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Herbicide screening for weed control and crop safety in California melon production

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Research Article

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Abstract

Weed management in cantaloupe and other melon crops is important to maximize fruit yield; however, there are few registered herbicides available in California. Several independent herbicide trials were conducted at University of California field stations in Davis (Yolo County), Five Points (Fresno County), and Holtville (Imperial County) from 2013 to 2019 to evaluate both registered and unregistered herbicides and incorporation methods (sprinklers, cultivation, or none) for crop safety and weed control in melons. Although specific treatments varied among locations depending on local practice and research objectives, ethalfluralin and halosulfuron were used in all experiments, and bensulide and *S*-metolachlor were evaluated in 4 of 6 site-years. Additional herbicides included clethodim, clomazone, DCPA, napropamide, pendimethalin, sethoxydim, and sulfentrazone. Among registered herbicides, halosulfuron, halosulfuron + ethalfluralin, and ethalfluralin + bensulide combinations provided consistently beneficial weed control across all site-years compared to the nontreated control. *S*-metolachlor performed as well as the best of the registered herbicides tested at each site-year; although moderate injury was noted at the Davis location, this did not reduce melon yield. The method used to incorporate preplant herbicides had a significant impact on weed control efficacy but varied by location. Mechanical incorporation of preplant herbicides resulted in improved weed control and yield compared to sprinklers. Early-season weed control, whether by herbicides or hand weeding, resulted in significant yield increase in most site-years.

Introduction

In 2018, worldwide melon production was 33 billion kg (FAO 2019). The United States was the seventh largest producer, with most of the production occurring in California (USDA-NASS 2017). In 2021, California produced over 300 million kg of cantaloupe and honeydew (both *Cucumis melo* L.), accounting for about 65% of US melon production (USDA-NASS 2022).

Weed competition in melons and other cucurbits can substantially reduce crop yields (Adkins et al. 2010; Allen and Van Sickle 2016; Terry et al. 1997). For example, Monks and Schultheis (1998) reported that marketable yield of triploid watermelon (*Citrullus lanatus* Thunb.) was reduced by 5,582 kg ha^{-1} for each week of competition with large crabgrass [*Digitaria sanguinalis* (L.) Scop.]. Gilbert et al. (2008) reported that season-long competition with American black nightshade (*Solanum americanum* Mill.), at densities of 2 plants m^{-2} reduced diploid watermelon yields 54% to 80% in a mulched system and 68% to 100% in bare-ground production. In addition to directly affecting yields, weeds may also serve as an alternate host for pests and diseases of cucurbits, particularly viruses, which can significantly affect crop growth and subsequent fruit development (Aguiar et al. 2018; Ali et al. 2012; Kavalappara et al. 2022; Webster et al. 2015). Consequently, controlling weeds in melons, especially early in the season, is crucial for reducing yield loss potential.

Because of the vining nature of cucurbits, the use of mechanical cultivation is limited in these crops (Gilreath and Everett 1983). Hand weeding can be effective at removing weeds, but it is dependent on the availability and affordability of a large labor pool (Taylor et al. 2012). The use of nonchemical weed control methods, such as cover crops (Kosterna 2014; Monday et al. 2015; Wang et al. 2008) and soil solarization (Ozores-Hampton et al. 2012; Reddy 2013), may not provide many growers with sufficient economic returns (Wang et al. 2009). Herbicides available for use in cucurbits, which are relatively limited in number, often have a narrow control spectrum and lower overall rate ranges to ensure crop safety (Brandenberger et al. 2005; Carvalho et al. 2022; Figueroa and Kogan 2005; Grey et al. 2000; Johnson and Mullinix 2005; Norsworthy and Meister 2007; Webster and Culpepper 2005). Consequently, there is a need to

Table 1. Herbicide products evaluated in a series of melon experiments in California during 2013–2019.

Herbicide	Trade name	Formulation	Company	Location (year)
Bensulide	Prefar® 4-E	480 g L^{-1}	Gowan Company, Yuma, AZ	Five Points (2018 & 2019), Holtville (2018)
Clethodim	Clethodim 2E®	240 g L^{-1}	Albaugh Inc., Ankeny, IA	Five Points (2018 & 2019), Holtville (2018)
DCPA	Dacthal® W-75	75%	AMVAC, Los Angeles, CA	Five Points (2019)
Ethalfluralin	Curbit® EC	360 g L^{-1}	Loveland Products Inc., Loveland, CO	All locations and years
Halosulfuron	Sandea®	75%	Gowan Company, Yuma, AZ	All locations and years
Napropamide	Devrinol® DF	50%	United Phosphorus Inc., King of Prussia, PA	Five Points (2019)
Pendimethalin	Prowl® H_2O	456 g L^{-1}	BASF Corp., Research Triangle, NC	Five Points (2019)
Sethoxydim	Poast®	180 g L^{-1}	BASF Corp., Research Triangle, NC	Five Points (2018)
S-metolachlor	Dual Magnum®	914 g L^{-1}	Syngenta Crop Protection LLC, Greensboro, NC	Davis (2013 & 2015), Five Points (2019), Holtville (2015)
Sulfentrazone	Zeus®	480 g L^{-1}	FMC Corp. Agricultural Products Group, Philadelphia, PA	Davis (2013 & 2015), Holtville, 2015

screen additional herbicides for potential use in California melon production. Moreover, the herbicides should be evaluated to identify suitable incorporation techniques for ensuring crop safety and improving weed control efficacy.

Due to the introduction of expensive new hybrid varieties, transplanting has been gaining traction in California cantaloupe and honeydew production, and this may require changes in the weed management program for these crops. For example, although bensulide, ethalfluralin, and halosulfuron are safe in direct-seeded melons (Boyhan et al. 1995; Brandenberger et al. 2005), these herbicides have to be evaluated for safety in melon transplants.

Specific goals of this research were to evaluate (i) efficacy and crop safety of preemergence use of *S*-metolachlor, sulfentrazone, and clomazone, which are not registered for use in California melons, compared to registered herbicides, and (ii) the effect of incorporation methods on efficacy and crop safety of registered herbicides in transplanted melons.

Materials and Methods

A series of related field studies were conducted from 2013 to 2019 to address issues concerning the use of herbicides for early-season weed control in California melon production. Studies were conducted at sites in the northern Central Valley (University of California, Davis, CA), southern Central Valley (West Side Research and Extension Center, Five Points, CA), and the Imperial Valley (Desert Research and Extension Center, Holtville, CA) to represent the full range of California melon production regions. Trials at Davis (38.54° N, 121.78° W) were on Yolo fine silty loam [sand/silt/clay = 7:67:26, organic matter 2.05%, pH 7.2, cation exchange capacity (CEC) 18.9 mEq]. Soil at Five Points (36.34° N, 120.11° W) was Cerini clay loam (sand/silt/clay = 33:37:30, organic matter 0.74%, pH 7.8, CEC 20.0 mEq). At Holtville (32.80° N, 115.45° W), soil was Imperial-Glenbar silty clay loam (sand/silt/clay = 17:48:35, organic matter 0.50%, pH 8.2, CEC 18.5 mEq).

Efficacy and Crop Safety of Herbicides in Direct-Seeded Melons

At Davis (2013, 2015) and Holtville (2015), weed control and crop safety of post-plant, preemergence herbicides were evaluated in direct-seeded melons. Applications of *S*-metolachlor and sulfentrazone, which are not currently labeled for use in melons in the United States, were compared to registered products (Table 1). Crop production and management practices for irrigation, fertilization, and pest management, excluding weed control, were implemented based on melon production guidelines developed by University of California Cooperative Extension (Hartz et al. 2008).

At Davis, melon beds were established in a north–south orientation with centers spaced 1.5 m apart. Cantaloupe ('Oro Rico' and 'Yosemite') and honeydew ('Saturno') were direct-seeded into pre-irrigated beds on June 6, 2013 and June 15, 2015. Alternate beds were seeded, leaving 3 m between seed lines; the seeding rate was 1.1 kg ha^{-1}, and planting depth was 7.5 cm. Irrigation (1.25 cm) was applied using solid-set sprinklers following preemergence herbicide applications; between-bed furrow irrigation was used afterwards. The experimental design was a split-plot with three main plots (crop cultivars) and seven subplots (six herbicides and a nontreated control). Furrows were cultivated at approximately 4 and 8 wk after crop emergence to ensure uniform flow of irrigation water.

At Holtville, beds were 2 m wide and were arranged east-to-west in "Yuma beds", where the bed tops are sloped toward the south for increased sun exposure. Cantaloupe ('Navigator') was direct-seeded into dry beds at 1.1 kg ha^{-1} and a depth of 7.5 cm on April 8, 2015. Plots were irrigated using a single drip line on the surface of each bed. Plots were arranged in a randomized complete block design in three replications.

In all three trials, treated plots were 9 m long, with a 3-m untreated buffer between plots along the same bed. Preemergence herbicides were broadcast-applied over the bed tops after planting, prior to crop and weed emergence. Treatments were applied using a CO_2-pressurized backpack sprayer delivering 187 L ha^{-1} through four 8002VS flat-fan nozzles spaced at 51 cm. At both sites, treatments included ethalfluralin, halosulfuron, *S*-metolachlor, sulfentrazone, and a nontreated control (Tables 2–5). At Holtville, half rates of the aforementioned herbicides, as well as full and half rates of bensulide, were also included (Tables 4 and 5). The Davis experiment also included clomazone and a tank-mix of ethalfluralin + clomazone (Tables 2 and 3).

Weed density (plants m^{-2}) was recorded 2, 4, and 6 wk after crop emergence (WAE) at Davis. At Holtville, weed density and percent weed cover (where 0% = no weeds and 100% = complete weed cover) were recorded 2 and 5 WAE. Weed density data were the means of weed counts from two 1-m^2 quadrats randomly placed on the bed top. At Davis, percent crop injury (where 0% = no injury and 100% = crop death) was rated 3, 4, and 6 WAE. At Holtville, leaf counts and vine lengths for each plot were recorded 6 and 8 WAE, as a proxy for crop health. Cantaloupes were harvested when fruits were fully netted and had reached the three-quarters to full-slip stage; honeydew melons were harvested when the blossom ends began to soften and yellow. Harvested melons met USDA No. 1 grade standards. Fruits that were undersized, bruised, cracked, soft, sun-scalded, or otherwise

Table 2. Effect of preemergence treatments on weed density in melon trials near Davis, CA, in 2013 and 2015.

		2013			2015		
Herbicide	Rate	2 WAE [a]	4 WAE	6 WAE	2 WAE	4 WAE	6 WAE
	g ai ha^{-1}	% Relative to nontreated[b]					
Nontreated	–	100 (*23.4*) a	100 (*18.0*) a	100 (*13.1*) a	100 (*7.7*) a	100 (*23.8*) a	100 (*25.8*) a
Clomazone	224	26 b	31 b	35 ab	62 ab	72 a	73 a
Ethalfluralin	1,682	20 bc	18 bc	15 b	13 bc	23 bc	22 bc
Ethalfluralin + clomazone	896 + 224	5 cd	11 bc	12 b	25 bc	17 bc	23 bc
Halosulfuron	39	3 d	7 c	8 b	17 bc	18 bc	20 bc
S-metolachlor	1,330	6 cd	7 c	8 b	13 bc	7 c	20 bc
Sulfentrazone	112	<1 d	7 c	6 b	1 c	2 c	7 c
P value		<0.0001	<0.0001	0.0002	<0.0001	<0.0001	<0.0001

[a]Abbreviation: WAE, weeks after emergence.
[b]No. of weeds m^{-2} in untreated are given in italics in parentheses. Data are averaged over two cantaloupe and one honeydew cultivars. Means within each evaluation period followed by the same letter are not significantly different (P ≤ 0.05). Analyses were performed on actual weed density values (before conversion to percent relative to untreated).

Table 3. Effect of preemergence herbicides on early-season crop injury and marketable fruit in melon trials near Davis, CA, in 2013 and 2015.

		2013				2015			
		Crop injury				Crop injury			
	Rate	3 WAE[a]	4 WAE	6 WAE	Yield	3 WAE	4 WAE	6 WAE	Yield
	g ai ha^{-1}	% Injury[b]			No. of fruits per plot	% Injury			No. of fruits per plot
Nontreated	–	0 d	0 d	0 b	30 b	0 c	0 d	0 c	8 c
Clomazone	224	1 cd	1 cd	0 b	43 ab	13 bc	10 c	3 bc	8 c
Ethalfluralin	1,682	2 cd	1 cd	0 b	53 a	17 bc	6 cd	1 bc	38 a
Ethalfluralin + clomazone	896 + 224	9 bcd	4 bcd	0 b	50 a	15 bc	9 c	2 bc	21 b
Halosulfuron	39	10 bc	6 bc	0 b	52 a	10 bc	8 c	1 c	39 a
S-metolachlor	1,330	16 b	6 b	0 b	48 ab	25 b	25 b	11 b	36 a
Sulfentrazone	112	66 a	46 a	26 a	43 ab	61 a	65 a	45 a	39 a
P value		<0.0001	<0.0001	<0.0001	0.0264	<0.0001	<0.0001	<0.0001	<0.0001

[a]Abbreviation: WAE, weeks after emergence.
[b]Data are averaged over two cantaloupe and one honeydew cultivars. Means within each evaluation period followed by the same letter are not significantly different (P ≤ 0.05).

Table 4. Early-season weed control evaluations in a melon herbicide study near Holtville, CA (Desert REC) in 2015.[a]

		Weed density 2 WAE		Weed cover		
Herbicide	Rate	Broadleaves	Grasses	2 WAE	5 WAE	Yield
	g ai ha^{-1}	% of control[b]		% of control		No. of fruits per plot
Nontreated	–	100 (*111.7*) a	100 (*6.9*) a	100 (*15.9*) a	100 (*94.3*) A	48
Bensulide	5,600	7 b	12 bc	10 bc	54 bc	53
Bensulide	2,800	44 a	135 a	48 ab	88 A	36
Ethalfluralin	1,682	<1 b	0 c	<1 bc	32 cd	50
Ethalfluralin	841	2 b	0 c	13 bc	57 bc	50
Halosulfuron	39	12 a	30 a	3 bc	78 ab	56
Halosulfuron	20	18 a	58 ab	9 bc	97 A	42
S-metolachlor	1,330	0 b	4 bc	<1 bc	18 D	50
S-metolachlor	670	2 b	4 bc	3 bc	37 cd	52
Sulfentrazone	112	61 a	154 a	76 a	97 A	50
Sulfentrazone	56	68 a	255 a	84 a	102 A	41
P value		<0.0001	0.0002	0.0002	NA	0.5664

[a]Abbreviations: NA, not available; REC, Research and Extension Center; WAE, weeks after emergence.
[b]No. of weeds m^{-2} in untreated are given in italics in parentheses. Values followed by the same letter are not significantly different (*P* ≤ 0.05). Analyses were performed on actual weed density and cover values (before conversion to percent relative to nontreated controls).

damaged were not picked. Plots were picked every 3 to 4 d over the course of 2 wk, and the total fruit numbers were summarized.

Influence of Incorporation Methods on Efficacy and Crop Safety of Registered Herbicides in Transplanted Melons

The impacts of incorporation method on the efficacy and safety of registered herbicides in transplanted melons were evaluated at Holtville (2018) and Five Points (2018, 2019). At Holtville, herbicide incorporation by sprinkler irrigation was compared to nonincorporation. At Five Points, mechanical incorporation was compared to incorporation by sprinkler irrigation. At both sites, post-plant, over-the-top treatments were also included for comparison to the preemergence herbicides. Each trial was arranged as a randomized complete block design with four replications within each incorporation treatment. Individual plots

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Table 5. Weed control and melon yield at Holtville, CA (Desert REC) in 2018.[a]

				Weed control				
				3 WAP[a]		8 WAP		
Incorporation	Herbicide	Rate	Timing	Broadleaf	Grass	Broadleaf	Grass	Yield
		g ai ha^{-1}		% control[b]				No. of fruits per plot
None	Nontreated	–	–	*na*	*na*	*na*	*na*	12 bc
	Halosulfuron	54	PRE	90	88	3 d	13 c	11 c
	Ethalfluralin	2,014	PRE	94	96	28 bc	65 ab	16 abc
	Bensulide	6,720	PRE	87	85	14 cd	48 b	15 bc
	Halosulfuron	54	POST	*na*	*na*	25 c	0 c	16 abc
	Clethodim	140	POST	*na*	*na*	0 d	48 b	12 bc
Sprinkler	Nontreated	–	–	*na*	*na*	*na*	*na*	13 bc
	Halosulfuron	54	PRE	97	94	82 a	69 ab	25 a
	Ethalfluralin	2,014	PRE	88	90	66 a	80 a	20 abc
	Bensulide	6,720	PRE	88	94	46 b	79 ab	21 ab
	Halosulfuron	54	POST	*na*	*na*	25 c	0 c	19 abc
	Clethodim	140	POST	*na*	*na*	0 c	56 ab	19 abc
P value				*na*	*na*	<0.0001	<0.0001	0.0002
Main effect								
	No incorp.					14.8	34.5	14.0
	Sprinkler					43.7	56.8	19.7
	P value					0.0019	0.0654	<0.0001

[a]Abbreviations: PRE, preemergence; POST, postemergence; REC, Research and Extension Center; WAP, weeks after planting.
[b]Means comparisons include all treatments (i.e., are not separated by incorporation type). Weed control is on a scale of 0% (no control) to 100% (complete control). Data listed not applicable (*na*) were not included in analysis.

were 2 m wide by 9 m long, with a single drip subsurface line in the center of the bed at 25 cm depth.

Sprinkler incorporation vs. nonincorporated

The efficacy and safety of pre-plant applications of halosulfuron, ethalfluralin, and bensulide incorporated by sprinkler irrigation were compared to preplant applications made to beds that were irrigated solely by subsurface drip (Table 5). This experiment also included post-planting treatments of halosulfuron and clethodim (Table 5). Preplant treatments were applied on April 3, 2018 to weed-free beds using a backpack sprayer. Cantaloupe ('Fiji') seedlings approximately 6 wk old were transplanted the next day. Sprinkler-incorporated plots were irrigated for 12 h with the overhead sprinkler system; drip irrigation was run for the same time period for nonincorporated treatments. All plots were drip irrigated thereafter to match crop evaporative demand. Post-plant treatments were applied over-the-top at 4 wk after transplanting (WAP), with no adjuvants. Irrigation, fertilization, and insect pest management were implemented based on the melon production guide for California low desert region. Broadleaf and grass weed control (where 0% = no control and 100% = complete control) and crop safety rating data were collected weekly from 2 WAP to 8 WAP, and marketable fruits were harvested on June 21, 2018.

Mechanical vs. sprinkler incorporation

At Five Points (2018 and 2019), mechanical vs. sprinkler incorporation was compared for several preplant herbicides, along with select postemergence treatments.

On May 31, 2018 preplant herbicides were applied using a CO_2-backpack sprayer delivering 560 L ha^{-1} through four 8004 flat-fan nozzles. Preplant treatments included halosulfuron, ethalfluralin, and bensulide. In mechanical incorporation plots, treatments were incorporated to 5 cm immediately after application using a rotary power mulcher. Cantaloupe ('Fiji') seedlings were transplanted in the beds using a mechanical transplanter (MT 5000 WD, Mechanical Transplanter Co., Holland, MI) at a 60-cm spacing and 8-cm planting depth. The following day, sprinkler irrigation was applied to sprinkler-incorporated plots in a 6-h set (2.5 cm water).

Postemergence treatments were applied on June 26, 2018, 4 WAP, and included halosulfuron, clethodim, and sethoxydim. No adjuvants were used for any of the postemergence treatments. There were 20 treatments in total, including the nontreated control and hand weeded plots (Table 6).

After transplanting, the field was irrigated via buried drip tape, and fertilizer and aphid and mildew control treatments were applied as needed. Beds were not cultivated after transplanting, except in the hand-weeded plots. Weed cover and crop phytotoxicity were visually evaluated at 2-wk intervals throughout the growing season based on a modified Braun-Blanquet scale (Westhoff and Van Der Maarel 1978) (0 = no weed cover or no crop injury, 1 = 1% to 7%, 2 = 8% to 25%, 3 = 26% to 50%, 4 = 51% to 75%, 5 = 76% to 93%, and 6 = 94% to 100%). Fruits were harvested on August 17, 2018 and counted and sorted by size in each plot.

For the 2019 Five Points studies, herbicide treatments were adjusted to better match the weed spectrum present. Clethodim and sethoxydim were dropped, and napropamide, *S*-metolachlor, and pendimethalin were added (Table 7). The herbicides were applied and mechanically incorporated to a 5-cm depth on May 30, 2019; then melons were transplanted and irrigated sprinkler-incorporated treatments were applied on May 31, 2019, using the same methods as in 2018. Postemergence herbicide treatments were applied on June 10, 2019 (Table 7). The melon production and management practices were similar to 2018. Weed control and crop safety rating data were collected as described previously at 1.5, 4, 7, and 9.5 WAP, and fruit was harvested on August 20, 2019.

Data Analysis

Data were analyzed using SAS (Version 9.4, SAS Institute, Cary, NC). PROC GLIMMIX was used to analyze data for the trials comparing unregistered herbicides with registered herbicides for efficacy and crop safety in direct-seeded melons (Davis in 2013 and

Table 6. Visual weed cover and melon yield at Five Points, CA (West Side REC) in 2018.[a]

Incorporation	Herbicide	Rate	Timing	Weed cover 4 WAP[a]	Weed cover 8 WAP	Yield
		g ai ha^{-1}		———% Cover———		No. of fruits per plot
Mechanical	Nontreated	–	–	65 ab[b]	95 ab	39 b–h
	Halosulfuron	54	PPI	22 a-d	24 cd	50 a–d
	Ethalfluralin	2,014	PPI	12 bcd	3 d	52 ab
	Bensulide	6,720	PPI	11 cd	87 ab	45 a–f
	Halosulfuron	54	POST	*na*	92 ab	43 a–g
	Clethodim	140	POST	*na*	94 ab	35 c–h
	Ethalfluralin + bensulide	2,014 + 6,720	PPI	10 cd	4 d	55 a
	Sethoxydim	315	POST	*na*	97 ab	35 c–h
	Halosulfuron	54 + 54	PPI + POST	20 bcd	13 d	51 abc
	Hand weeded	–	–	1 d	0 d	57 a
Sprinkler	Nontreated	–	–	74 a	98 a	25 h
	Halosulfuron	54	PPI	28 a-d	72 b	37 b–h
	Ethalfluralin	2,014	PPI	28 a-d	82 ab	33 e–h
	Bensulide	6,720	PPI	62 abc	97 ab	28 gh
	Halosulfuron	54	POST	*na*	91 ab	41 a–g
	Clethodim	140	POST	*na*	97 ab	29 fgh
	Ethalfluralin + bensulide	2,014 + 6,720	PPI	14 bcd	94 ab	35 c–h
	Sethoxydim	315	POST	*na*	97 ab	28 gh
	Halosulfuron	54 + 54	PPI + POST	14 bcd	41 c	46 a–e
	Hand weeded	–	–	0 d	0 d	56 A
P value[a]				<0.0001	<0.0001	<0.0001
Main effect						
	Mechanical			26.8	50.8	46.1
	Sprinkler			42.7	76.8	35.7
	P-value			0.0277	0.0042	< 0.0001

[a]Abbreviations: POST, postemergence; PPI, preplant incorporated; REC, Research and Extension Center; WAP, weeks after planting.
[b]Means comparisons include all treatments (i.e., are not separated by incorporation type). POST treatments were applied 4 WAP (not applicable on that evaluation date). Weed cover includes broadleaf and grass weeds.

2015, Holtville in 2015). Herbicide treatment was considered the main effect and replication as a random variable. For the trials evaluating the influence of incorporation methods on efficacy and crop safety of registered herbicides in transplanted melons (Five Points in 2018 and 2019, Holtville in 2018), data were analyzed using PROC MIXED. In this case, incorporation method, herbicide treatment, and the interaction between incorporation and herbicide were used as the main effects and replication as a random effect. Means were separated using Student Newman-Keuls tests at $\alpha = 0.05$.

Analyses were performed on original data, but some of the tables present values that have been standardized to help in comparing treatments. For example, Tables 2 and 4 present mean weed density and/or cover as a percent relative to nontreated control plots. Tables 6 and 7 present weed cover as a percent derived from midpoints of the modified Braun-Blanquet ratings for each plot.

Results and Discussion

Efficacy and Crop Safety of Herbicides in Melons

At Davis, broadleaf weeds, specifically common purslane (*Portulaca oleracea* L.), redroot pigweed (*Amaranthus retroflexus* L.), and prostrate pigweed (*Amaranthus blitoides* S. Watson) dominated the trial site in both 2013 and 2015. Except for clomazone at 6 WAE in 2013 and all ratings in 2015, herbicide treatments resulted in significant reductions in weed density relative to nontreated control plots, which averaged 8 to 26 plants m^{-2} (Table 2). In 2013, ethalfluralin, clomazone, and ethalfluralin + clomazone reduced weed counts 65% to 95% 2 to 6 WAE. Halosulfuron, *S*-metolachlor, and sulfentrazone reduced weed counts 92% to 99%. In 2013, at the 6-WAE observation date, there was also a significant crop-by-herbicide interaction with respect to weed density ($P < 0.05$); weed numbers in the untreated cantaloupe plots averaged 16 plants m^{-2}, whereas the honeydew plots averaged 7 plants m^{-2} (data not shown). In 2015, ethalfluralin and ethalfluralin + clomazone reduced weed counts 75% to 87%, relative to the nontreated control, 2 to 6 WAE. Halosulfuron and *S*-metolachlor reduced weed counts 80% to 93%, and sulfentrazone reduced weed counts 93% to 99%. *S*-metolachlor and sulfentrazone can provide some control of select small-seeded broadleaf weed species, like pigweeds (*Amaranthus* spp.) and common lambsquarters, as well as nutsedges (*Cyperus* spp.), which are common problems in California fruit and vegetable production (Johnson and Mullinix 2005; Norsworthy and Meister 2007; Peachey et al. 2012). Sulfentrazone can also suppress the emergence of field bindweed (*Convolvulus arvensis*), which is a significant pest in the San Joaquin and Sacramento valleys (L.M. Sosnoskie, personal observation).

Significant differences were observed among herbicide treatments with respect to seeded-melon injury. Crop injury was generally minor (delayed emergence, stunting, and some chlorosis), with most of the herbicides causing <10% damage to all melon cultivars (Table 3). *S*-metolachlor injury, which included stunting and leaf puckering, was greatest at 3 to 4 WAE; whereas no damage was observed at 6 WAE in 2013, melon injury was 11% at 6 WAE in 2015. Melon plant damage (up to 66%) was most severe in the sulfentrazone treatment, with plants in treated plots exhibiting severe stunting, tissue necrosis, and partial stand loss. In 2013, there was a significant crop-by-herbicide interaction with respect to crop injury at 6 WAE ($P < 0.05$). Cantaloupe injury in the

Table 7. Visual weed cover and melon yield at Five Points, CA (West Side REC) in 2019.[a]

Incorporation	Herbicide	Rate	Timing	Weed cover: 3.5 WAP[a] Broadleaf	3.5 WAP[a] Grass	7 WAP Broadleaf	7 WAP Grass	Yield
		g ai ha^{-1}		——% Cover——				No. of fruits per plot
Mechanical	Nontreated	–	–	38 a–f[b]	0 b	38 b–e	1 ab	43 ab
	Ethalfluralin	2,014	PPI	8 ef	0 b	6 de	0 b	55 a
	Ethalfluralin + bensulide	2,014 + 6,720	PPI	5 f	0 b	4 de	0 b	61 a
	Napropamide	280	PPI	26 b–f	0 b	29 cde	0 b	49 ab
	S-metolachlor	1,067	PPI	4 f	0 b	4 de	0 b	61 a
	Pendimethalin	1,595	PPI	3 f	0 b	4 de	0 b	51 a
	Bensulide	6,720	PPI	13 def	0 b	21 cde	0 b	50 a
	Halosulfuron	54	PRE	3 f	0 b	7 de	0 b	59 a
	DCPA	8,399	POST	34 a–f	1 b	34 b–e	0 b	48 ab
	Halosulfuron	54	POST	9 ef	2 b	25 cde	2 ab	59 a
	Hand weeded	–	–	21 c–f	0 b	1 e	0 b	60 a
Sprinkler	Nontreated	–	–	84 ab	21 a	82 ab	18 ab	35 abc
	Ethalfluralin	2,014	PPI	49 a–f	0 b	79 ab	0 b	40 ab
	Ethalfluralin + bensulide	2,014 + 6,720	PPI	55 a–f	0 b	55 abc	0 b	45 ab
	Napropamide	280	PPI	73 a–d	0 b	97 a	0 b	19 bc
	S-metolachlor	1,067	PPI	47 a–f	0 b	56 abc	0 b	43 ab
	Pendimethalin	1,595	PPI	93 a	0 b	97 a	0 b	9 c
	Bensulide	6,720	PPI	79 abc	0 b	90 a	0 b	39 ab
	Halosulfuron	54	PRE	6 f	0 b	11 cde	0 b	63 a
	DCPA	8,399	POST	67 a–e	25 a	79 ab	17 ab	36 abc
	Halosulfuron	54	POST	38 a–f	23 a	50 a–d	23 a	63 a
	Hand weeded	–	–	50 a-f	5 b	1 e	4 ab	51 a
P value[a]				<0.0001	0.0012	<0.0001	0.0018	<0.0001
Main effect								
	Mechanical			14.9	0.2	15.7	0.2	54.0
	Sprinkler			58.3	6.7	63.3	5.6	40.3
	P value			<0.0001	0.0082	<0.0001	0.0107	<0.0001

[a]PPI, preplant incorporated; PRE, preemergence; POST, postemergence; REC, Research and Extension Center; WAP, weeks after planting.
[b]Means comparisons include all treatments (i.e., are not separated by incorporation type).

sulfentrazone treatment averaged 28%, whereas mean injury to honeydew was 22% (data not shown). Injury did not appear to affect the melon fruit yield in any treatments (Table 3). Nontreated controls had the lowest or near-lowest yields in both years (30 marketable fruits per plot in 2013, 8 fruits per plot in 2015), presumably as a result of weed pressure. Similarly, yields in clomazone-treated plots were equally affected in 2015 (8 fruits per plot) because of reduced weed control. Yields in all other treated plots were comparable (43 to 53 fruits per plot in 2013, 36 to 39 fruits per plot in 2015), except for a moderately low yield in the ethalfluralin + clomazone treatment (21 fruits per plot) in 2015.

In 2015, at Holtville, dominant weeds included common purslane and the pigweeds mentioned above, as well as common lambsquarters (*Chenopodium album* L.) and junglerice [*Echinochloa colona* (L.) Link]. Broadleaf and grassy weed densities averaged 112 and 7 plants m^{-2}, respectively, in nontreated control plots (Table 4). Ethalfluralin (both rates), *S*-metolachlor (both rates), and the high rate of bensulide reduced broadleaf and grass weed densities at 2 WAE and weed cover at 2 and 5 WAE. Both rates of halosulfuron and the low rate of bensulide did not significantly reduce broadleaf and grass densities, relative to the nontreated controls, although halosulfuron did reduce percent weed cover at 2 WAE. Unlike the Davis studies, sulfentrazone did not significantly reduce weed density or cover, relative to the nontreated control plots.

In this trial, vine length and number of leaves per vine were recorded as an indicator of plant health. Although analysis showed some differences among treatments, these differences did not correspond with treatments in any meaningful way (data not shown). This differs from the observations in the Davis studies, which showed significant crop response to *S*-metolachlor and sulfentrazone. There were no differences in marketable fruit yield among treatments (Table 4).

Influence of Incorporation Methods on Efficacy and Crop Safety of Registered Herbicides in Melons

At Holtville in 2018, the dominant weeds were common lambsquarters, mustards (*Brassica* spp.), sowthistles (*Sonchus* spp.), common purslane, tumble pigweed (*Amaranthus albus* L.), and various grasses. At the early evaluation timing (3 WAP), preemergence broadleaf and grass weed control in unincorporated treatments (85% to 96%) was similar to sprinkler-incorporated treatments (88% to 97%) (Table 5). At 8 WAP, weed control from all preemergence herbicides was significantly greater for the sprinkler-incorporated treatments (46% to 82%) as compared to the unincorporated treatments (3% to 65%). Postemergence applications of halosulfuron or clethodim resulted in relatively poor weed control at 8 WAP, highlighting the importance of residual at-plant products for weed suppression. Furthermore, although the use of drip irrigation alone may be sufficient to establish transplants, it is not an effective tool for incorporating herbicides and providing season-long control. The postemergence application of halosulfuron also resulted in temporary crop injury of <10% (data not shown).

Yields were low across all treatments in this trial (Table 5), probably as a result of the later-than-typical planting date for the desert production area. In sprinkler-incorporated plots, all treatments had numerically higher yield than the nontreated control plots, but this was not always statistically significant. In a

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single-factor comparison of incorporation effects, it was found that yields in sprinkler-incorporated plots were greater than in unincorporated plots ($P < 0.0001$); mean fruit counts, excluding control plots, were 20 fruits per plot and 14 fruits per plot in sprinkler-incorporated plots and unincorporated plots, respectively.

At Five Points (2018, 2019), the dominant weeds were broadleaves, including groundcherry (*Physalis* spp.), puncturevine (*Tribulus terrestris* L.), field bindweed, common purslane, common lambsquarters, Venice mallow (*Hibiscus trionum* L.), and redroot pigweed. Grass weed density was low in 2018, so grass cover was not recorded for that year. For both years, mechanically incorporated herbicide treatments had significantly less weed cover as compared to the sprinkler-incorporated applications, although there was significant variability with respect to the performance of individual active ingredients (Tables 6 and 7). In particular, mechanically incorporated ethalfluralin, ethalfluralin + bensulide, and halosulfuron resulted in excellent weed control (0 to 25% cover) at 7 to 8 WAP in both years. Mechanically incorporated *S*-metolachlor and pendimethalin, which were only tested in 2019, also resulted in excellent weed cover reduction. Among sprinkler-incorporated treatments, only halosulfuron (2018 and 2019) or ethalfluralin + bensulide (2019) reduced weed cover. The postemergence treatments were not effective in either year. However, two of the postemergence treatments in 2018 were grass herbicides (clethodim, sethoxydim), and grass weed density was low; thus, these herbicides were not expected to reduce overall weed cover because of the dominance of broadleaf weeds at that location.

Significant crop injury occurred, both years, in response to halosulfuron and ethalfluralin at Five Points. Stunting and chlorosis were noted during early evaluations for these treatments in both incorporation types (data not shown); however, symptoms faded by 4 WAP, and no apparent impact on yield was observed (Table 7).

The overall yields remained unaffected, and mostly large fruits (≤9 fruits per box) were recorded for both years (data not shown). Hand-weeded plots produced the highest yields and were statistically better than several treatments (Table 6). In 2018, the greatest fruit yields were recorded for plots treated with halosulfuron + halosulfuron (sequential), ethalfluralin + bensulide [preplant incorporated (PPI)], halosulfuron (PPI), or ethalfluralin alone (PPI) (Table 6). Fruit yield was generally higher ($P < 0.0001$) in mechanically incorporated plots (mean 46 fruits per plot) than in sprinkler-incorporated plots (mean 36 fruits per plot).

In 2019, the fruit yields were similar to the hand-weeded control with most treatments except for sprinkler-irrigated ethalfluralin or pendimethalin (Table 7). Moreover, fruit yield was higher ($P < 0.0001$) in mechanically incorporated plots (mean 54 fruits per plot) than in sprinkler-incorporated plots (mean 40 fruits per plot).

These trials confirm the importance of early-season weed control in melons, in both direct-seeded or transplanted crops. Effective weed management early in the season, by herbicides or by hand weeding, resulted in significant yield increase in most trials. At Davis in 2013, plots with the best weed management yielded a mean of 48 fruits, vs. 30 fruits per plot in control plots, an increase of 60%. In 2015, well-managed plots in Davis yielded a mean of 38 fruits compared to 8 fruits per plot in control plots. This result occurred even though sulfentrazone treatments severely injured seeded melons to the point that stand densities were reduced in some plots. At Five Points, the best marketable yields occurred with treatments wherein weeds were controlled (Tables 6 and 7); however, there were no significant yield differences among treatments at Holtville in 2015 (Table 4).

The method used to incorporate preplant herbicides had a major impact on herbicide performance overall, but varied by location. At Holtville (2018), sprinkler incorporation of preemergence herbicide treatments, as compared to unincorporated treatments, resulted in significantly better weed control and higher melon yields. At Five Points (2018, 2019), mechanical incorporation of PPI treatments resulted in reduced weed cover and increased melon yields compared to sprinkler incorporation. Differences between these two sites may have been influenced by the amount of irrigation water applied (12-h vs 6-h irrigation sets).

In comparing registered herbicides with potential new registrations for use in melons, the unregistered *S*-metolachlor performed similarly to the registered herbicides tested at each site. *S*-metolachlor was among the best-performing treatments at both Davis (2013 and 2015) and at Holtville in 2015, and resulted in fruit yield comparable to the best herbicide treatment at each site. Treatments at Davis were sprinkler incorporated, but treatments at Holtville were only activated with the buried drip irrigation. Thus, *S*-metolachlor may represent a more consistent herbicide option than ethalfluralin or halosulfuron across different crop sites and different incorporation scenarios. Sulfentrazone, another unregistered herbicide, was effective at Davis but was not effective at Holtville. In two trials at Davis, the unregistered herbicide clomazone provided poor weed control, resulting in reduced yields in 2015. *S*-metolachlor caused moderate injury in both years at Davis, whereas sulfentrazone caused more severe injury; however, neither treatment ultimately reduced total melon yields. In addition, neither chemical resulted in melon injury at Holtville.

In the screening trials, *S*-metolachlor (not registered in California melons) appeared to provide the best balance of efficacy and flexibility. At Davis, *S*-metolachlor resulted in better weed control than the registered herbicide ethalfluralin, and at Holtville it outperformed the registered herbicide halosulfuron. Therefore, *S*-metolachlor has potential for use in transplanted melons, but it needs to be evaluated further with respect to melon varieties, soil types, and various incorporation methods before widespread adoption in California.

Practical Implications

Weeds are a significant threat to the production of cucurbits, like cantaloupe and honeydew melon. Weed control in cucurbit crops is made difficult by the relatively low numbers of registered herbicides, the limited spectrum of weed control provided by these products, and the potential for crop injury. Identifying new chemical tools, particularly residual herbicides applied at planting to provide early-season weed control, has been a consistent priority of California's melon producers. So, too, has been the evaluation of different incorporation strategies for soil-applied products under hot and dry production conditions. To address these goals, University of California scientists conducted a series of research and demonstration trials across a diversity of agricultural environments in California: the Imperial, San Joaquin, and Sacramento valleys, which collectively account for approximately two-thirds of the melons produced in the United States. *S*-metolachlor, a novel chemistry that was evaluated for California melon production, performed as well as the best of the registered herbicides tested at each site-year; injury (i.e., stunting), when it did occur, did not reduce melon yields under the conditions of our research trials. The method used to incorporate preplant herbicides had a significant impact on weed control efficacy but varied by location. Mechanical incorporation of preplant herbicides resulted in improved weed control and yield compared to sprinklers in several trials. Under hot and dry conditions that facilitate evaporative loss, producers must ensure that sufficient water is delivered to activate soil-applied herbicides. Although the use of drip irrigation alone can be effectively used to establish melon transplants, it is not an effective tool for incorporating herbicides and providing season-long control under rain-free conditions common during the growing season in California.

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References

Adkins JI, Stall WM, Santos BM, Olson SM, Ferrell JA (2010) Critical period of interference between American black nightshade and triploid watermelon. Weed Technol 24:397–400

Aguiar RWS, Alves GB, Queiroz AP, Nascimento IR, Lima MF (2018) Evaluation of weeds as virus reservoirs in watermelon crops. Planta Daninha 36. https://doi.org/10.1590/S0100-83582018360100032

Ali A, Abdalla O, Bruton B, Fish W, Sikora E, Zang S, Taylor M (2012) Occurrence of viruses infecting watermelon, other cucurbits, and weeds in the parts of southern United States. Plant Heath Prog, 10.1094/PHP-2012-0824-01-RS

Allen, JD, Van Sickle G (2016) Pest management strategic plan for cantaloupe, honeydew, and mixed melon production in California. https://ipmdata.ipmcenters.org/documents/pmsps/2016 CA Melon PMSP.pdf. Accessed: August 8, 2022

Boyhan GE, Kovach SP, Norton JD, Abrahams BR, Hollingsworth MH, Dangler JM (1995) Preemergent herbicides for cantaloupe and watermelon. J Veg Crop Prod 1:79–92

Brandenberger LP, Talbert RE, Wiedenfeld RP, Shrefler JW, Webber CL, Malik M (2005) Effects of halosulfuron on weed control in commercial honeydew crops. Weed Technol 19:346–350

Carvalho DR, Lins HA, Souza MF, Silva TS, Porto MAF, Mendonca V, Silva DV (2022) Weed control in melon with preemergence herbicides. Pesqui Agropecu Bras, 10.1590/S1678-3921.pab2022.v57.02334

[FAO] Food and Agriculture Organization of the United Nations (2019) FAOSTAT. http://www.fao.org/faostat/en/#search/melon. Accessed: October 28, 2020

Figueroa R, Kogan M (2005) Clomazone selectivity among six cucurbit crops. Agrociencia 39:611–618

Gilbert CA, Stall WM, Chase CA, Charudattan R (2008) Season-long interference of American black nightshade with watermelon. Weed Technol 22:186–189.

Gilreath JP, Everett PH (1983) Weed control in watermelon grown in South Florida. Proc South Weed Sci Soc 36:159–163

Grey TL, Bridges DC, NeSmith DS (2000) Tolerance of cucurbits to the herbicides clomazone, ethalfluralin and pendimethalin. I. Summer squash. HortScience 35:632–636

Hartz T, Cantwell M, Mickler J, Mueller S, Stoddard S, Turini T (2008) Cantaloupe production in California. University of California Vegetable Research and Information Center. http://anrcatalog.ucanr.edu/pdf/7218.pdf. Accessed: August 8, 2022

Johnson WC, Mullinix BG (2005) Herbicide application method on weed management and crop injury in transplanted cantaloupe production. Weed Technol 19:108–112

Kavalappara SR, Riley DG, Cremonez PSG, Perier JD, Bag S (2022) Wild radish (*Raphanus raphanistrum* L.) is a potential reservoir host of cucurbit chlorotic yellows virus. Viruses 14:593

Kosterna E (2014) The effect of different types of straw mulches on weed-control in vegetables cultivation. Ecol Eng 15:109–117

Monday TA, Lawrence DA, Foshee WG, Wehtje GR, Gilliam CH (2015) Pre and post herbicides in combination with a rye cover crop for control of yellow nutsedge and pigweed in watermelon. Intl J Veg Sci 21:264–271

Monks DW, Schultheis JR (1998) Critical weed-free period for large crabgrass (*Digitaria sanguinalis*) in transplanted watermelon (*Citrullus lanatus*). Weed Sci 46:530–532

Norsworthy JK, Meister CW (2007) Tolerance of cantaloupe to postemergence applications of rimsulfuron and halosulfuron. Weed Technol 21:30–36

Ozores-Hampton MR, McSorley R, Stansly PA (2012) Effects of long-term organic amendments and soil sanitation on weed and nematode populations in pepper and watermelon crops in Florida. Crop Production 41:106–112

Peachey E, Doohan D, Koch T (2012) Selectivity of fomesafen based systems for preemergence weed control in cucurbit crops. Crop Prot 40:91–97

Reddy PP (2013) Soil solarisation. Pages 159–183 *in* Recent advances in crop protection. New Delhi: Springer. https://doi.org/10.1007/978-81-322-0723-8_11

Taylor JE, Charlton D, Yunez-Naude A (2012) The end of farm labor abundance. Appl Econ Perspect Policy 34:587–598

Terry ER Jr., Stall WM, Shilling DG, Bewick TA, Kostewicz SR (1997) Smooth amaranth interference with watermelon and muskmelon production. HortScience 32:630–632

[USDA-NASS] United States Department of Agriculture National Statistics Service (2017) Statistics of Vegetables and Melons. https://www.nass.usda.gov/Publications/Ag_Statistics/2017/Chapter04.pdf. Accessed: October 28, 2020

[USDA-NASS] United States Department of Agriculture National Statistics Service (2022). Vegetables 2021 Summary (February 2022). https://downloads.usda.library.cornell.edu/usda-esmis/files/02870v86p/zs25zc490/9593vz15q/vegean22.pdf

Wang G, McGiffen ME, Ogbuchiekwe EJ, Butler L (2009) Economic return of purple and yellow nutsedge management in vegetable production of southern California. Crop Prot 28:319–326

Wang G, Ngouajio M, McGiffen ME, Hutchinson CM (2008) Summer cover crop and management system affect lettuce and cantaloupe production system. Agron J 100:1587–1593

Webster CG, Frantz G, Reitz SR, Funderburk JE, Mellinger HC, McAvoy E, Turechek WW, Marshall SH, Tantiwanich Y, McGrath MT, Daughtrey ML (2015) Emergence of groundnut ringspot virus and tomato chlorotic spot virus in vegetables in Florida and the southeastern United States. Phytopathology 105:388–398

Webster TM, Culpepper AS (2005) Halosulfuron has a variable effect on cucurbit growth and yield. HortScience 40:707–710

Westhoff V, Van Der Maarel E (1978) The Braun-Blanquet Approach. Pages 287–399 *in* Whittaker RH, ed. Classification of Plant Communities, vol 5–1. Dordrecht: Springer