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# Improving cole crop safety and weed control response with chloroacetamide and oxyfluorfen herbicide combinations

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## Research Article

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## Abstract

In 2022, trials were carried out in New Jersey and New York to assess the efficacy of weed management and the response of two cole crops to various herbicide combinations and rates. The experiments involved the application of *S*-metolachlor and microencapsulated (ME) acetochlor either alone or combined with oxyfluorfen. Different application timings of oxyfluorfen were tested in greenhouse and field studies. Results from the greenhouse trials show that substituting *S*–metolachlor with ME acetochlor in over-the-top applied mixes with oxyfluorfen caused 15% to 22% less crop injury and increased seedling biomass by 33%. In field studies, nontreated plots exhibited significant weed growth, reaching up to 71% coverage 28 d after transplanting (DATr), whereas herbicide-treated plots exhibited weed cover at or below 10% by 28 DATr. Mixtures or sequential applications of oxyfluorfen and chloroacetamides achieved excellent control (≥99%) of the weed species complex compared to single applications of oxyfluorfen or chloroacetamides. However, applying both oxyfluorfen and a chloroacetamide posttransplanting, either as a tank mixture or in sequence, resulted in ≥19% injury. Despite the effective weed control achieved with herbicide treatments, mixing herbicides posttransplanting reduced relative commercial yield by 46% to 94% compared to oxyfluorfen applied alone or followed by chloroacetamides. The findings from these experiments will inform regional crop safety guidelines and support potential modifications to oxyfluorfen labels regarding sequential applications with chloroacetamides.

## Introduction

In 2022, cabbage (*Brassica oleracea* L. var. *capitata*) and broccoli (*Brassica oleracea* L. var. *italica* Plenck) was grown on 25,500 and 59,700 ha, respectively, in the United States with a combined crop value of almost US$1.5 billion (USDA-NASS 2024). Cole crops, many of which have shallow root systems and are short in stature, can be susceptible to weed interference, especially when it occurs early in the season (Bell 1995; Bellinder 2012; Chen et al. 2011; Fennimore et al. 2010; Latif et al. 2021; Sikkema et al. 2007a, 2007b; Smart et al. 2001; Yu et al. 2018). Competing weeds can significantly reduce yield in cabbage, with an estimated mean loss of 54% across 44 studies conducted over 20 yr (M. VanGessel, personal communication). In broccoli, even low weed densities can exceed the crop's economic threshold, resulting in delayed harvest and reduced yield (Bell 1995; Latif et al. 2021). While competition for shared resources is a significant concern in cole crop production, weeds can also have substantial indirect impacts, including supporting populations of *Brassica* pests and pathogens and serving as occupational hazards for agricultural workers during harvest (Al-Khatib et al. 1995; Bridges 1994; Chen et al. 2011; Dillard and Hunter 1996; Guerena 2020; McErlich and Boydston 2013).

Herbicides are essential for managing weeds in cabbage and broccoli cultivation, yet their efficacy is limited by the few registered products available and their narrow control spectrums (Sikkema et al. 2007b; Wyenandt et al. 2024). *S*-metolachlor (Weed Science Society of America [WSSA] Group 15; chloroacetamide) and oxyfluorfen (WSSA Group 14; diphenylether) are important preemergence (PRE) herbicides for the control of many weed species in cole crop production, including pigweed species (*Amaranthus* spp.), hairy galinsoga (*Galinsoga quadriradiata* Cav.), nightshade species (*Solanum* spp.), common lambsquarters (*Chenopodium album* L.), and smartweed species (*Polygonum* spp.), as well as many annual grasses (Al-Khatib et al. 1995; Anonymous 2020; Besançon et al. 2020; Bhowmik and McGlew 1986; Cutulle et al. 2019; Pineda–Bermudez et al. 2023; Yu et al. 2018). Oxyfluorfen also received 24c special local need labels for postemergence (POST) use after a minimum of 2 wk after transplanting of broccoli, cabbage, and cauliflower (*Brassica oleracea* L. var. *botrytis*) in several states, including New Jersey and New York (Anonymous 2021, 2022). Although *S*-metolachlor posttransplant (POST-Tr) followed by (fb) oxyfluorfen POST 14 d after transplanting (DATr) has been shown to be an effective combination, the sequential use of oxyfluorfen and chloroacetamide herbicides in the same season is discouraged because of injury potential in cole crops (Anonymous 2020; Bellinder 2012). Pineda–Bermudez et al. (2023) reported >20% cabbage and broccoli injury, which was characterized by stunting and necrosis, in response to *S*-metolachlor POST-Tr at 0.72 kg ai ha$^{-1}$ fb oxyfluorfen POST at 0.21 kg ai ha$^{-1}$. Similar results were observed by Bellinder (2012), who documented almost 30% cabbage injury. While cabbage and broccoli can recover from some early-season herbicide-induced damage, adverse weather conditions that reduce crop vigor may negatively impact later growth and head development (LMS, personal observation).

Acetochlor (WSSA Group 15; chloroacetamide) is registered for use in alfalfa (*Medicago sativa* L.), field corn (*Zea mays* L.), and soybean [*Glycine max* (L.) Merr.], among other crops, for the residual control of many common and troublesome grass and broadleaf weeds, including barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.], foxtails (*Setaria* spp.), *Panicum* spp., pigweeds, common lambsquarters, and *Galinsoga* spp. (Lingenfelter et al. 2024; Van Wychen 2022). Acetochlor can be formulated as an emulsifiable concentrate (EC) (Harness®, Bayer Crop Science, Research Triangle Park, NC, USA) or as a microencapsulated (ME) product (Warrant®, Bayer Crop Science). Unlike the EC, the ME formulation has the active ingredient (ai) enclosed in a matrix of polymers that slows the release of the herbicide (Guo et al. 2014). A few studies have demonstrated that ME acetochlor provides greater crop safety compared to the EC formulation when applied POST over foliage (Fogleman et al. 2018; Godwin 2017).

Few studies have explored the effectiveness of chloroacetamide herbicides in cole crops, including ME formulations that could enhance crop safety. Identifying herbicides that are safer to cabbage and broccoli, particularly when used in combination with oxyfluorfen, would greatly benefit growers by improving weed control efficacy. Preliminary greenhouse screenings conducted in NY and NJ showed reduced cabbage injury when ME acetochlor was applied POST in combination with oxyfluorfen or sulfentrazone as compared to *S*-metolachlor and EC acetochlor (LMS and TEB, unpublished data). Thus the objectives of this study were (1) to compare the weed control efficacy and crop safety of ME acetochlor and *S*-metolachlor, an EC, both alone and in combination with oxyfluorfen and (2) to determine the optimal application sequence of chloroacetamide herbicides in relation to oxyfluorfen while still achieving satisfactory weed control.

## Materials and Methods

### *Greenhouse Experiments*

Greenhouse trials were conducted in 2022 at Cornell AgriTech in Geneva, NY (42.87°N, 77.03°W), and at the Rutgers Philip E. Marucci Center for Blueberry and Cranberry Research in Chatsworth, NJ (39.42°N, 74.30°W). Cabbage 'Padoc' and broccoli 'Emerald Crown' cultivars were seeded in New York, whereas cabbage 'Botran' and broccoli 'Imperial' cultivars were used in New Jersey. Five seeds were planted in 10-cm-square pots containing a commercial growing medium (Sun Gro®, Sun Gro® Horticulture, Agawam, MA, USA) and hand watered daily. Once emerged, plants were thinned to a single plant per pot and fertilized weekly with Jack's Professional General-Purpose 20-20-20 fertilizer (JR Peters, Allentown, PA, USA) to provide a nitrogen concentration of 750 ppm. Greenhouses were set to a constant temperature of 20 C (±2 C) with a 16-h day length in New York and a 12-h day length in New Jersey. Natural lighting was supplemented with high-pressure sodium lamps equidistantly placed above the bench to deliver a photosynthetically active radiation flux density of 640 µmol m$^{-2}$ s$^{-1}$.

Herbicide treatments were applied over the top (OTT) of cabbage and broccoli plants at the 2- to 3-leaf stages on February 11 and March 25 at the New Jersey location and on February 14 and April 18 at the New York site. Applications were made using a single-nozzle track spray chamber (DeVries Manufacturing, Hollandale, MN, USA) equipped with an 8002EVS flat-fan TeeJet® nozzle (TeeJet® Technologies, Glendale Heights, IL, USA) in New York and a $CO_2$ backpack sprayer fitted with two XR8004VS nozzles (TeeJet® Technologies) spaced 46 cm apart in New Jersey. Both systems were calibrated to deliver 187 L ha$^{-1}$ at 103 kPa. Treatments included oxyfluorfen (GoalTender®, Nufarm, Alsip, IL, USA) at 210 g ha$^{-1}$ alone or mixed with *S*-metolachlor (Dual Magnum®, Syngenta Crop Protection, Greensboro, NC, USA) at 1,420 g ha$^{-1}$ or ME acetochlor (Warrant®) at 1,430 g ha$^{-1}$. Both chloroacetamide herbicides were also applied separately at the same rates. A nontreated control was included for comparison. The experiment was arranged in a randomized complete-block design with ten replicates per treatment; the study was conducted twice in time at each location.

### *Field Experiments*

In 2022, experiments to evaluate weed control efficacy and crop safety of *S*-metolachlor or ME acetochlor tank mixed or in sequence with oxyfluorfen in cabbage and broccoli were conducted at Cornell AgriTech in Geneva, NY, and at the Rutgers Agricultural Research and Extension Center in Bridgeton, NJ (39.52°N, 75.20° W). Soil in Geneva was a Honeoye loam (fine-loamy, mixed, semiactive, mesic Glossic Hapludalfs) with 38% sand, 44% silt, 18% clay, 2.5% organic matter, and 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, 2.4% organic matter, and pH 5.7.

Prior to transplanting, all fields were cultivated to remove any emerged weeds and cultipacked to prepare a smooth bed for transplanting. Cabbage variety 'Padoc' and broccoli variety 'Emerald Crown' were used at both locations. In New York, the plots measured 7.6 × 3.1 m. Each plot consisted of two rows of broccoli alongside two rows of cabbage, spaced 76.2 cm apart, with individual plant spacing within rows set at 51 cm. In New Jersey, the plots were slightly larger, measuring 9.1 × 3.1 m, with the same arrangement of crops and same spacing as in New York. Cole crops were manually transplanted into bare-ground, flat beds on May 10 in New York and on August 4 in New Jersey. All transplants had 3 to 4 leaves upon planting, and their root balls were buried at least 5 cm deep at both locations. Both sites received 1.5 cm of supplemental irrigation on the day of planting to aid in transplant establishment and to incorporate soil-applied herbicides. Additional irrigation was provided as necessary throughout the growing season in New Jersey, while the New York site relied primarily on rainfall. Dry conditions in Geneva (Table 1) did necessitate a second irrigation event after transplanting to promote crop development. Pest and crop management practices, including fertilization and insect and disease control, followed local guidelines at both sites (Wyenandt et al. 2024).

The trial was structured as a split-plot design comprising four replicates. Herbicide treatments were designated as the main plots,

**Table 1.** Average monthly rainfall in 2022 and 30-yr monthly rainfall average for Geneva, NY, and Bridgeton, NJ.

| | Geneva | | Bridgeton | |
|---|---|---|---|---|
| Month | 2022 | 30-yr avg. | 2022 | 30-yr avg. |
| | mm | | | |
| May | 42 | 83 | 127 | 89 |
| Jun | 117 | 92 | 71 | 106 |
| Jul | 18 | 95 | 51 | 113 |
| Aug | 23 | 89 | 55 | 124 |
| Sep | 27 | 83 | 101 | 112 |
| Oct | 5 | 97 | 150 | 96 |
| Nov | 39 | 65 | 91 | 80 |
| *Total* | *271* | *604* | *646* | *720* |

while cole crop species served as the subplots. Single herbicide treatments consisted of oxyfluorfen (GoalTender®) at 560 g $ha^{-1}$ applied 24 h before transplanting (PRE-Tr) and *S*-metolachlor (Dual Magnum®) at 1,420 g $ha^{-1}$ and ME acetochlor (Warrant®) at 1,430 g $ha^{-1}$ applied OTT within 24 h of transplanting (POST-Tr). Tank-mixed treatments included *S*-metolachlor at 1,420 g $ha^{-1}$ or ME acetochlor at 1,430 g $ha^{-1}$ + oxyfluorfen at 560 g $ha^{-1}$ POST-Tr. One set of sequential treatments included oxyfluorfen (560 g $ha^{-1}$) PRE-Tr fb *S*-metolachlor (1,420 g $ha^{-1}$) or ME acetochlor (1,430 g $ha^{-1}$) POST-Tr. The second set of sequential treatments included *S*-metolachlor (1,420 g $ha^{-1}$) or ME acetochlor (1,430 g $ha^{-1}$) applied POST-Tr fb oxyfluorfen at 280 g $ha^{-1}$ 14 DATr (POST). A nontreated weedy control was included for comparison purposes. The chosen application rates correspond to labeled recommendations with respect to soil texture and organic matter content. At both locations, treatments were applied using a $CO_2$ backpack sprayer calibrated to deliver 187 L $ha^{-1}$. Booms were fitted with two XR11002VS nozzles (TeeJet® Technologies) spaced 48 cm apart in New York and with four XR8004VS nozzles (TeeJet® Technologies) set 46 cm apart in New Jersey.

### Data Collection

For the greenhouse trial, ratings included a visual evaluation of crop necrosis and stunting 14 d after treatment (DAT) using a scale ranging from 0% (indicating no visible damage or stunting) to 100% (indicating plant death or complete lack of growth). Aboveground plant biomass was collected individually 14 DAT, placed into paper bags, dried at 65 C for 96 h, and subsequently weighed.

Crop injury assessments were conducted at 14, 21, and 28 DAT. Injury, which consisted primarily of crop stunting with some minimal leaf burn, was rated on a scale from 0% (indicating no visible damage or stunting) to 100% (indicating plant death). Weed cover, a visual estimate of the percentage of plot area covered with weeds, was also evaluated at 14, 21, and 28 DAT using a scale ranging from 0% (no weed cover) to 100% (soil completely covered by weeds). In New York, at 14 and 28 DAT, individual weed plants were counted in a 0.25-$m^2$ quadrat positioned in the direct center of each cabbage and broccoli subplot within each herbicide treatment whole plot. For both locations, aboveground weed biomass was collected from two 0.25-$m^2$ quadrats placed in the center of each crop subplot at harvest. A single harvest occurred at both locations when a majority of cabbage and broccoli plants were considered U.S. No. 1 according to U.S. Department of Agriculture grades and standards (USDA-AMS 2006, 2016). In New York and New Jersey, cabbage and broccoli was harvested on July 13 (65 DAT) and October 6 (63 DAT), respectively. At both locations, mean head weight was determined by averaging the data from ten adjacent heads per row of cabbage and broccoli.

### Statistical Analysis

Because of unequal variances, weed cover and crop injury data were arcsine square root transformed prior to analysis and back-transformed for presentation of the data (Grafen and Hails 2002). Data were subjected to ANOVA using the PROC GLIMMIX procedure in SAS version 9.4 (SAS Institute, Cary, NC, USA). Cole crop species and herbicide treatments were considered fixed effects, whereas locations, runs nested within location, and replicates nested within location by run were treated as random effects. When Crop × Herbicide treatment interactions were significant, data were separately analyzed by crop. In the absence of significant interaction, data were combined over fixed effects, and mean comparisons between treatments were performed using Tukey's HSD at $\alpha = 0.05$. For the field experiments, orthogonal contrasts were used to evaluate differences for (1) the solo application of oxyfluorfen PRE-Tr or chloroacetamides POST-Tr compared to mixed and sequential applications (hereinafter grouped under combined applications), (2) the solo application of oxyfluorfen PRE-Tr compared to both chloroacetamide herbicides applied alone POST-Tr, and (3) EC *S*-metolachlor compared to ME acetochlor in combined applications. A $P \leq 0.05$ significance level was used for analysis of all orthogonal contrasts.

## Results and Discussion

### Greenhouse Study

#### Crop Injury

The interaction between herbicide treatment and cole crop was significant for both crop necrosis ($P = 0.024$) and stunting ($P = 0.0020$). Thus broccoli and cabbage data were examined separately (Table 2). Broccoli necrosis 14 DAT was minimal (≤3%) for both *S*–metolachlor and ME acetochlor OTT when applied alone but was significantly greater (7%) in response to oxyfluorfen. When mixed with oxyfluorfen, the EC formulation of *S*-metolachlor caused greater necrotic injury on broccoli (19%) than the ME-formulated acetochlor (4%). The stunting response of broccoli to *S*-metolachlor and ME acetochlor OTT, when applied alone, was minimal (≤2%) compared to oxyfluorfen (11%). ME acetochlor in a tank mixture with oxyfluorfen caused less broccoli stunting (5%) than *S*–metolachlor (24%). For cabbage, necrosis was minimal for *S*-metolachlor, ME acetochlor, and oxyfluorfen when applied alone OTT (≤5%); ME acetochlor caused less burning (1%) to cabbage leaves as compared to a similar application of *S*-metolachlor (4%). Substituting *S*-metolachlor with ME acetochlor in a tank mix with oxyfluorfen reduced necrosis of cabbage seedlings from 27% to 6%. All OTT herbicide treatments resulted in ≤6% cabbage stunting, except for *S*-metolachlor + oxyfluorfen, which resulted in 26% stunting.

#### Crop Relative Dry Biomass

There were no interactions between herbicide treatments and cole crops with respect to dry biomass, expressed as a percentage of the nontreated check, so broccoli and cabbage data were combined (Table 2). *S*-metolachlor and ME acetochlor applied alone did not significantly reduce dry biomass compared to the nontreated control. Conversely, oxyfluorfen OTT reduced crop biomass 23%

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**Table 2.** Effect of over-the-top herbicide treatments on cabbage and broccoli injury and relative dry biomass 14 d after treatment for greenhouse experimentations conducted at Geneva, NY, and Chatsworth, NJ, in 2022.[a,b]

| Treatment | Rate | Broccoli | | Cabbage | | |
|---|---|---|---|---|---|---|
| | | Necrosis | Stunting | Necrosis | Stunting | RDW |
| | g ai ha$^{-1}$ | % nontreated control | | | | |
| *S*-metolachlor | 1,420 | 3 c | 2 cd | 4 b | 3 b | 91 ab |
| ME acetochlor | 1,420 | 0 d | 0 d | 1 c | 4 b | 92 a |
| Oxyfluorfen | 210 | 7 b | 11 b | 5 b | 6 b | 77 c |
| *S*-metolachlor + oxyfluorfen | 1,420 + 210 | 19 a | 24 a | 27 a | 26 a | 56 d |
| ME acetochlor + oxyfluorfen | 1,420 + 210 | 4 bc | 5 bc | 6 b | 4 b | 83 bc |

[a]Abbreviation: RDW, relative dry weight.
[b]Main effect means within a column followed by the same letter are not significantly different according to Tukey's HSD ($P \leq 0.05$).

when applied alone and 44% when combined with *S*-metolachlor. When oxyfluorfen was tank mixed with ME acetochlor, crop biomass was reduced 17%.

## Field Study

### Weed Coverage, Control, and Biomass

Prevalent species at the Geneva site included common ragweed (*Ambrosia artemisiifolia* L.), common lambsquarters, ladysthumb (*Persicaria maculosa* Gray), prostrate knotweed (*Polygonum aviculare* L.), and other *Polygonum* species, grouped under smartweed spp., as well as annual grasses, including foxtails and barnyardgrass. Pigweeds and crabgrasses were present in low numbers in the New York trial. Dominant species at the Bridgeton site included hairy galinsoga, common lambsquarters, and annual grasses, including stinkgrass [*Eragrostis cilianensis* (All.) Vign. ex Janchen] and goosegrass [*Eleusine indica* (L.) Gaertn.].

For all observation timings, weed cover and weed control were significantly different for herbicide treatment ($P < 0.0001$) but not for crop ($P = 0.9499$) nor for the interaction between herbicide treatments and crops ($P = 0.8603$); consequently, data were combined over crops (Tables 3 and 4). Weed cover in the nontreated check was 9%, 20%, 35%, and 71% at 7, 14, 21, and 28 DAT, respectively. Weed cover was ≤3% at 7 and 14 DAT for all herbicide treatments (data not shown). At 21 and 28 DAT, weed cover ranged from 5% to 10% where *S*-metolachlor and ME acetochlor were applied alone POST-Tr; this is higher than the cover ratings for all other treatments, which did not exceed 3% (Table 3). For all observation timings and tank mixes, no differences were observed between the *S*–metolachlor- and the ME acetochlor-containing programs with respect to weed cover. Tank mixes and sequential herbicide programs of oxyfluorfen with chloroacetamides were more effective at reducing estimated weed cover compared to the single-ai chloroacetamide treatments.

All herbicide treatments provided ≥97% control of common lambsquarters, common ragweed, smartweed spp., hairy galinsoga, and annual grasses 7 and 14 DAT (data not shown). Tank mixes and sequential applications of oxyfluorfen with either *S*-metolachlor or ME acetochlor provided ≥99% control of all weed species up to 28 DAT. At 21 DAT (data not shown) and 28 DAT, oxyfluorfen applied alone PRE-Tr provided better control of common lambsquarters (100%) than solo POST-Tr applications of both chloroacetamides (Table 4). For both observation timings, *S*–metolachlor provided significantly better control of common lambsquarters (98% and 94%) than ME acetochlor (92% and 84%). At 28 DAT, smartweed control was significantly higher with oxyfluorfen PRE-Tr (96%) compared to POST-Tr applications of *S*–metolachlor (92%) and ME acetochlor (89%). Similar trends were observed for common ragweed; oxyfluorfen applied alone controlled common ragweed 97% compared to 90% and 89% for *S*-metolachlor and ME acetochlor, respectively. Excellent grass control (≥97%) was observed with all treatments, including oxyfluorfen PRE-Tr. All treatments containing the chloroacetamide herbicides completely controlled (100%) hairy galinsoga; by comparison, oxyfluorfen applied alone PRE-Tr controlled galinsoga 87% (data not shown). Oxyfluorfen PRE-Tr applied alone provided better control of common lambsquarters, common ragweed, and smartweeds 28 DAT than did chloroacetamides. There were no differences between the three single-ai treatments for control of grasses or hairy galinsoga. With few exceptions, orthogonal contrast analyses showed that the tank mixes and sequential herbicide programs were more effective at controlling weeds than were these herbicides applied singly. No differences in weed control were observed between the *S*-metolachlor-containing programs and the ME acetochlor-containing programs.

Overall weed density 28 DAT and biomass at harvest were both affected by herbicide treatments ($P < 0.0001$) but not by crops ($P = 0.7937$ and $P = 0.1871$, respectively) nor by the interaction between herbicide treatments and crops ($P = 0.0589$ and $P = 0.9748$, respectively); as such, data were averaged over crops (Table 4). Overall, total broadleaf density 28 DAT in NY was reduced 89% to 99% by all herbicide treatments relative to the nontreated control (246 plants m$^{-2}$), although the single-ai programs were significantly less effective than tank mixes and sequential programs, averaging 20 and 3 plants m$^{-2}$, respectively (data not shown). Grass density was 216 plants m$^{-2}$ in the nontreated control. Higher grass density was noted for the solo PRE-Tr application of oxyfluorfen (9 plants m$^{-2}$) as compared to *S*-metolachlor POST-Tr (5 plants m$^{-2}$), as well as the tank mix and sequential herbicide programs (≤2 plants m$^{-2}$). Grass densities in the solo POST-Tr ME acetochlor treatment (8 plants m$^{-2}$) did not differ significantly from those in the solo application of oxyfluorfen or *S*–metolachlor (data not shown).

Compared to the nontreated control (1,320 g m$^{-2}$), weed biomass collected at harvest was reduced 91% to ≥99% in response to all herbicide treatments (Table 4). Among herbicides, solo POST-Tr applications of *S*-metolachlor (118 g m$^{-2}$) and ME acetochlor (60 g m$^{-2}$) were the least effective herbicide treatments for suppressing weed growth season-long, fb oxyfluorfen PRE-Tr (33 g m$^{-2}$). Tank mixes and sequential applications of oxyfluorfen and *S*–metolachlor or ME acetochlor reduced biomass levels to ≤13 g m$^{-2}$. Orthogonal contrast analyses demonstrated that, given the weed populations present at the New York site, oxyfluorfen applied alone PRE-Tr was more effective at reducing weed biomass than was solo application of chloroacetamides. Orthogonal contrast analyses also confirmed the need to mix oxyfluorfen

**Table 3.** Effect of herbicide treatments and timing of application on weed coverage in cabbage and broccoli field trials conducted at Geneva, NY, and Bridgeton, NJ, in 2022.[a,b]

| Treatment | Rate | Timing | DATr 21 | DATr 28 |
|---|---|---|---|---|
| | g ai ha$^{-1}$ | | % | |
| Nontreated control | 0 | — | 35 a | 71 a |
| Oxyfluorfen | 560 | PRE-Tr | 2 cd | 3 c |
| *S*-metolachlor | 1,420 | POST-Tr | 5 bc | 9 b |
| ME acetochlor | 1,430 | POST-Tr | 7 b | 10 b |
| Oxyfluorfen fb *S*-metolachlor | 560 fb 1,420 | PRE-Tr fb POST-Tr | 1 d | 2 cd |
| Oxyfluorfen + *S*-metolachlor | 560 + 1,420 | POST-Tr | 0 d | 0 d |
| *S*-metolachlor fb oxyfluorfen | 1,420 fb 280 | POST-Tr fb POST | 1 d | 1 cd |
| Oxyfluorfen fb ME acetochlor | 560 fb 1,430 | PRE-Tr fb POST-Tr | 1 d | 2 cd |
| Oxyfluorfen + ME acetochlor | 560 + 1,430 | POST-Tr | 1 d | 1 cd |
| ME acetochlor fb oxyfluorfen | 1,430 fb 280 | POST-Tr fb POST | 1 d | 1 cd |

| Orthogonal contrast | P-value 21 DATr | P-value 28 DATr |
|---|---|---|
| Single ai (2–4) vs. tank mixes and sequential applications (5–10) | <0.0001 | <0.0001 |
| Oxyfluorfen (2) vs. chloroacetamide (3–4) alone | 0.0436 | 0.0025 |
| *S*-metolachlor (5–7) vs. acetochlor (8–10) in combined applications | 0.6294 | 0.7341 |

[a]Abbreviations: ai, active ingredient; DATr, days after transplanting; fb, followed by; ME, microencapsulated; POST, 14 d posttransplant application; POST-Tr, 1 d posttransplant application; PRE-Tr, pretransplant application.
[b]Main effect means within a column followed by the same letter are not significantly different according to Tukey's HSD ($P \leq 0.05$).

**Table 4.** Effect of herbicide treatments and timing of application on common lambsquarters, smartweed spp., common ragweed, and grass weed control and overall weed biomass fresh weight 28 d after treatment in cabbage and broccoli field trials conducted at Geneva, NY, and Bridgeton, NJ, in 2022.[a,b,c]

| Treatment | Rate | Timing | Weed control CHEAL | POLY spp. | AMBEL | Grasses | Weed biomass FW |
|---|---|---|---|---|---|---|---|
| | g ai ha$^{-1}$ | | % | | | | g m$^{-2}$ |
| Oxyfluorfen | 560 | PRE-Tr | 100 a | 96 b | 97 a | 97 b | 1,320 a |
| *S*-metolachlor | 1,420 | POST-Tr | 94 b | 92 c | 89 b | 98 b | 33 cd |
| ME acetochlor | 1,430 | POST-Tr | 84 c | 89 c | 90 b | 98 b | 118 b |
| Oxyfluorfen fb *S*-metolachlor | 560 fb 1,420 | PRE-Tr fb POST-Tr | 99 a | 100 a | 99 a | 100 a | 60 bc |
| Oxyfluorfen + *S*-metolachlor | 560 + 1,420 | POST-Tr | 100 a | 100 a | 100 a | 100 a | 6 d |
| *S*-metolachlor fb oxyfluorfen | 1,420 fb 280 | POST-Tr fb POST | 100 a | 100 a | 100 a | 100 a | 4 d |
| Oxyfluorfen fb ME acetochlor | 560 fb 1,430 | PRE-Tr fb POST-Tr | 100 a | 100 a | 99 a | 99 ab | 4 d |
| Oxyfluorfen + ME acetochlor | 560 + 1,430 | POST-Tr | 100 a | 100 a | 99 a | 100 a | 13 cd |
| ME acetochlor fb oxyfluorfen | 1,430 fb 280 | POST-Tr fb POST | 100 a | 100 a | 100 a | 100 a | 4 d |

| Orthogonal contrast | P-value CHEAL | POLY spp. | AMBEL | Grasses | Weed biomass FW |
|---|---|---|---|---|---|
| Single ai (2–4) vs. tank mixes and sequential applications (5–10) | <0.0001 | <0.0001 | <0.0001 | <0.0001 | 0.0011 |
| Oxyfluorfen (2) vs. chloroacetamide (3–4) alone | <0.0001 | <0.0001 | 0.0011 | 0.6009 | 0.0001 |
| *S*-metolachlor (5–7) vs. acetochlor (8–10) in combined applications | 0.9373 | 1.0000 | 0.2726 | 0.5362 | 0.0586 |

[a]Abbreviations: ai, active ingredient; AMBEL, common ragweed; CHEAL, common lambsquarters; fb, followed by; FW, fresh weight; ME, microencapsulated; POLY, smartweed; POST, 14 d posttransplant application; POST-Tr, 1 d posttransplant application; PRE-Tr, pretransplant application.
[b]CHEAL and grasses were collected from both locations, whereas AMBEL and smartweed were collected only from Geneva, NY.
[c]Main effect means within a column followed by the same letter are not significantly different according to Tukey's HSD ($P \leq 0.05$).

and chloroacetamide herbicides to maximize weed biomass reduction (99%) compared to single-ai treatments (82%).

### Crop Injury and Yield

Observed injury, which was characterized by stunting and some leaf burn, was affected by herbicide treatment at 14, 21, and 28 DAT ($P < 0.0001$) and crop at 14 DAT ($P < 0.0001$) but not by the interaction between the two factors ($P \geq 0.0558$) (Table 5). Averaged over cabbage and broccoli, *S*-metolachlor POST-Tr was the most injurious treatment of the solo applied ai. *S*–metolachlor caused 4%, 8%, and 3% stunting at 14, 21, and 28 DAT, respectively; injury from oxyfluorfen PRE-Tr and ME acetochlor POST-Tr did not exceed 2% at any observation timing. Orthogonal contrast analyses indicated greater crop injury for herbicide programs where oxyfluorfen was used in combination with the chloroacetamides compared to ai used singly. However, the order in which chemistries were applied affected the amount of damage sustained by the crop. When oxyfluorfen PRE-Tr was fb *S*-metolachlor or ME acetochlor POST-Tr, maximum observed injury did not exceed 9% and 4% (21 DAT), respectively; at 28 DAT, visible crop damage was minimal (2% to 3%). Sequential applications where *S*-metolachlor and ME acetochlor POST-Tr were fb oxyfluorfen POST 14 DAT injured cabbage and broccoli up to 31% and 25%, respectively (21 DAT); at 28 DAT, injury was 28%

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**Table 5.** Effect of herbicide treatments and timing of application on crop injury and commercial cole crop yield at harvest for field trials conducted at Geneva, NY, and Bridgeton, NJ, in 2022.[a,b,c]

| Treatment | Rate | Timing | Injury | | | | Commercial yield |
|---|---|---|---|---|---|---|---|
| | | | 7 DATr | 14 DATr | 21 DATr | 28 DATr | |
| | g ai ha$^{-1}$ | | —— % —— | | | | % NTC |
| Herbicide | | | | | | | |
| Oxyfluorfen | 560 | PRE-Tr | 1 | 1 c | 1 d | 1 cd | 268 a |
| *S*-metolachlor | 1,420 | POST-Tr | 1 | 4 b | 8 bc | 3 bc | 175 c |
| ME acetochlor | 1,430 | POST-Tr | 0 | 2 bc | 2 d | 0 d | 220 b |
| Oxyfluorfen fb *S*-metolachlor | 560 fb 1,420 | PRE-Tr fb POST-Tr | 1 | 5 b | 9 bc | 3 bc | 278 a |
| Oxyfluorfen + *S*-metolachlor | 560 + 1,420 | POST-Tr | 2 | 24 a | 15 b | 5 b | 223 b |
| *S*-metolachlor fb oxyfluorfen | 1,420 fb 280 | POST-Tr fb POST | 1 | 2 bc | 31 a | 28 a | 253 ab |
| Oxyfluorfen fb ME acetochlor | 560 fb 1,430 | PRE-Tr fb POST-Tr | 1 | 3 bc | 4 cd | 2 b–d | 262 a |
| Oxyfluorfen + ME acetochlor | 560 + 1,430 | POST-Tr | 2 | 19 a | 13 bc | 5 b | 218 b |
| ME acetochlor fb oxyfluorfen | 1,430 fb 280 | POST-Tr fb POST | 1 | 2 bc | 25 a | 21 a | 205 bc |
| Crop | | | | | | | |
| Broccoli | | | 1 | 5 | 13 a | 6 | 242 |
| Cabbage | | | 1 | 5 | 8 b | 5 | 225 |

| Orthogonal contrast | P-value | | | | |
|---|---|---|---|---|---|
| | 7 DATr | 14 DATr | 21 DATr | 28 DATr | Commercial yield |
| Single ai (2–4) vs. tank mixes and sequential applications (5–10) | 0.5005 | <0.0001 | <0.0001 | <0.0001 | 0.2473 |
| Oxyfluorfen (2) vs. chloroacetamide (3–4) alone | 0.8676 | 0.0162 | 0.0069 | 0.0877 | 0.0120 |
| *S*-metolachlor (5–7) vs. acetochlor (8–10) in combined applications | 0.0410 | 0.0693 | 0.0063 | 0.0318 | 0.2274 |

[a]Abbreviations: ai, active ingredient; DATr, days after transplanting; fb, followed by; ME, microencapsulated; NTC, nontreated control; POST, 14 d posttransplant application; POST-Tr, 1 d posttransplant application; PRE-Tr, pretransplant application.
[b]Injury consisted primarily of crop stunting with some minimal leaf burn.
[c]Main effect means within a column followed by the same letter are not significantly different according to Tukey's HSD ($P \leq 0.05$).

and 21%. POST-Tr tank mixing of oxyfluorfen and chloroacetamides caused ≥19% injury 14 DAT but no more than 5% 28 DAT. Orthogonal contrast analyses suggest that combinations of *S*–metolachlor with oxyfluorfen were more injurious to cabbage and broccoli than combinations of ME acetochlor with oxyfluorfen. Averaged over herbicide treatments, greater injury was observed for broccoli compared to cabbage, but only at 21 DAT.

Relative commercial yield (RCY) expressed as a percentage of the nontreated control was affected by herbicide treatment ($P = 0.0356$) but not by crop ($P = 0.1442$) nor by the interaction between herbicide treatment and crop ($P = 0.9440$); as such, data are averaged over crops. Averaged over cabbage and broccoli, RCY of the nontreated control was 384 g head$^{-1}$; when herbicides were applied, mean RCY across treatments was 846 g head$^{-1}$ (data not shown). RCYs were the highest when oxyfluorfen was applied PRE-Tr singly or fb chloroacetamides POST-Tr (≥262%). Weeds were well controlled by these treatments, and visible crop injury, in the form of stunting and leaf necrosis, was minimal. Two of the lowest RCYs occurred when the chloroacetamides were applied POST-Tr singly, which were the two treatments with the highest levels of weed biomass; the RCY for ME acetochlor was greater (220%) than it was for *S*-metolachlor (175%), likely due to the lower weed biomass measured for this treatment. RCYs for the POST-Tr tank mixes of oxyfluorfen with *S*-metolachlor or ME acetochlor and the sequential treatments where POST-Tr applications of *S*-metolachlor and ME acetochlor were fb POST applications of oxyfluorfen ranged from 205% to 253%. While effective for weed control, these treatments also caused the greatest amount of early-season stunting and leaf burn observed in the trial.

Cole crops are sensitive to crop–weed competition, particularly early in the season, when transplants are still becoming established. Latif et al. (2021) found that the critical control period for transplanted broccoli lies between 15 and 30 DAT. Similarly, Weaver (1984) found that the critical weed control period for transplanted cabbage is between 21 and 35 DAT. For vegetable crops, labor costs constitute a significant portion of total production expenses compared to other commodities. Consequently, herbicides play a crucial role in weed management in cabbage and broccoli production systems. In our studies, oxyfluorfen, *S*–metolachlor, and ME acetochlor applied alone and in combination provided ≥84% weed control across species, significantly reduced weed cover, and prevented weed biomass accumulation relative to the nontreated control. The performance of *S*-metolachlor and oxyfluorfen against common and troublesome weeds in cole crop production has been documented in numerous studies (Bhowmik and McGlew 1986; Chomas and Kells 2004; Cutulle et al. 2019; Li et al. 2016; Pineda-Bermudez et al. 2023; Soltani et al. 2018; Soltani et al. 2014). ME acetochlor has not been investigated for weed control in cole crops, although its weed control efficacy has been demonstrated in other crops (Ferebee et al. 2019; Jhala et al. 2015).

The minor injury observed in response to *S*-metolachlor applied alone to cabbage and broccoli in both greenhouse and field trials is consistent with previous reports describing POST–Tr safety in cole crops (Bellinder et al. 1989; Bellinder and Warholic 1988; Reis et al. 2017; Sikkema et al. 2007a; Yu et al. 2018). The safety of oxyfluorfen in cole crops, when applied PRE-Tr and POST, has also been documented (Bhowmik and McGlew 1986; Cutulle et al. 2019; Pineda-Bermudez et al. 2023; Sikkema et al. 2007b). The stunting and necrosis observed with oxyfluorfen in the greenhouse study were not completely unexpected given label warnings about possible injury to cole crops following POST treatments (Anonymous 2021, 2022) and the fact that plant cuticles were likely thinner in the more protected greenhouse environment.

Like *S*-metolachlor, no significant injury or biomass reduction was observed when ME acetochlor was applied singly OTT. The safety of ME acetochlor, relative to EC herbicide formulations, has been explored in other cropping systems. For POST treatments, EC

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acetochlor injured rice (*Oryza sativa* L.) 23% and 18% at 2 wk after treatment and 4 wk after flooding, respectively, whereas injury from the ME formulation was 11% for both observation timings (Fogleman et al. 2018). Bellinder and Warholic (1988) compared EC and ME formulations of alachlor to metolachlor and other chloroacetamide herbicides. Although they observed variable, and sometimes extreme (up to 60%), injury in their trials, they did not detect significant differences among the ai with respect to their potential to cause injury or reduce yields.

Tank mixes or sequential applications that incorporate multiple modes of action offer a broader spectrum of weed control and are recommended for managing herbicide resistance (Norsworthy et al. 2012). All combinations of *S*-metolachlor and acetochlor with oxyfluorfen were effective for weed control in this study, although there was significant variability with respect to crop injury potential. Like in the studies of Bellinder (2012) and Pineda–Bermudez et al. (2023), all treatments that included oxyfluorfen POST-Tr or POST caused significant injury to both cabbage and broccoli and reduced yields. Oxyfluorfen applied PRE-Tr and fb *S*-metolachlor or ME acetochlor combined both excellent weed control and good crop safety. The comparison of *S*-metolachlor with ME acetochlor did not substantially impact crop injury potential in the field despite promising greenhouse results. This discrepancy could be attributed to various environmental factors in the field, such as temperature or moisture stress, which might have offset the phytotoxicity advantages linked with the ME formulation.

## Practical Implications

Cabbage and broccoli are sensitive to weed competition, particularly early in the season, when transplants are not fully established. This study investigated the possible use of ME acetochlor in place of *S*-metolachlor to reduce crop injury in tank mixes and sequential applications. Greenhouse trials demonstrated that ME acetochlor resulted in less crop injury than *S*-metolachlor when tank mixed with oxyfluorfen; however, these results were not supported in field trials. *S*-metolachlor and oxyfluorfen are important tools for managing weeds PRE and POST in cole crop production. *S*-metolachlor and oxyfluorfen have complementary control spectrums; however, label language advises against using both in a single season due to injury concerns. Results from this study show that oxyfluorfen PRE-Tr fb *S*-metolachlor or ME acetochlor POST-Tr provides good crop safety and is effective at suppressing local weed communities. Growers with late-spring- or fall-planted crops may find this sequence beneficial for managing weed species that can emerge continuously throughout the summer, such as hairy galinsoga, or for managing pigweed species that have evolved herbicide resistance to POST herbicides. Additionally, the POST herbicide options labeled for use on cole crops remain limited, justifying the need to optimize residual weed control through sequential applications, as demonstrated in this study.

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