Evaluation of sulfentrazone and S-metolachlor in brassica vegetables

Authors: Rachuy, John S., and Fennimore, Steven A.

Source: Weed Technology, 36(4) : 592-596

Published By: Weed Science Society of America

URL: https://doi.org/10.1017/wet.2022.39

Weed Technology

www.cambridge.org/wet

Evaluation of sulfentrazone and *S*-metolachlor in brassica vegetables

John S. Rachuy[1] and Steven A. Fennimore[2]

[1]Staff Research Associate III, Department of Plant Sciences, University of California, Davis, Salinas, CA, USA and [2]Professor of Cooperative Extension and Vegetable Weed Specialist, Department of Plant Sciences, University of California, Davis, Salinas, CA, USA

Note

Cite this article: Rachuy JS and Fennimore SA (2022) Evaluation of sulfentrazone and *S*-metolachlor in brassica vegetables. Weed Technol. **36**: 592–596. doi: 10.1017/wet.2022.39

Received: 28 January 2022
Revised: 8 April 2022
Accepted: 6 May 2022
First published online: 2 June 2022

Associate Editor:
Darren Robinson, University of Guelph

Nomenclature:
DCPA; sulfentrazone; *S*-metolachlor; bok choi, *Brassica rapa* L. subsp. *Chinensis* (Rupr.) Olsson; broccoli rabe, *Brassica rapa* L. var. *rapa*; brussels sprouts, *Brassica oleracea* L. var. *gemmifera* DC.; collard, *Brassica oleracea* L. var. *acephala* DC.; mizuna, *Brassica rapa* L. subsp. *japonica*; kale, *Brassica oleracea* L. var. *sabellica* L.; mustard greens, *Brassica juncea* (L.) Czern.; radish, *Raphanus sativus* L.

Keywords:
Crop tolerance; vegetable herbicides

Author for correspondence:
Steven A. Fennimore, Department of Plant Sciences, University of California, Davis, 1636 E. Alisal Street, Salinas, CA 93905.
Email: safennimore@ucdavis.edu

Abstract

Small-acreage brassica vegetables need additional herbicide options. Among the vegetables grown in California are a number of niche crops, such as bok choi and brussels sprouts, that have a limited number of registered herbicides, such as DCPA. Sulfentrazone and *S*-metolachlor have food use tolerances for use on brassica head and stem Group 5-16, which includes crops like bok choi and brussels sprouts, as well as brassica leafy greens Subgroup 4-16B, which includes crops like kale. However, there is a lack of data for *S*-metolachlor and sulfentrazone on a wide variety of seeded and transplanted brassica vegetables. *S*-metolachlor applied preemergence (PRE) was evaluated on six direct-seeded brassica vegetables during 2019 and 2020, including bok choi, broccoli rabe, collard, mizuna, radish, and mustard greens. *S*-metolachlor and sulfentrazone were both evaluated PRE in transplanted brussels sprouts and kale. The results indicate that most of the seeded brassica vegetables were tolerant of *S*-metolachlor and that transplanted brassica vegetables were tolerant of both *S*-metolachlor and sulfentrazone. Broccoli rabe was moderately injured in 2020, but yields did not vary among treatments either year.

Introduction

Most vegetable crops lack sufficient herbicide coverage to protect crops from weed competition without other inputs like cultivation and hand weeding (Fennimore and Doohan 2008). There are many reasons for this, including the diverse numbers of crops and crop varieties, small acreages and limited market potential, high crop values, and potential liability to the registrants for crop damage from herbicides (Fennimore and Cutulle 2019). Herbicides commonly used in vegetable crops, such as DCPA and pronamide, were developed before 1980, when costs were lower and the regulatory barriers were less demanding (Fennimore and Doohan 2008). DCPA is used in *Allium* vegetables, such as onion (*Allium cepa* L.), and many brassica vegetables, such as broccoli. DCPA was registered in 1958 and is labeled on many vegetable crops. However, regulatory concerns have been raised about a DCPA metabolite that is highly mobile in soil and has been found in groundwater (Istok et al. 1993; Lohstroh and Koshlukova 2017). Although DCPA remains available for use in brassica vegetables, there is no guarantee that this product used at rates as high as 11.2 kg ha^{-1} will be available in the long term; therefore sustainable brassica vegetable production may require comparable preemergence alternatives to DCPA (Blecker et al. 2018; Daugovish et al. 2019).

The U.S. Environmental Protection Agency has granted food use tolerances for *S*-metolachlor and sulfentrazone for use on brassica head and stem Group 5-16 vegetables, which include broccoli, brussels sprouts, cabbage (*Brassica oleracea* L. var. *capitata*), bok choi, and cauliflower (*Brassica oleracea* L. var. *botrytis*), as well as brassica leafy greens Subgroup 4-16B, which includes 20 crops, such as kale (Anonymous 2022a, 2022c; USEPA 2017, 2018). *S*-metolachlor is a selective chloroacetamide herbicide that controls weeds by inhibiting the synthesis of long-chain fatty acids. *S*-metolachlor is widely used on corn (*Zea mays* L.), soybean [*Glycine max* (L.) Merr.], potato (*Solanum tuberosum* L.), sugar beet (*Beta vulgaris* L.), sunflower (*Helianthus annuus* L.), and tomato (*Solanum lycopersicum* L.). Soil half-life of *S*-metolachlor under California field conditions was estimated at 97 d (Shaner 2014). Sulfentrazone is an aryl triazinone herbicide that acts on the protoporphyrinogen oxidase enzyme that disrupts susceptible plant membranes and is primarily absorbed by roots. The soil half-life of sulfentrazone was determined to be in the range of 121 to 302 d (Shaner 2014). Sulfentrazone is labeled for use on brassica crops, such as cabbage (Anonymous 2022e).

S-metolachlor and sulfentrazone use in brassica head and stem Group 5-16 and brassica leafy greens Subgroup 4-16B has not been well characterized on seeded or transplanted crops under California conditions. Many of these crops, such as broccoli, are both seeded and transplanted (Le Strange et al. 2010). Therefore the objective of this work was to measure the selectivity of *S*-metolachlor on seeded root and tuber vegetables, such as radish and head and stem and leafy

Table 1. Herbicide tolerance in Brassica vegetable crops: trial number, year, crop, variety, planting, and harvest dates.

Trial no.	Year	Crop	Variety	Planting date	Harvest date
1	2019	Bok choi	'Mei Qing'	6 May	24 Jun
		Broccoli rabe	'Zamboni'	6 May	24 Jun
2	2020	Bok choi	'Mei Qing'	1 Jun	15 Jul
		Broccoli rabe	'Zamboni'	1 Jun	9–17 Jul
3	2019	Collard greens	'Flash'	6 May	26 Jun
		Mizuna	'Mizuna'	6 May	26 Jun
4	2020	Collard greens	'Flash'	24 Sep	23 Nov
		Mizuna	'Mizuna'	24 Sep	6–12 Nov
5	2019	Radish	'Roxane'	20 Jun	2 Aug
		Mustard greens	'Red Giant'	20 Jun	2 Aug
6	2020	Radish	'Roxane'	14 Oct	20 Nov
		Mustard greens	'Southern Giant Curled'	14 Oct	2 Dec
7	2019	Kale	'Black Magic'	20 Jun	20 Aug
		Brussels sprouts	'Confidant'	20 Jun	6 Nov
8	2020	Kale	'Black Magic'	16 Jul	9 Sep
9	2020	Brussels sprouts	'Confidant'	30 Jul	8–10 Dec

Table 2. Crop injury estimates at 15 d after treatment and fresh weights (at harvest) on direct-seeded bok choi.

Treatment	Rate	Crop injury		Fresh weight	
		2019	2020	2019	2020
	kg ai ha^{-1}	— % —		— 1,000s kg ha^{-1} —	
Nontreated	0.00	0	0	4.53	4.42
DCPA	8.41	9	9	4.80	4.12
S-metolachlor	0.37	1	3	4.42	4.08
S-metolachlor	0.56	0	10	4.62	4.21
S-metolachlor	0.73	4	11	4.73	4.06
Treatment prob. (F)		0.26	0.07	0.78	0.87

Table 3. Crop injury estimates at 15 d after treatment and fresh weights (at harvest) for direct-seeded collards.

Treatment	Rate	Crop injury		Fresh weight	
		2019	2020	2019	2020
	kg ai ha^{-1}	— % —		— 1,000s kg ha^{-1} —	
Nontreated	0.00	0	0	1.66	1.39
DCPA	8.41	0	10	1.64	1.08
S-metolachlor	0.37	0	4	1.37	1.39
S-metolachlor	0.56	0	13	1.48	1.35
S-metolachlor	0.73	3	11	1.59	1.48
Treatment prob. (F)		0.44	0.06	0.67	0.41

green vegetables, and the selectivity of *S*-metolachlor and sulfentrazone on transplanted brussels sprouts and kale.

Materials and Methods

Crop tolerance field studies were conducted in 2019 and repeated in 2020 at the Hartnell research farm at Salinas, CA (36.10°N, 121.36°W), on Antioch sandy loam soil, fine, smectitic, thermic Typic Natrixeralf (53% sand, 32% silt, and 15% clay) with a pH of 7.0 and 2.1% organic matter. *S*-metolachlor (DualMagnum® 7.62E, Syngenta Crop Protection, Greensboro, NC, USA) was applied PRE at 0.37, 0.56, and 0.73 kg ha^{-1}, and the standard DCPA (DACTHAL® 6 F, AMVAC, Los Angeles, CA, USA) was applied PRE at 8.41 kg ha^{-1} on direct-seeded bok choi, broccoli rabe, collard, mizuna, mustard greens, and radish and on transplanted brussels sprouts and kale. The transplanted brussels sprouts and kale were also treated with sulfentrazone (Zeus® 4 F, FMC, Philadelphia, PA, USA) PRE at 0.08 and 0.11 kg ha^{-1}. All herbicides were applied with a CO_2 backpack sprayer. Application volumes in 2019 were 439 L ha^{-1} for DCPA and 280 L ha^{-1} for all other treatments, and in 2020, all treatments were applied at 374 L ha^{-1}. Plots were single 1-m-wide × 6.1-m-long beds. Treatments were replicated four times and arranged in a randomized complete block design. Trial numbers, years, crops, varieties, and planting and harvest dates are listed in Table 1.

After planting, the trials were sprinkler irrigated for 2 h, during which time 1.7 cm of water was applied to set transplants or germinate seed. The plots were cultivated and hand weeded as needed to minimize weed competition, fertilized with 330 kg ha^{-1} 21-0-0-24 (S), and sprinkler irrigated twice weekly until emergence, then once per week until harvest.

Data collected were crop injury estimates at 2 w after treatment based on a scale ranging from 0 (no injury) to 10 (plant death), which was converted to percentages for presentation in tables. The crop injury assessments included stunting and foliar injury in an overall injury score. Weed densities were measured 18 to 28 d after planting on the tops of the raised beds using a 48.3 × 53.3 cm (0.257 m^2) quadrat, with the longer side laid across the width of the bed top and the sample area covering all plant lines. After weed density counts, all trials were cultivated and hand weeded. Crops were harvested at commercial maturity typical for the Salinas Valley. Bok choi, kale, and brussels sprouts were harvested from 2.13 m of bed, mizuna from 1.52 m of bed, and broccoli rabe from 3.05 m of bed both years. Collard was harvested from 3.05 m of bed in 2019 and 1.52 m of bed in 2020. Radish and mustard greens were harvested from 2.13 m of bed in 2019 and 1.52 m of bed in 2020. Data were subjected to analysis of variance, and mean separation was performed using Fisher's protected LSD. Agriculture Research Management (ARM) 7, version 7.0.5 (Gyllings Data Management Inc., Brookings, SD, USA) was used for data analysis.

Results and Discussion

Seeded Crops

DCPA and *S*-metolachlor caused little or no visible injury to bok choi, collard, radish, or mustard greens (Tables 2, 3, 4, and 5). *S*-metolachlor resulted in slight injury to broccoli rabe in 2019, possibly due to unusually cool and wet weather during May 15 to 26, 2019 (9 to 20 d after planting), when temperatures were 7 C below normal and 5 cm of rain fell (Table 6; UCIPM 2022). *S*-metolachlor, on the other hand, caused much greater initial injury in 2020 during normal warm and dry weather typical of the area. Injury to sweet potato [*Ipomoea batatas* (L.) Lam.] from *S*-metolachlor was less under cooler conditions of 25 C than at 35 C (Abukari et al. 2015). The year-to-year variation in broccoli rabe injury may suggest reduced sensitivity to *S*-metolachlor in cool weather and increased sensitivity in warm weather, but verification

Table 4. Crop injury estimates at 15 d after treatment and fresh weights (at harvest) on direct-seeded radish.[a]

Treatment	Rate	Crop injury		Fresh weight	
		2019	2020	2019	2020
	kg ai ha^{-1}	— % —		— 1,000s kg ha^{-1} —	
Nontreated	0.00	0	0 b	1.35	0.92
DCPA	8.41	0	0 b	1.55	0.78
S-metolachlor	0.37	0	0 b	1.59	0.96
S-metolachlor	0.56	3	9 a	1.59	0.94
S-metolachlor	0.73	8	11 a	1.59	0.72
Treatment prob. (F)		0.06	0.0023	0.49	0.053

[a]Means followed by the same letter within a column are not statistically different according to Fisher's protected LSD (α = 0.05).

Table 5. Crop injury estimates at 15 d after treatment and fresh weights (at harvest) on direct-seeded mustard greens.

Treatment	Rate	Crop injury		Fresh weight	
		2019	2020	2019	2020
	kg ai ha^{-1}	— % —		— 1,000s kg ha^{-1} —	
Nontreated	0.00	0	0	1.77	1.01
DCPA	8.41	0	0	2.13	1.01
S-metolachlor	0.37	0	0	1.93	1.03
S-metolachlor	0.56	0	0	2.00	0.96
S-metolachlor	0.73	3	0	2.13	0.85
Treatment prob. (F)		0.44	1.00	0.84	0.87

Table 6. Crop injury estimates at 15 d after treatment and fresh weights (at harvest) on direct-seeded broccoli rabe.[a]

Treatment	Rate	Crop injury		Fresh weight	
		2019	2020	2019	2020
	kg ai ha^{-1}	— % —		— 1,000s kg ha^{-1} —	
Nontreated	0.00	0 b	0 d	0.21	0.15
DCPA	8.41	13 a	24 bc	0.16	0.17
S-metolachlor	0.37	0 b	21 c	0.18	0.17
S-metolachlor	0.56	5 b	34 ab	0.17	0.17
S-metolachlor	0.73	3 b	36 a	0.15	0.15
Treatment prob. (F)		0.0102	0.0001	0.22	0.72

[a]Means followed by the same letter within a column are not statistically different according to Fisher's protected LSD (α = 0.05).

Table 7. Crop injury estimates at 15 d after treatment and fresh weights (at harvest) on direct-seeded mizuna.[a]

Treatment	Rate	Crop injury		Fresh weight	
		2019	2020	2019	2020
	kg ai ha^{-1}	— % —		— 1,000s kg ha^{-1} —	
Nontreated	0.00	0	0 c	2.08	1.29
DCPA	8.41	6	15 a	2.29	1.07
S-metolachlor	0.37	3	6 bc	1.39	1.21
S-metolachlor	0.56	6	10 ab	1.86	1.21
S-metolachlor	0.73	6	13 ab	1.95	1.04
Treatment prob. (F)		0.69	0.0064	0.38	0.83

[a]Means followed by the same letter within a column are not statistically different according to Fisher's protected LSD (α = 0.05).

Table 8. Crop injury estimates at 14 d after treatment and fresh weights (at harvest) on transplanted brussels sprouts.

Treatment	Rate	Crop injury		Fresh weight	
		2019	2020	2019	2020
	kg ai ha^{-1}	— % —		— 1,000s kg ha^{-1} —	
Nontreated	0.00	0	0	0.90	1.35
DCPA	8.41	0	0	0.94	1.30
Sulfentrazone	0.08	0	0	0.96	1.35
Sulfentrazone	0.11	0	0	0.92	1.41
S-metolachlor	0.37	0	0	0.94	1.21
S-metolachlor	0.56	4	0	0.85	1.23
S-metolachlor	0.73	0	0	0.87	1.28
Treatment prob. (F)		0.07	1.00	0.99	0.44

Table 9. Crop injury estimates at 15 d after treatment and fresh weights (at harvest) on transplanted kale.

Treatment	Rate	Crop injury		Fresh weight	
		2019	2020	2019	2020
	kg ai ha^{-1}	— % —		— 1,000s kg ha^{-1} —	
Nontreated	0.00	0	0	2.67	2.22
DCPA	8.41	0	6	2.76	1.93
Sulfentrazone	0.08	5	0	2.51	2.26
Sulfentrazone	0.11	1	4	2.67	2.00
S-metolachlor	0.37	0	5	2.51	2.02
S-metolachlor	0.56	0	0	2.80	2.04
S-metolachlor	0.73	3	6	2.58	2.08
Treatment prob. (F)		0.33	0.39	0.97	0.47

of this will require more research. Also, broccoli rabe visible injury declined to low levels by 42 d after treatment (data not shown) and resulted in similar fresh weights at harvest both years (Table 6). DCPA caused slight to moderate injury to broccoli rabe—greater than the nontreated both years—but did not reduce yields (Table 6). DCPA and *S*-metolachlor caused slight injury to mizuna in 2019. However, both DCPA and *S*-metolachlor treatments resulted in 6% to 15% injury to mizuna in 2020, significantly greater than the nontreated, with the exception of the 0.37 kg ai ha^{-1} *S*-metolachlor treatment (Table 7). Mizuna in 2020 was grown during late September to early November, during much warmer conditions, when 750 GDD base 10 C occurred, compared to 572 GDD base 10 C in 2019 (UCIPM 2022). Increased mizuna injury may have been due to warmer conditions in 2020 than in 2019. The lower mizuna fresh weights in 2020 than in 2019 were across all treatments, which suggests that conditions for crop development were more ideal in 2019 than in 2020. The DCPA and *S*-metolachlor did not reduce harvestable yields in any of the seeded crops, including broccoli rabe and mizuna, relative to the nontreated (Tables 2, 3, 4, 5, 6, and 7).

Transplanted Crops

Brussels sprouts and kale were established as transplants. DCPA, sulfentrazone, and *S*-metolachlor caused little or no visible injury to brussels sprouts or kale (Tables 8 and 9). None of the herbicide treatments reduced brussels sprout or kale yield (Tables 8 and 9).

Weed Control

The predominant weeds in the trial site were burning nettle (*Urtica urens* L.), common purslane (*Portulaca oleracea* L.), and shepherd's-purse [*Capsella bursa-pastoris* (L.) Medik.] (Tables 10 and 11). *S*-metolachlor at 0.56 and 0.73 kg ai ha^{-1} generally

Table 10. Common purslane and shepherd's-purse densities in direct-seeded vegetable trials.[a]

Treatment	Rate	Common purslane			Shepherd's-purse	
		Trial 1, 30 May 2019	Trial 3, 30 May 2019	Trial 5, 11 Jul 2019	Trial 2, 24 Jun 2020	Trial 6, 4 Nov 2020
	kg ai ha^{-1}	no. m^{-2}				
Nontreated	0.00	196 a	2,030 a	620 a	108 a	43 a
DCPA	8.41	150 a	127 b	192 ab	62 ab	8 b
S-metolachlor	0.37	126 ab	39 c	208 b	12 b	10 b
S-metolachlor	0.56	21 c	26 c	134 bc	18 b	4 b
S-metolachlor	0.73	27 bc	11 c	77 c	5 b	2 b
Treatment prob. (F)		0.0102	0.0001	0.0001	0.014	0.014

[a]Means followed by the same letter within a column are not statistically different according to Fisher's protected LSD (α = 0.05).

Table 11. Common purslane and burning nettle densities in transplanted vegetable trials.[a]

Treatment	Rate	Common purslane		Burning nettle		
		Trial 7, 9 Jul 2019	Trial 8, 4 Aug 2020	Trial 7, 9 Jul 2019	Trial 8, 4 Aug 2020	Trial 9, 17 Aug 2020
	kg ai ha^{-1}	no. m^{-2}				
Nontreated	0.00	134 a	144 a	14 a	103 a	75 a
DCPA	8.41	78 b	78 bc	2 cd	23 b	7 c
Sulfentrazone	0.08	25 c	118 ab	0 d	10 b	4 c
Sulfentrazone	0.11	11 c	51 c	0 d	2 b	2 c
S-metolachlor	0.37	72 b	106 abc	10 ab	39 b	26 b
S-metolachlor	0.56	32 c	112 ab	7 bc	23 b	8 bc
S-metolachlor	0.73	25 c	84 bc	4 bcd	30 b	9 bc
Treatment prob. (F)		0.0001	0.0499	0.0008	0.0148	0.0001

[a]Means followed by the same letter within a column are not statistically different according to Fisher's protected LSD (α = 0.05).

controlled common purslane and shepherd's-purse as well or better than DCPA. The *S*-metolachlor 0.37 kg ai ha^{-1} controlled shepherd's-purse as well or better than DCPA but was inconsistent on common purslane (Table 10). In the transplanted trials, sulfentrazone at 0.08 and 0.11 kg ai ha^{-1} controlled common purslane and burning nettle as well or better than DCPA. *S*-metolachlor at 0.56 and 0.73 kg ai ha^{-1} generally controlled common purslane and burning nettle in the transplanted trials as well or better than DCPA. *S*-metolachlor at 0.37 kg ai ha^{-1} did not adequately control common purslane and burning nettle (Table 11).

S-metolachlor is already an important vegetable herbicide and has potential for expanded use. In Florida, sulfentrazone and *S*-metolachlor were evaluated on tomato and sulfentrazone on strawberry [*Fragaria ×ananassa* (Weston) Duchesne ex Rozier] (Sandhu et al. 2022). Sulfentrazone was safe on both tomato and strawberry, and *S*-metolachlor was safe on tomato. In the Pacific Northwest, *S*-metolachlor is registered on radish grown for seed (Peachey 2021). *S*-metolachlor was applied to 12 vegetable and flower crops in California during 2018, with the largest uses in carrot (*Daucus carota* L.), flowers, pepper (*Capsicum annuum* L.), spinach (*Spinacia oleracea* L.), tomato, and potato (CDPR 2021). *S*-metolachlor has been tested in combination with sulfentrazone for use in pepper in Canada (Robinson et al. 2008). The *S*-metolachlor label for Canada lists 14 vegetables (Anonymous 2022d). The U.S. label for *S*-metolachlor (DualMagnum®) has plant-back restrictions of 60 d for a number of vegetable crop groups, including Group 1B root vegetables, Group 3.07 green onion, Group 4-16 brassica leafy greens, and Group 9 cucurbits (Anonymous 2022b).

Results of this work indicate that expansion of labeled crops for *S*-metolachlor should include direct-seeded bok choi, collard, mizuna, radish, and mustard greens as well as transplanted brussels sprouts and kale. We also recommend that sulfentrazone be labeled for use on transplanted brussels sprouts and kale.

Acknowledgment. We thank the IR-4 program for financial support of this project. No conflicts of interest have been declared.

References

Abukari IA, Shankle MW, Reddy KR (2015) Sweetpotato [*Ipomoea batatas* (L.) Lam.] response to *S*-metolachlor and rainfall under three temperature regimes. Am J Plant Sci 6:702–717

Anonymous (2022a) DACTHAL® Flowable sample label. AMVAC. https://www.amvac.com/products/dacthal-flowable. Accessed: January 13, 2022

Anonymous (2022e) DualMagnum® sample label. Wilmington, DE: Sygenta. 54 p

Anonymous (2022c) IR-4 project: entire crop group table. https://www.ir4project.org/fc/crop-grouping/entire-crop-group-table/. Accessed: January 13, 2022

Anonymous (2022d) *S*-metolachlor 960 sample label. Calgary, Alberta: Corteva Canada. 26 p

Anonymous (2022b) Zeus® sample label. FMC. https://ag.fmc.com/us/en/herbicides/zeus-herbicide. Accessed: January 13, 2022

Blecker S, Fennimore S, Goodhue R, Mace K, Steggall J, Tregeagle D, Tolhurst T, Wei H (2018) Economic value of the herbicide DACTHAL for brassica and allium crops in California. https://giannini.ucop.edu/publications/are-update/issues/2018/22/2/economic-value-of-the-herbicide-dacthal-for-brassi/. Accessed: December 13, 2021

[CDPR] California Department of Pesticide Regulation (2021) 2018 annual pesticide use report. https://www.cdpr.ca.gov/docs/pur/pur18rep/18_pur.htm. Accessed: March 31, 2022

Daugovish O, Smith RF, Fennimore SA (2019) Herbicide treatment table. https://www2.ipm.ucanr.edu/agriculture/cole-crops/Herbicide-Treatment-Table/. Accessed: March 22, 2022

Fennimore SA, Cutulle M (2019) Robotic weeders can improve weed control options for specialty crops. Pest Manag Sci 75:1767–1774

Fennimore SA, Doohan DJ (2008) The challenges of specialty crop weed control, future directions. Weed Technol 22:364–372

Istok JD, Smyth JD, Flint AL (1993) Multivariate geostatistical analysis of ground-water contamination: a case history. Ground Water 31:63–74

Le Strange M, Cahn MD, Koike ST, Smith RF, Daugovish O, Fennimore SA, Natwick ET, Dara SK, Takele E, Cantwell MI (2010) Broccoli production in California. University of California ANR Publication Number 7211. https://anrcatalog.ucanr.edu/Details.aspx?itemNo=7211. Accessed: January 12, 2022

Lohstroh P, Koshlukova S (2017) Evaluation of the potential human health effects from drinking ground water containing DACTHAL (DCPA) degradates. https://www.cdpr.ca.gov/docs/hha/memos/tpa%20in%20ground%20water%20reply%20final%2002232017%20complete%20executed.pdf. Accessed: March 21, 2022

Peachey E, ed. (2021) Pacific Northwest weed management handbook. https://pnwhandbooks.org/weed. Accessed: January 27, 2022

Robinson ED, McNaughton K, Soltani N (2008) Weed management in transplanted bell pepper (*Capsicum annuum*) with pretransplant tank mixes of sulfentrazone, *S*-metolachlor, and dimethenamid-p. HortScience 43: 1492–1494

Sandhu RK, Reuss LE, Boyd NS (2022) Evaluation of sulfentrazone alone or in combination with other PRE and POST herbicides for weed control in tomato (*Solanum lycopersicum*) and strawberry (*Fragaria x ananassa*). HortScience 57:215–220

Shaner DL (2014) Herbicide Handbook. 10th ed. Lawrence, KS: Weed Science Society of America. 513 p

[UCIPM] University of California Integrated Pest Management System (2022) California weather data: south Salinas. http://ipm.ucanr.edu/WEATHER/index.html. Accessed: March 23, 2022

[USEPA] U.S. Environmental Protection Agency (2017) Title 40: protection of environment. https://www.govinfo.gov/content/pkg/CFR-2017-title40-vol26/xml/CFR-2017-title40-vol26-sec180-41.xml. Accessed: March 31, 2022

[USEPA] U.S. Environmental Protection Agency (2018) Sulfentrazone; pesticide tolerances. https://www.federalregister.gov/documents/2018/04/13/2018-07740/sulfentrazone-pesticide-tolerances. Accessed: March 31, 2022