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Weed control and crop tolerance with *S*-metolachlor in seeded summer squash and cucumber

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Research Article

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Bensulide; clomazone; ethalfluralin; *S*-metolachlor; American black nightshade, *Solanum americanum* Mill.; carpetweed, *Mollugo verticillata* L.; giant foxtail, *Setaria faberi* Herrm.; large crabgrass, *Digitaria sanguinalis* (L.) Scop.; smooth pigweed, *Amaranthus hybridus* L.; cucumber, *Cucumis sativus* L.; summer squash, *Cucurbita pepo* L.

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Abstract

Residual herbicides remain the primary tool for efficient weed control in cucurbit crops because of the lack of crop tolerance to many POST herbicide options. Field experiments were conducted in New Jersey in 2018 and 2019 to determine weed control efficacy and tolerance of direct-seeded cucumber 'Python' and summer squash 'Gold Prize' to *S*-metolachlor applied at 0.7 or 1.4 kg ai ha^{-1} at planting (PRE) or when crops reached the second- to third-leaf stage (EPOST). Regardless of applied rate, *S*-metolachlor PRE or EPOST provided 96% to 100% control 3 wk after planting (WAP) of smooth pigweed, large crabgrass, and giant foxtail. *S*-metolachlor PRE significantly improved American black nightshade and carpetweed control 3 WAP with respect to bensulide, and smooth pigweed with respect to clomazone + ethalfluralin. Summer squash showed excellent tolerance, regardless of *S*-metolachlor rate or timing of application, with stunting not exceeding 17% 4 WAP and 3% 7 WAP at the 1.4 kg ha^{-1} rate. Marketable yield decreased by 15% with *S*-metolachlor PRE or POST at 1.4 kg ha^{-1} with respect to clomazone + ethalfluralin, a reduction not noted when comparing with bensulide or the handweeded control. Marketable fruit number $plant^{-1}$ and individual fruit weight were not affected by *S*-metolachlor applications. Conversely, cucumber was more sensitive to *S*-metolachlor than summer squash was with 30% seedling emergence reduction and 36% to 43% stunting 4 WAP when *S*-metolachlor was applied PRE at 1.4 kg ha^{-1}. EPOST application resulted in 15% to 26% cucumber injury 1 wk after treatment. Marketable yield declined by 21% and 39% with the 0.7 and 1.4 kg ha^{-1} rates of *S*-metolachlor, respectively, compared with clomazone + ethalfluralin. Therefore, *S*-metolachlor may be a novel alternative to already labeled residual herbicides for summer squash, but unacceptable injury and yield reduction do not support its registration on cucumber.

Introduction

Cucurbits are a prominent crop in the northeastern United States, accounting for $91 million in production value and representing approximately 22% of the total vegetable production value for the region in 2018 (USDA-NASS 2019a). In New Jersey, 3,560 ha of cucurbits were planted in 2018, the largest acreage of all fresh-market vegetable commodities. Cucumber and summer squash are the two major cucurbit crops of New Jersey and have a combined production value of $13 million (USDA-NASS 2019b).

Weed control remains an important challenge in cucurbit production because of the low crop tolerance to herbicides, the extended growing season of some crops such as pumpkins or winter squash, the vining habit of most species that prevents the use of cultivation to manage weeds, and the higher economic costs and time requirements associated with nonchemical strategies such as handweeding or cultivation (Grey et al. 2000b; Peachey et al. 2012; Starke et al. 2006; Wallace and Bellinder 1992). Monks and Schultheis (1998) found that competition of large crabgrass with watermelon [Citrullus lanatus (Thunb.) Matsum. & Nakai] for 4, 6, and 10 wk resulted in reduction in fruit number by 25%, 66%, and 82%, respectively. Season-long interference of various weed species including *Amaranthus* spp., common lambsquarters (*Chenopodium album* L.), common ragweed (*Ambrosia artemisiifolia* L.), and ivyleaf morningglory (*Ipomoea hederacea* Jacq.) caused a 35% reduction in the number of marketable watermelons (Vollmer et al. 2020). Peachey et al. (2012) reported 63% and 86% yield reduction from weed competition in cucumber and summer squash, respectively, compared with the handweeded check.

Summer squash and cucumber in New Jersey are grown either on bare ground or in raised beds protected by polyethylene mulch that will help with disease and pest management. Regardless of cropping system, herbicides remain a critical component of weed management strategies for these two crops. The lack of available and effective POST herbicide options for controlling broadleaf weeds emphasizes the need for PRE herbicides at planting. Clomazone, bensulide, and halosulfuron are labeled PRE herbicides in New Jersey for use pretransplant or at seeding of summer squash and cucumber, whereas ethalfluralin is only labeled for direct-seeded cucurbits (Wyenandt et al. 2019). The application of halosulfuron PRE or POST is hindered by the spread of acetolactate synthase herbicide–resistant common ragweed and Palmer amaranth (*Amaranthus palmeri* S. Watson) (Heap 2019). Clomazone at 0.5 to 0.8 kg ha^{-1} provides adequate control of hairy galinsoga (*Galinsoga quadriradiata* Cav.), common lambsquarters, common ragweed, and common purslane (*Portulaca oleracea* L.) (Brown and Masiunas 2002; Jordan et al. 1994; Scott et al. 1995), but is ineffective on yellow nutsedge (*Cyperus esculentus* L.), smooth pigweed, or nightshades (*Solanum* spp.) (Al-Khatib et al. 1995; Nurse et al. 2006; Trader et al. 2008).

The large diversity of genetic background and seed size of cucurbitaceous crops results in a broad range of interspecific and intervarietal tolerance to soil-applied herbicides, as demonstrated by previous studies on pumpkin (Ferebee et al. 2019), summer squash (Grey et al. 2000b; Sosnoskie et al. 2008; Trader et al. 2008; Webster et al. 2003), watermelon (Grey et al. 2000a; Macrae et al. 2008), cantaloupe (*Cucumis melo* L.) (Johnson and Mullinix 2005), or cucumber (Peachey et al. 2012). However, the use of multiple, effective herbicide sites of action (SOAs) is one of several weed management strategies that could alleviate the rapid spread of resistance to herbicides (Norsworthy et al. 2012). Thus, adding a new SOA to the list of currently registered herbicides for summer squash and cucumber would be beneficial toward management of herbicide resistance and troublesome weeds not controlled by currently registered herbicides.

S-metolachlor is a very-long-chain fatty acid biosynthesis inhibitor (WSSA Group 15) that would provide a different SOA not currently available for summer squash and cucumber production. *S*-metolachlor (Dual Magnum®; Syngenta Crop Protection, Greensboro, NC) received a Section 24(c) special local needs registration for use in these two crops in New York and Massachusetts, but not in New Jersey or any other state in the northeastern United States. *S*-metolachlor controls many annual grasses as well as some small-seeded annual broadleaf species such as pigweeds, carpetweed, or nightshades, and will help suppress yellow nutsedge (Shaner 2014; Wallace et al. 2020; Wyenandt et al. 2019). Sosnoskie et al. (2008) reported that PRE application of *S*-metolachlor at 0.5 to 1 kg ha^{-1} reduced cumulative fruit number and yield of summer squash by 17% and 20%, respectively, whereas POST application 3 wk after planting (WAP) at 0.5 kg ha^{-1} had no significant effect. Peachey et al. (2012) did not report any reduced crop emergence or marketable yield with *S*-metolachlor applied PRE alone at 1.1 or 2.1 kg ha^{-1} in cucumber and zucchini. Considering the lack of information on tolerance of cucurbits to *S*-metolachlor and the limited options for rotating SOAs applied PRE, a study was conducted to evaluate weed control, crop tolerance, and yield of summer squash and cucumber to *S*-metolachlor applied alone or mixed with bensulide at two timings.

Materials and Methods

The tests were conducted in 2 site-years at the Rutgers Agricultural Research and Extension Center in Bridgeton, New Jersey (39.31°N, 75.12°W). In 2018, soil was a Sassafras sandy loam (fine-loamy, siliceous, semiactive, mesic Typic Hapludults), 63% sand, 26% silt, and 10% clay, with pH of 6.2 and 1.1% organic matter content. In 2019, soil was a Fallsington sandy loams (Fine-loamy, mixed, active, mesic Typic Endoaquults), 53% sand, 35% silt, and 12% clay, with pH of 6.2 and 1.5% organic matter content.

Plant Material

Cucumber ‘Python’ and summer squash ‘Gold Prize’ were seeded on June 8, 2018, and June 5, 2019, in previously disked, flat seedbeds at an average depth of 2.1 cm. Plot size was 1.5 m wide by 6.1 m long with plants spaced 0.3 m and 0.5 m along the row for cucumber and summer squash, respectively. Fields were fertilized prior to planting with calcium nitrate to provide 60 kg N ha^{-1}. Fungicides and insecticides were applied several times each year for mildew and cucumber beetle control according to the “Mid-Atlantic Commercial Vegetable Production Recommendations” (Wyenandt et al. 2019). The field was irrigated as needed with an irrigation gun set to deliver 2.5 cm water wk^{-1}.

Treatments

The experimental design was a randomized complete block with treatments arranged as a 2 × 10 factorial with cucurbit species (cucumber or summer squash) as the first factor and herbicide treatment as the second factor. PRE herbicide treatments at seeding consisted of bensulide (Prefar® 0.5 kg ai L^{-1}; Gowan Co., Yuma, AZ) at 4.5 kg ha^{-1}, clomazone + ethalfluralin (Strategy® 0.3 kg ai L^{-1}; Loveland Products, Greeley, CO) at 0.2 and 0.7 kg ha^{-1}, *S*-metolachlor (Dual Magnum® 0.9 kg ai L^{-1}; Syngenta Crop Protection) at 0.7 and 1.4 kg ha^{-1}, alone or mixed with bensulide at 4.5 kg ha^{-1}. Bensulide and clomazone + ethalfluralin are considered standard PRE herbicide treatments for cucumber and summer squash in New Jersey. *S*-metolachlor was also applied at the second- to third-leaf stage (EPOST) 3 WAP at 0.7 or 1.4 kg ha^{-1} on plots treated beforehand at seeding with bensulide alone at 4.5 kg ha^{-1}. Both crops were at the third fully expanded leaf stage at the time of EPOST application on June 25, 2018, and June 26, 2019. A handweeded and a weedy check were also included. Herbicides were applied in water with a CO_2-pressurized backpack sprayer equipped with XR11002 flat-fan nozzles (TeeJet, Glendale Heights, IL) calibrated to deliver 190 L ha^{-1} at 205 kPa. The field was irrigated with 1.3 cm of water within 6 to 8 h of application to incorporate herbicides.

Data Collection

Crop seedlings were counted in the whole plots at 2 and 5 WAP. Assessment of cucumber and summer squash tolerance was conducted 2, 4, and 7 WAP by visually scoring crop canopy for leaf injury (necrosis and chlorosis) and general stunting on a 0% (no injury or stunting) to 100% (entire canopy affected or plant death) scale (Frans et al. 1986). Weed control was visually rated by species 3 WAP on a 0% (no control) to 100% (death of all plants) scale, based on a composite estimation of weed density reduction, growth inhibition, and foliar injury (Frans et al. 1986). Weed control in plots treated EPOST was also rated 3 wk after the *S*-metolachlor application (6 WAP). To minimize the effect of weed competition on crop development and yield, weekly handweeding was conducted after the 3 WAP rating for plots treated with PRE herbicides at planting, whereas handweeding started 6 WAP for plots sprayed with EPOST herbicides.

Cucumbers and summer squashes were harvested and graded according to U.S. Department of Agriculture grades and standards instruction (USDA-AMS 2016; USDA-AMS 2018). Yield data for both crops consisted of count and weight of marketable, including

Table 1. Weed control averaged across years and crop species 3 wk after herbicide application at Bridgeton, New Jersey.

			EPPO Code[c]					
Herbicide	Rate	Application timing[a,b]	AMACH	CHEAL	SOLAM	MOLVE	SETFA	DIGSA
	kg ai ha^{-1}		%					
Clomazone + ethalfluralin	0.2 + 0.7	PRE	91c	99a	59b	99a	100	98
Bensulide	4.5	PRE	100a	78c	7c	47b	97	98
S-metolachlor	0.7	PRE	100a	58d	99a	99a	97	96
S-metolachlor	1.4	PRE	100a	62d	100a	100a	96	98
Bensulide + *S*-metolachlor	4.5 + 0.7	PRE	99a	77c	100a	98a	99	96
Bensulide + *S*-metolachlor	4.5 + 1.4	PRE	100a	86b	100a	100a	99	98
Bensulide + *S*-metolachlor	4.5 + 0.7	PRE + EPOST	100a	55d	13c	1c	98	98
Bensulide + *S*-metolachlor	4.5 + 1.4	PRE + EPOST	98b	61d	19c	2c	100	100

[a] PRE applied at planting. EPOST applied 21 d after planting.

[b] Abbreviations: AMBEL, common ragweed; AMACH, smooth pigweed; CHEAL, common lambsquarters; DIGSA, large crabgrass; EPPO, European and Mediterranean Plant Protection Organization; MOLVE, carpetweed; SETFA, giant foxtail; SOLAM, American black nightshade.

[c] Means within a column followed by the same letters are not significantly different from each other according to Fisher's protected LSD test at $P \leq 0.05$. If no letters are included in a column, then no statistical differences were noted.

U.S. No. 1 and No. 2, and cull fruits. In both years, cucumbers were picked five times and summer squashes six times. Cucumbers were harvested between July 25 and August 23 in 2018, and between July 24 and August 14 in 2019. Summer squashes were harvested between July 20 and August 27 in 2018, and between July 17 and August 14 in 2019.

Statistical Analysis

Data were combined across years and locations (hereafter referred to as "environment"). Environments, residual herbicide application, cucurbit species, and all interactions containing these three factors were considered fixed effects, whereas replications (nested within environments) were considered random effects (Carmer et al. 1989). Data were subjected to ANOVA using the generalized linear mixed model (GLIMMIX) procedure in SAS, version 9.4 (SAS Institute Inc., Cary, NC) to determine if years could be combined for regression analysis. Because of unequal variance, weed control and crop injury data were converted using the arcsine square root transformation prior to ANOVA and back-transformed for presentation purposes (Grafen and Hails 2002). Mean comparisons were performed using the Fisher protected LSD test when *F* values were statistically significant ($P \leq 0.05$). Weedy and handweeded plots were excluded from the weed control analysis because values were 0% and 100%, respectively.

Results and Discussion

The two-way interaction of herbicide treatment by environment was not significant ($P > 0.05$) for weed control, crop tolerance, crop emergence, and crop yield. Thus, corresponding data were pooled across environments.

Weed Control

In the absence of a significant cucurbit species by herbicide treatment interaction, weed control ratings were pooled across cucurbit species (Table 1). The dominant weed species at the experimental sites were smooth pigweed, common lambsquarters, hairy galinsoga, American black nightshade, carpetweed, giant foxtail, and large crabgrass.

Smooth Pigweed. *S*-metolachlor or bensulide PRE controlled smooth pigweed at least 99% 3 WAP, whereas control significantly dropped to 91% with clomazone and ethalfluralin (Table 1). EPOST treatments provided at least 98% control. However, in the absence of weed control evaluation 6 WAP for bensulide alone, it is not possible to determine if excellent smooth pigweed control was the result of *S*-metolachlor applied EPOST or if bensulide PRE was still providing residual control. Other researchers had also reported a lack of smooth pigweed control with clomazone compared with other PRE herbicides (Liebl and Norman 1991; Trader et al. 2008). Efficacy of *S*-metolachlor on various pigweed species has been reported in previous studies. *S*-metolachlor applied PRE at 0.8 to1.3 kg ha^{-1} at transplanting provided 80% to 96% Palmer amaranth control in sweetpotato [*Ipomoea batatas* (L.) Lam.] (Meyers et al. 2010). *S*-metolachlor PRE at 1.05 kg ha^{-1} can reduce redroot pigweed density by 98% in white bean (*Phaseolus vulgaris* L.) (Li et al. 2016) and 85% in kidney beans (*P. vulgaris* L.) (Soltani et al. 2014).

Common Lambsquarters. *S*-metolachlor alone was not effective at controlling common lambsquarters regardless of rate or timing of application, in agreement with other studies (Table 1). Common lambsquarters control 4 wk after treatment (WAT) was only 66% with *S*-metolachlor PRE at 2.2 kg ha^{-1} in corn (Chomas and Kells 2004), and 55% and 52% in kidney bean and white bean, respectively, with *S*-metolachlor PRE at 1.05 kg ha^{-1} (Li et al. 2016; Soltani et al. 2014). Common lambsquarters control 3 WAP was 99% with clomazone + ethalfluralin, but only 78%, on average, with bensulide alone or tank-mixed with *S*-metolachlor PRE at 0.7 kg ha^{-1}. Increasing *S*-metolachlor rate PRE to 1.4 kg ha^{-1} significantly improved common lambsquarters control by 8%. Herbicide programs that included clomazone PRE have been reported to control common lambsquarters at least 98% in cotton (Troxler et al. 2002).

American Black Nightshade. Clomazone + ethalfluralin or bensulide PRE was not effective on nightshade, providing less than 60% control, whereas all treatments that included *S*-metolachlor PRE at 0.7 or 1.4 kg ha^{-1} resulted in at least 99% control 3 WAP (Table 1). Conversely, *S*-metolachlor applied EPOST did not control nightshade. Because bensulide PRE did not control this species, the delayed *S*-metolachlor application was sprayed after nightshade seedlings had already emerged. In previous studies, metolachlor or *S*-metolachlor applied PRE at rates ranging from 0.5 to 2.5 kg ha^{-1} provided excellent control (≥95%) of eastern black nightshade (*Solanum ptychanthum* Dunal), hairy nightshade (*Solanum physalifolium* Rusby) or American black nightshade (Hutchinson 2012; Norsworthy and Smith 2005; Ogg 1986). Metolachlor at 1.1 or 1.7 kg ha^{-1} provided between 25% and 84% hairy nightshade control 12 WAT, with highest control

Table 2. Cucumber emergence averaged across years in response to clomazone + ethalfluralin, bensulide, and S-metolachlor applied PRE and EPOST at Bridgeton, New Jersey.

Treatment	Rate[a]	Application timing[b]	2 WAP[c]	5 WAP
	kg ai ha^{-1}		——— plants m^{-1} ———	
Handweeded	NA	NA	2.7a	2.5a
Weedy	NA	NA	2.6a	2.7a
Clomazone + ethalfluralin	0.2 + 0.7	PRE	2.3ab	2.3ab
Bensulide	4.5	PRE	2.4ab	2.4ab
S-metolachlor	0.7	PRE	2.2ab	2.2ab
S-metolachlor	1.4	PRE	1.9bc	1.9c
Bensulide + *S*-metolachlor	4.5 + 0.7	PRE	2.4ab	2.3ab
Bensulide + *S*-metolachlor	4.5 + 1.4	PRE	1.6c	1.6c
Bensulide + *S*-metolachlor	4.5 + 0.7	PRE + EPOST	2.6a	2.5a
Bensulide + *S*-metolachlor	4.5 + 1.4	PRE + EPOST	2.5a	2.2ab

[a] Abbreviations: NA, not applicable; WAP, wk after planting.
[b] PRE applied at planting. EPOST applied 21 d after planting.
[c] Means within a column followed by the same letters are not significantly different from each other according to Fisher protected LSD test at $P \leq 0.05$.

Table 3. Cucumber and summer squash injury averaged across years in response to clomazone + ethalfluralin, bensulide, and S-metolachlor applied PRE and EPOST at Bridgeton, New Jersey.

Herbicide	Rate	Application timing[a]	2 WAP	4 WAP[b,c,d] Cucumber	4 WAP[b,c,d] Squash	7 WAP
	kg ai ha^{-1}		————	——— % ———	————	————
Clomazone + ethalfluralin	0.2 + 0.7	PRE	1b	0c	0	1c
Bensulide	4.5	PRE	1b	0c	0	1c
S-metolachlor	0.7	PRE	1b	0c	0	1c
S-metolachlor	1.4	PRE	4a	1c	0	1c
Bensulide + *S*-metolachlor	4.5 + 0.7	PRE	0b	0c	0	2bc
Bensulide + *S*-metolachlor	4.5 + 1.4	PRE	1b	0c	0	2bc
Bensulide + *S*-metolachlor	4.5 + 0.7	PRE + EPOST	NA	15b	0	5a
Bensulide + *S*-metolachlor	4.5 + 1.4	PRE + EPOST	NA	26a	0	4ab

[a] PRE applied at planting. EPOST applied 21 d after planting.
[b] Abbreviations: NA, not applicable; WAP, wk after planting.
[c] Because of a significant herbicide by crop species interaction 4 WAP, data for this rating were separated by crop species.
[d] Means within a column followed by the same letters are not significantly different from each other according to Fisher protected LSD test at $P \leq 0.05$. If no letters are included in a column, then no statistical differences were noted.

observed when conditions after herbicide application were cool and wet, potentially resulting in good herbicide activation and slower microbial degradation (Guttieri and Eberlein 1997).

Carpetweed. PRE application of clomazone + ethalfluralin or any treatment containing S-metolachlor resulted in at least 95% carpetweed control, whereas bensulide controlled carpetweed only 47% (Table 1). Lack of control with bensulide applied PRE resulted in only 21% to 32% carpetweed control with S-metolachlor applied EPOST. These findings are similar to those of other studies, in which bensulide PRE at 2.2 kg ha^{-1} did not exceed 40% carpetweed control, whereas S-metolachlor at 0.7 kg ha^{-1} provided 96 % control 8 WAT (Norsworthy and Smith 2005).

Giant Foxtail and Large Crabgrass. All treatments provided at least 96% control of giant foxtail and large crabgrass, regardless or S-metolachlor rate or timing of application (Table 1). Other researchers have also reported excellent (≥90%) control of these species with S-metolachlor applied PRE (Norsworthy and Smith 2005; Soltani et al. 2014).

Cucumber and Summer Squash Emergence

The herbicide treatment by cucurbit species interaction was significant ($P < 0.001$) for crop emergence; therefore, data were analyzed by crop. Summer squash emergence at 2 and 5 WAP was similar for all treatments and was not affected by herbicide application, with an average of 2 plants m^{-1} of linear row (data not shown). Cucumber emergence 2 WAP was not affected by clomazone + ethalfluralin, bensulide, or S-metolachlor at 0.7 kg ha^{-1} applied PRE compared with both weedy and handweeded checks, with an average of 2.5 plants m^{-1} (Table 2). However, S-metolachlor PRE at 1.4 kg ha^{-1} alone or mixed with bensulide reduced cucumber emergence 2 WAP by 29% and 40%, respectively, compared with the checks. Cucumber provided similar results 5 WAP, with a 28% reduction in the number of emerged seedlings with S-metolachlor applied at 1.4 kg ha^{-1} compared with 0.7 kg ha^{-1} or to standard PRE herbicides. S-metolachlor applied EPOST 3 WAP on already emerged cucumber seedlings did not reduce cucumber stands 5 WAP.

Cucumber and Summer Squash Tolerance

In the absence of a significant herbicide by cucurbit species interaction ($P \geq 0.05$), data were pooled across cucurbit species for crop injury 2 and 7 WAP (Table 3) and for crop stunting 2 WAP (Table 4).

S-metolachlor alone at 1.4 kg ha^{-1} caused a higher level of injury (4%) than any other treatment (≤1%) 2 WAP, mostly in the form of leaf cupping and chlorosis (Table 3). By 4 and 7 WAP, plants in

Table 4. Cucumber and summer squash stunting averaged across years in response to clomazone + ethalfluralin, bensulide, and *S*-metolachlor applied PRE and EPOST at Bridgeton, New Jersey.

Herbicide	Rate	Application timing[a]	2 WAP[d]	4 WAP[b,c]		7 WAP[c]	
				Cucumber	Squash	Cucumber	Squash
	kg ai ha^{-1}		%				
Clomazone + ethalfluralin	0.2 + 0.7	PRE	4c	2de	3c–e	0d	0b
Bensulide	4.5	PRE	1d	1e	0e	0d	0b
S-metolachlor	0.7	PRE	14b	13b	5b–d	0d	0b
S-metolachlor	1.4	PRE	34a	36a	17a	10b	1ab
Bensulide + *S*-metolachlor	4.5 + 0.7	PRE	14b	11bc	8a–c	0d	0b
Bensulide + *S*-metolachlor	4.5 + 1.4	PRE	36a	43a	12ab	9b	1ab
Bensulide + *S*-metolachlor	4.5 + 0.7	PRE + EPOST	NA	5cd	2de	6c	1ab
Bensulide + *S*-metolachlor	4.5 + 1.4	PRE + EPOST	NA	11bc	3c–e	17a	3a

[a] PRE applied at planting. EPOST applied 21 d after planting.
[b] Abbreviations: NA, not applicable; WAP, wk after planting.
[c] Means within a column followed by the same letters are not significantly different from each other according to Fisher's protected LSD test at $P \leq 0.05$. If no letters are included in a column, then no statistical differences were noted.
[d] In the absence of significant herbicide by crop species interaction 2 WAP, data for this rating were pooled across years and crop species.

all plots that received *S*-metolachlor PRE regardless of crop or herbicide rate did not show more injury than those in plots treated with clomazone + ethalfluralin or bensulide standards. By 4 WAP, *S*-metolachlor applied EPOST at 0.7 or 1.4 kg ha^{-1} caused 15% and 26% cucumber injury, respectively, but did not damage summer squash. Injury consisted primarily of leaf cupping at 7% and 16%, and chlorosis at 4%, and 6%, with the 0.7 and 1.4 kg ha^{-1} rates, respectively (data not shown). Lower cucumber tolerance to *S*-metolachlor was demonstrated by the persistence of injury 7 WAP, with an average of 4% injury across herbicide treatments in contrast to the absence of injury on summer squash (data not shown).

S-metolachlor PRE at 0.7 and 1.4 kg ha^{-1} caused 14% and 35% stunting 2 WAP, respectively, averaged across crops, whereas stunting remained less than 5% with bensulide or clomazone + ethalfluralin standards (Table 4). This trend persisted 4 WAP, with 12% and 39% stunting, respectively, for the 0.7 and 1.4 kg ha^{-1} rates of *S*-metolachlor compared with no more than 2% for the bensulide alone and clomazone + ethalfluralin standards. Summer squash exhibited higher tolerance to *S*-metolachlor with only the PRE application at 1.4 kg ha^{-1} causing 15% stunting, on average, 4 WAP. *S*-metolachlor applied EPOST at 1.4 kg ha^{-1} stunted the cucumber plants 11%, whereas the 0.7 kg ha^{-1} rate had no effect compared with the clomazone + ethalfluralin standard. Similar EPOST application of *S*-metolachlor had no effect on stunting of summer squash. Greater than 6% stunting persisted by 7 WAP with *S*-metolachlor PRE at 1.4 kg ha^{-1} or any rate EPOST on cucumber, whereas summer squash stunting did not exceed 3% at the highest *S*-metolachlor rate applied EPOST.

Squash tolerance to *S*-metolachlor applied PRE was also noted on pumpkin, with no more than 3% injury 4 WAP at a 0.9 kg ha^{-1} rate in two Virginia trials (Ferebee et al. 2019). Sosnoskie et al. (2008) reported an average 20% summer squash yield reduction with *S*-metolachlor PRE at 0.5 or 1 kg ha^{-1} but no effect with POST application at the same rates.

Limited damage was noted 4 WAP on cucumber, with only 1% and 4% injury with *S*-metolachlor applied PRE at 1.1 and 2.1 kg ha^{-1} (Peachey et al. 2012). However, the higher clay (20%) and organic matter (2.4%) content in this study may have increased *S*-metolachlor adsorption to soil particles, decreasing its uptake by the crop and thereby reducing the level of injury. Metolachlor more readily adsorbs to clay soils than to soil with low organic matter and clay content, and more readily adsorbs to organic matter than to clay (Shaner 2014).

Cucumber and Summer Squash Yield

The herbicide treatment by cucurbit crop interaction was significant ($P < 0.05$) for marketable yield and fruit number; thus, data are presented by crop species (Tables 5 and 6).

Summer squash total and marketable fruit weights from the handweeded check plots were 61,500 and 57,900 kg ha^{-1}, respectively (Table 5). Fruit weight declined 50%, on average, when weeds were allowed to compete all season long. Total and marketable fruit weights in herbicide-sprayed plots ranged from 54,800 to 70,700 kg ha^{-1} and 51,900 to 66,500 kg ha^{-1}, respectively, with no treatment yielding significantly less than the handweeded check. This was primarily because all herbicide-treated plots were kept weed-free from 3 wk after the EPOST application until harvest. The weight of total or marketable fruits as well as total fruit number were significantly reduced by 17% to 22% with *S*-metolachlor PRE or EPOST at 1.4 kg ha^{-1} in comparison with the clomazone + ethalfluralin standard. However, none of the *S*-metolachlor treatments differed from the bensulide standard with regard to summer squash fruit production. Fruit weight and number in plots treated with bensulide were lower than in those sprayed with clomazone + ethalfluralin. This is probably due to lower weed control with bensulide between 3 and 6 WAP compared with clomazone + ethalfluralin, which allowed weeds to compete with young seed. The number of marketable fruits per plant and individual fruit weight were not significantly different between treatments, averaging, respectively, 8.2 fruits and 628 g (data not shown).

Because of its prostrate growth habit, cucumber was more sensitive to weed competition than was summer squash; the former incurred 85% yield loss in the weedy check plots compared with the handweeded plots (Table 6). Cucumber treated with *S*-metolachlor at 0.7 kg ha^{-1} yielded the same as that treated with bensulide, regardless of application timing. Increasing *S*-metolachlor rate to 1.4 kg ha^{-1} decreased cucumber fruit weight and number by 36% and 33%, respectively, averaged across PRE treatments and compared with the clomazone + ethalfluralin standard. EPOST application at the same rate had a more drastic effect on yield and fruit number, which were decreased by 43% and 38%, respectively.

Table 5. Summer squash yield averaged across years in response to clomazone + ethalfluralin, bensulide, and *S*-metolachlor applied PRE and EPOST at Bridgeton, New Jersey.

			Fruit weight[c]		Fruit number[c]	
Herbicide	Rate[a]	Application timing[b]	Marketable	Total	Marketable	Total
			—— kg ha^{-1} ——		—— 1,000 fruits ha^{-1} ——	
Handweeded	NA	NA	57,900ab	61,500ab	92ab	101ab
Weedy	NA	NA	28,700c	29,600c	47c	49c
Clomazone + ethalfluralin	0.2 + 0.7	PRE	66,500a	70,700a	105a	115a
Bensulide	4.5	PRE	54,400b	58,000b	85b	92b
S-metolachlor	0.7	PRE	56,500ab	61,100ab	90ab	102ab
S-metolachlor	1.4	PRE	52,100b	56,000b	85b	93b
Bensulide + *S*-metolachlor	4.5 + 0.7	PRE	54,900ab	59,600ab	86b	97ab
Bensulide + *S*-metolachlor	4.5 + 1.4	PRE	51,900b	54,800b	84b	91b
Bensulide + *S*-metolachlor	4.5 + 0.7	PRE + EPOST	55,600ab	59,800ab	87b	96b
Bensulide + *S*-metolachlor	4.5 + 1.4	PRE + EPOST	54,500b	57,800b	87b	95b

[a] Abbreviation: NA, not applicable.

[b] PRE applied at planting. EPOST applied 21 d after planting.

[c] Yield and fruit number data were pooled over environments. Means within a column followed by the same letters are not significantly different from each other according to Fisher protected LSD test at $P \leq 0.05$.

Table 6. Cucumber yield averaged across years in response to clomazone + ethalfluralin, bensulide, and *S*-metolachlor applied PRE and EPOST at Bridgeton, New Jersey.

			Fruit weight[c]		Fruit number[c]			
Herbicide	Rate[a]	Application timing[b]	Marketable	Total	Marketable	Total	Average marketable fruit number	Average marketable fruit weight
			—— kg ha^{-1} ——		—— 1,000 fruits ha^{-1} ——		plant^{-1}	g fruit^{-1}
Handweeded	NA	NA	76,900a	82,500a	197a	219a	10.7a	390a
Weedy	NA	NA	10,600f	12,800e	30d	39e	1.8d	330d
Clomazone + ethalfluralin	0.2 + 0.7	PRE	68,000ab	72,300a	187a	205ab	11.0a	371ab
Bensulide	4.5	PRE	60,800bc	66,200ab	161ab	178a–d	8.7a–c	375ab
S-metolachlor	0.7	PRE	51,100c–e	54,400b–d	141bc	155b–d	9.9a	365a–c
S-metolachlor	1.4	PRE	43,800de	47,100cd	125bc	141cd	9.7ab	346cd
Bensulide + *S*-metolachlor	4.5 + 0.7	PRE	60,000b–d	65,000a–c	161ab	183a–c	11.3a	377ab
Bensulide + *S*-metolachlor	4.5 + 1.4	PRE	42,600e	46,400d	121bc	137cd	10.9a	354bc
Bensulide + *S*-metolachlor	4.5 + 0.7	PRE + EPOST	50,100c–e	52,900b–d	140bc	150cd	7.4bc	355bc
Bensulide + *S*-metolachlor	4.5 + 1.4	PRE + EPOST	38,400e	41,800d	115c	129d	7.1c	334d

[a] Abbreviation: NA, not applicable.

[b] PRE applied at planting. EPOST applied 21 d after planting.

[c] Yield data were pooled over environments. Means within a column followed by the same letters are not significantly different from each other according to Fisher protected LSD test at $P \leq 0.05$.

Total and marketable yields for *S*-metolachlor at 1.4 kg ha^{-1}, regardless of timing of application, were also significantly lower than for the bensulide standard. *S*-metolachlor applied PRE at 1.4 kg ha^{-1} did not significantly affected the number of marketable cucumbers per plant but did reduce marketable fruit weight by 40 g and 20 g, on average, compared with the handweeded check and clomazone + ethalfluralin standard, respectively. Similar comparison indicated EPOST application significantly lowered the number of fruits per plant by 33% and the individual fruit weight by 16 to 56 g, depending on the selected standard. Lower individual fruit weight for PRE application at the high rate or EPOST application can result from *S*-metolachlor injuries to the cucumber root system that limit the absorption of water and nutrients. Literature indicates that root absorption is an important pathway for *S*-metolachlor uptake in broadleaf species (Bollman et al. 2008; Le Baron et al. 1988). *S*-metolachlor reduced root enzymatic activity and inhibited the production and development of lateral roots in corn and rice (Liu et al. 2012) and reduced overall root biomass in bermudagrass [*Cynodon dactylon* (L.) Pers.] (Begitschke et al 2018). However, additional studies would be required to evaluate the effect of *S*-metolachlor on root development and architecture of sensitive crops or varieties within a crop species.

This study demonstrates the tolerance of summer squash cultivar 'Gold Prize' to *S*-metolachlor at 0.7 kg ha^{-1} applied PRE at planting or EPOST. Transitory injury and the absence of effect on squash yield were observed with *S*-metolachlor at 0.7 kg ha^{-1}. Doubling the rate of *S*-metolachlor reduced squash marketable yield in comparison with clomazone + ethalfluralin but not the bensulide standard. These results are in agreement with data from Georgia published by Sosnoskie et al. (2008), who did not report any effect of *S*-metolachlor applied EPOST at 0.5 or 1 kg ha^{-1} on yellow squash and green zucchini fruit yield. However, the same authors reported 9% to 48% yield reduction with similar PRE application, the detrimental effect of *S*-metolachlor being more pronounced on early than late-season yields. This was not the case in New Jersey despite similar soil texture, pH, and organic matter content. Difference in varietal sensitivity to *S*-metolachlor could explain the discrepancy between the two studies, but fruit yield in the Georgia study was, on average, 7 times lower than in New Jersey, which may have increased the negative effect of *S*-metolachlor applied PRE. This was illustrated by early-season harvest that did not exceed 1,200 kg ha^{-1} with a 48% fruit-yield reduction after *S*-metolachlor PRE compared with a 9% decrease for late-season harvest that yielded more than 7,000 kg ha^{-1}. Cucumber was very sensitive to *S*-metolachlor, with stunting persisting up to 7 WAP and significant stand and yield loss in response to PRE application at the 1.4 kg ha^{-1} rate.

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