluorfen	560	3	2 b	1	1 b	X	2 cd	X
Sulfentrazone	116	2	1 b	1	10 b	Y	26 b	X
Sulfentrazone	233	3	5 b	0	10 b	X	19 bc	X
S-metolachlor fb oxyfluorfen	715 fb 210	2	22 a	2	0 b	X	0 d	X
Crop								
Broccoli	–	0 b	3 b	0 b	–		–	
Cabbage	–	5 a	7 a	1 a	–		–	
Fixed source of variation				——— P > *F* ———				
Herbicide		0.0945	0.0002	0.2681	<0.0001			
Crop		<0.0001	0.0007	0.0193	0.0014			
Herbicide × crop		0.3320	0.7691	0.5558	0.0050			

[a]Abbreviations: DAP, d after planting; fb, followed by.
[b]Data were pooled across crop species or herbicides when the herbicide × crop interaction was not significant. Main effect means followed by the same letter within a column (a–c) or row within crop species (X–Y) are not significantly different from each other according to Tukey's honestly significance test (P ≤ 0.05).

At 21 DAP, plants treated with *S*-metolachlor fb oxyfluorfen exhibited 22% stunting, which was significantly more than was noted for other treatments and the nontreated control. The severe stunting observed in broccoli (61%) and cabbage (70%) in the nontreated checks at 42 DAP was likely the result of intense weed competition (Table 6). Stunting in broccoli (10%) and cabbage (26% and 19%, with the low and high rates of sulfentrazone, respectively) observed 42 DAP was also likely related to weed competition. When averaged over herbicide treatments, greater injury was observed in cabbage than in broccoli at 14 DAP (5% vs. 0%), 21 DAP (7% vs. 3%), and 28 DAP (1% vs. 0%).

Rachuy and Fennimore (2022) reported that transplanted brassica vegetables were tolerant to PRE applied *S*-metolachlor and sulfentrazone up to rates of 730 and 110 g ha^{-1}, respectively. There was little to no visible crop injury and no reduction in yield observed in transplanted brussels sprouts (*Brassica oleracea* L. var. *gemmifera* DC) or kale (*Brassica oleracea* L. var. *palmifolia)*. Similarly, Sikkema et al. (2007) did not observe significant crop injury nor a reduction in head size or yield from applications of oxyfluorfen (560 and 1,120 g ha^{-1}) or sulfentrazone (100 and 200 g ha^{-1}) applied PRE to transplanted broccoli, cabbage, and cauliflower (*Brassica oleracea* L. var. *botrytis*). Sikkema et al. (2007) hypothesized that the root system of transplanted cole crops is spatially separated from the herbicide-treated zone, which thus reduced the injury that was observed.

Haar et al. (2002) reported that seeded broccoli was tolerant to sulfentrazone applied PRE at 168 g ha^{-1} but showed significant injury and yield reduction with sulfentrazone at 280 g ha^{-1}, suggesting that this crop has a narrow window of tolerance for sulfentrazone. Sulfentrazone is a weak acid (pKa = 6.56), which especially impacts soil-herbicide dynamics when the soil pH is near the pKa (Grey et al. 1997). In our study, the soil pH was 6.3 in New York and 5.7 in New Jersey. Higher soil pH will increase root absorption of sulfentrazone, which may explain inconsistencies in study results with PRE-applied sulfentrazone at sites with different soil pH and moisture levels (Ferrell et al. 2003; Senseman 2007; Vencill 2002). Umeda et al. (1999) found that cabbage was more sensitive than broccoli to sulfentrazone injury when the herbicide was applied POST at rates of 140 and 280 g ha^{-1}. These patterns were similar to our study findings in New Jersey but not New York. However, Umeda et al. (1999) reported severe injury in sulfentrazone applied POST to cabbage, with marginally acceptable injury observed in broccoli (15%). The injury observed in cabbage and broccoli by Umeda et al. was greater than the average injury observed by any of the sulfentrazone rates in our study, averaged across crops, except for broccoli (15%) in New York at 28

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Table 7. Crop yield and crop head circumference as affected by residual herbicides and crop species in 2021 and 2022.[a,b,c]

		Yield					Head circumference			
			Bridgeton							
Treatment	Rate	Geneva	Broccoli		Cabbage		Broccoli		Cabbage	
Herbicide	g ha^{-1}	g head^{-1}					cm head^{-1}			
Nontreated weedy control	–	286	380	X	533 c	X	41 b	X	38 b	X
Oxyfluorfen	560	404	569	Y	1,981 a	X	51 a	Y	61 a	X
Sulfentrazone	116	345	463	Y	1,159 b	X	47 a	X	50 a	X
Sulfentrazone	233	305	501	Y	1,424 ab	X	49 a	X	54 a	X
S-metolachlor fb oxyfluorfen	715 fb 210	340	578	Y	1,761 ab	X	51 a	Y	59 a	X
Crop										
Broccoli	–	148 b	–		–		–		–	
Cabbage	–	553 a	–		–		–		–	
Fixed source of variation		$P > F$								
Herbicide		0.2184	<0.0001				<0.0001			
Crop		<0.0001	<0.0001				0.0016			
Herbicide × crop		0.8804	0.0002				0.0162			

[a]Abbreviation: fb, followed by.
[b]Crop yield data were collected from the experimental locations near Geneva, NY, and Bridgeton, NJ. Crop head circumference data were collected from the Bridgeton, NJ, location only.
[c]Data were pooled across crop species or herbicides when the herbicide x crop interaction was insignificant. The main effect means followed by the same letter within a column (a-c) or row within crop species (X–Y) are not significantly different from each other according to Tukey's honest significance test ($P \leq 0.05$).

DAT with high-rate sulfentrazone. Similarly, Smart et al. (2001) observed injury to seeded cabbage when sulfentrazone was applied POST at 23, 46, 93, 140, and 187 g ha^{-1}, with substantial injury observed at rates above 93 g ha^{-1}. However, cabbage head weight, circumference, and weight were reduced only by the highest rate. These results align with what we observed, which demonstrates that long-season cole crops, under good growing conditions, can outgrow up to 15% sulfentrazone-induced injury (Table 5) without suffering yield reduction (Table 7).

Differences observed between published sulfentrazone studies and the results from our study highlight the injury potential related to application timing to cabbage and broccoli, with differences by crop and location. Harrison and Peterson (1999) found that cultivar and temperature responses were related to observed crop injury in broccoli for oxyfluorfen-applied PRE, whereas collard (*Brassica oleracea* var. *viridis* L.) and broccoli were observed to have injury responses to oxyfluorfen-applied POST that varied depending on temperature and cultivar. In addition to the differences between the environmental and edaphic conditions at our New York and New Jersey sites, cultivar and planting date considerations may also explain crop injury variations.

Bellinder et al. (1989) reported improved cabbage tolerance to metolachlor applied 48 h after transplanting at 2.2 or 4.4 kg ha^{-1} compared to similar PRE-T applications, but that tolerance also depended on cabbage varieties. Significant differences in injury responses between the two locations where this study was conducted highlight the importance of evaluating crop tolerance in a variety of environmental and edaphic conditions in combination with timing of application. Umeda et al. (1999) demonstrated that the range between sufficient weed control and cabbage crop tolerance to sulfentrazone applied POST was narrow. Our study similarly reflected the rate differences in weed control success when sulfentrazone was applied PRE. However, crop tolerance did not vary substantially between sulfentrazone rates at either site. Like results reported by Bellinder (2012), *S*-metolachlor fb oxyfluorfen treatment resulted in increased crop injury following POST application of oxyfluorfen but complete crop recovery, was observed by the time of cabbage or broccoli harvest.

Yield

Crop yield data were also separated between locations due to significant location by herbicide interactions. In New York, there was no significant difference among treatment yields (Table 7). This was likely caused by weather-related stressors that occurred during head development in both years of the study, resulting in premature harvests. Harvest in 2021 occurred ahead of schedule due to increased disease and pest pressure related to above average rainfall in July following below average rainfall in June (Table 1). In 2022, Geneva received less than half the 30-yr average rainfall for May to November and supplemental irrigation was unavailable. Broccoli is particularly sensitive to heat stressors during the 3 wk prior to harvest in northeastern states and may have been particularly affected by a dry 2022 summer (Heather et al. 1992). Additionally, varietal differences in temperature or moisture stress tolerance, as well as structural differences, may have influenced the head weight and circumferences, particularly of broccoli. For example, Emerald Crown may be best for bunch production rather than crown, depending on the planting timing, and is not recommended for production during rainy seasons (Anonymous 2017; Björkman 2016). Field trials conducted in western New York and Long Island have reported mixed results with an early planting date for Emerald Crown, with a recommended planting in mid-summer. In trials conducted in western Pennsylvania, Avenger produced, on average, greater head weight than Emerald Crown when planted in the fall (Anonymous 2017; Sánchez et al. 2014). These interactive factors may have affected observed site differences in our study. Head weights and circumferences were affected by the interaction between crops and herbicide in New Jersey (Table 7). Cabbage head weight more than doubled in response to herbicides, compared with the control, and head circumference increased by 12 to 23 cm. Broccoli head circumference increased by ≥6 cm in response to herbicide treatment compared with the nontreated control.

Available studies describing the efficacy and safety of using sulfentrazone on specialty crops are limited, particularly on cole crops (Cutulle et al. 2019). Early season weed control is most important in conserving crop yields, particularly during the critical

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weed control period of 21 to 35 DAP for transplanted cabbage and 15 to 30 DAP for transplanted broccoli (Latif et al. 2021; Weaver 1984). In our study, treatments that provided the best early season weed control (14 to 28 DAP) were oxyfluorfen, high-rate sulfentrazone, and *S*-metolachlor fb oxyfluorfen, also yielded the greatest cabbage head weight in New Jersey. The use of PRE herbicides, especially on poorly competitive crops such as cabbage and broccoli, can greatly help reduce the labor required to minimize weed competition during this critical period of control. Amisi (2005) estimated that the cost of hand labor, assuming a minimum wage of US$6 h^{-1}, for hand weeding up to the critical control period of cabbage to be $192 ha^{-1}. Gianessi and Sankula (2003) calculated that labor associated with weed control in broccoli, without herbicides, was 20 h ha^{-1}.

Incorporating sulfentrazone into weed control programs, especially when combined with other herbicides, can increase yields and reduce the labor required to produce quality cabbage and broccoli in northeastern and Mid-Atlantic states. In Florida, Sandhu et al. (2022) found that sulfentrazone applied alone to in tomato (*Solanum lycopersicum* L.) was not effective at controlling weeds, but when applied PRE-T in combination with a POST application of halosulfuron, purple nutsedge (*Cyperus rotundus* L.) suppression was achieved. In Oregon, some producers who grow specialty crops such as rhubarb and strawberries have received Special Local Needs exemptions under FIFRA §24c to use sulfentrazone to control broadleaf weeds. Sulfentrazone may be able to supplement existing weed control programs depending on the specific weed spectrum and the timing of the emergence of weeds. For example, sulfentrazone could be a potential replacement for oxyfluorfen applied PRE-T, with oxyfluorfen applied as a POST-T application. Cole crop tolerance within these combination applications must be evaluated to guide use recommendations. Additionally, sequential use of PPO-inhibiting herbicides is not ideal for reducing the risk of herbicide resistance development (Norsworthy et al. 2012), which highlights the need for diversifying herbicide modes of action registered for use on cole crops.

Another possibility for including sulfentrazone in weed control programs in the Northeast and Mid-Atlantic regions would be to focus on the key weeds being controlled. Sulfentrazone is labeled to control sedges (*Cyperus* sp.) in turf when split-applied POST at 110 to 220 g ha^{-1} per application (Anonymous 2022a). Sosnoskie and Hanson (2016) reported improved control of field bindweed (*Convolvulus arvensis* L.), a troublesome species not controlled by oxyfluorfen, with PPI application of trifluralin at 1.12 kg ha^{1} plus sulfentrazone at 0.1 kg ha^{-1} compared to trifluralin alone. Trifluralin currently can be used to control field bindweed in cole crops, but due to injury concerns in cool, wet conditions along with the need for physical incorporation, many growers avoid applying it. More research needs to occur to further contextualize the conditions under which sulfentrazone would be preferable compared to current grower weed control standards for cole crops.

Differing planting restrictions after herbicide applications may highlight another potential use for sulfentrazone on diversified operations. Sulfentrazone has no planting restrictions for most vegetables, soybeans, and corn, whereas a 4-mo planting restriction on using it on rye and wheat. Conversely, oxyfluorfen has a 10-mo planting restriction for cereal grains and 0 to 30 d for some transplanted vegetables. Future research on sulfentrazone use on cole crops under northeastern and Mid-Atlantic conditions should focus on incorporating it into existing weed control programs to supplement and broaden the spectrum of weed control.

Practical Implications

Although cole crop production is significant in the northeastern United States, limited weed control options are available to growers. Weeds are significant contributors to yield loss in eastern cabbage and broccoli production, due to direct interference for light, water, and nutrients and indirect interference from pests and diseases. Sulfentrazone is an herbicide that can control broadleaf weeds such as redroot pigweed and common lambsquarters, but edaphic conditions may reduce its efficacy and crop safety. Available information focusing on the use of sulfentrazone on specialty crops in this region is limited, which makes use recommendations difficult. In this study, researchers in New York and New Jersey evaluated the crop safety and efficacy of weed control of sulfentrazone applied PRE at two rates to acidic silt loams. Sulfentrazone was compared to standard oxyfluorfen applied PRE or *S*-metolachlor applied POST-T fb oxyfluorfen applied 14 d later, which is an injurious herbicide combination not recommended to growers. Our results demonstrate that high-rate sulfentrazone was effective at controlling weeds such as hairy galinsoga, smartweeds, and common ragweed in New York and New Jersey, particularly early in the season. Cabbage was more sensitive to stunting associated weed competition, whereas broccoli was more sensitive to herbicide injury. However, at 233 g ha^{-1}, sulfentrazone caused transient crop injury that did not affect yields relative to the oxyfluorfen standard. Sulfentrazone applied PRE-T at 233 g ha^{-1} can be an effective tool in a weed control program in northeastern and Mid-Atlantic broccoli and cabbage production.

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