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Vegetable response to sulfentrazone soil residues at four planting intervals

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Research Article

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Sulfentrazone; carrot; *Daucus carota* subsp. *Sativus* (Hoffm.) Schübl. & G. Martens; lettuce; *Lactuca sativa* L.; onion; *Allium cepa* L.; spinach; *Spinacia oleracea* L.; tomato; *Lycopersicon lycopersicum* (L.) Karsten L. *esculentum* (L.) Mill.

Key Words:
Brassica vegetables; carryover; plant-back interval

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Abstract

Sulfentrazone was recently granted food-use tolerance approval for use on Brassica head and stem, as well as Brassica leafy vegetables. To date, one sulfentrazone registrant has listed those crops on its use label. In coastal California multiple crops per year including Brassica vegetables are grown in rapid succession; therefore, to avoid injury to rotational crops, herbicides used in those fields must be carefully selected. Given concerns about the relatively long soil persistence of sulfentrazone, studies were conducted to measure the response of direct-seeded carrot, lettuce, onion, spinach, and seeded tomato planted 3, 6, 9, and 12 mo after sulfentrazone application at 0, 112, 224, and 336 g ai ha^{-1}. Eight plant-back studies were conducted during 2010–11 and 2012–13. Data collected were injury estimates, and stand and dry weights. Results indicate that it is safe to plant carrot and tomato 3 mo after sulfentrazone application at rates up to 336 g ai ha^{-1}. Lettuce and green onion should not be planted within 9 mo of sulfentrazone application. Spinach should not be planted within 12 mo of sulfentrazone application.

Introduction

California is the largest vegetable producer in the United States with an annual value of $7.9 billion (USDA-NASS 2020). The major vegetable crops include carrot, lettuce, and tomato. However, among the vegetables grown in California are a number of niche crops such as bok choi [*Brassica rapa* L. subsp. *Chinensis* (Rupr.) Olsson] grown with the use of a limited number of registered herbicides such as DCPA (Anonymous 2019a). Sulfentrazone has now been given a food-use tolerance by the U.S. Environmental Protection Agency for use on Brassica head and stem group 5-16 plants, which includes broccoli (*Brassica oleracea* L. var. *italica* Plenck), Brussels sprouts [*Brassica oleracea* L. var. *gemmifera* (DC.) Zenker], cabbage (*Brassica oleracea* L. var. *capitata* L.), bok choi, and cauliflower (*Brassica oleracea* L. var. *botrytis* L.) as well as Brassica leafy greens subgroup 4-16B, which includes 20 crops such as kale (*Brassica oleracea* L. var. Sabellica L.; Anonymous 2020a; USEPA 2017, 2018). Use rates of sulfentrazone in Brassica head and stem vegetables in coarse soils are 32 to 128 g ai ha^{-1} (Anonymous 2020b). Previous data recorded in Salinas, CA, indicated that broccoli, collard (*Brassica oleracea* L. var. *acephala* DC), and kale have a high level of tolerance to sulfentrazone (Fennimore and Rachuy 2006; Haar et al. 2002).

The majority of recent major uses of sulfentrazone in California has been in grapes (*Vitis vinifera* L.), mint (*Mentha arvensis* L.), strawberry (*Fragaria* × *ananassa*. Duchesne), and English walnut (*Juglans regia* L.) on a total treated area of 3,158 ha (CDPR 2019). These crops, with the exception of strawberry, are perennial crops, and carryover of herbicides to sensitive rotational crops like vegetables has not been a major concern. In coastal California, where many of the Brassica vegetables are produced in 60- to 90-d cycles, the growing season is nearly year-round. Fields are used for multiple crops like carrot, lettuce, onion, spinach, tomato, and others produced in successive rotations, sometimes with only days between harvest of one crop and planting of the next (Fennimore et al. 2011). Therefore, if sulfentrazone is to be used in the Brassica crops it must have a limited persistence in the soil and be safe for use with rotational crops.

Sulfentrazone is an aryl triazinone herbicide that acts on the protoporphyrinogen oxidase enzyme that leads to membrane disruption in susceptible plants. Sulfentrazone is taken up by roots and foliage, but is primarily absorbed by roots. The soil half-life of sulfentrazone was determined to be in the range of 121 to 302 d (Shaner et al. 2014). Mueller et al. (2014), however, estimated the half-life of sulfentrazone at 36 to 69 d in Tennessee soils of pH 6.0. Tolerant crops such as wheat (*Triticum aestivum* L.) can be planted 3 mo after application, whereas sensitive crops such as sugarbeets (*Beta vulgaris* L.) cannot be planted until 24 mo have passed (Anonymous 2019b). The pKa of sulfentrazone is 6.56, and in the dissociated form it is more soluble and readily absorbed by plants through the roots (Ferrell et al. 2003). Thus, in soils with a pH of 7 commonly found in Coastal California, at least some sulfentrazone molecules would be partially in the dissociated anionic form and more likely to be absorbed by plants and cause injury (Chaney et al. 2009).

Pekarek et al. (2010) tested several rotational crops for tolerance to sulfentrazone at 0, 210, 420, and 840 g ha^{-1} approximately 1 yr after application. They found that sulfentrazone at 210 and 420 g ai ha^{-1} (i.e., 1× and 2×, respectively) was safe for use on rotational crops of cabbage, cucumber (*Cucumis sativus* L.), and sweet potato [*Ipomoea batatas* (L.) Lam.] planted 1 yr after application. Sulfentrazone at a 4× rate of 840 g ha^{-1} injured cabbage, cucumber, and sweet potato 1 yr after application. Other vegetable crops on which sulfentrazone has demonstrated crop safety include cabbage and bell pepper (*Capsicum annuum* L.; Robinson et al. 2008; Smart et al. 2001).

DCPA is the major herbicide used on Brassica vegetables including broccoli, bok choi, Brussels sprouts, cabbage, cauliflower, onion, kale, and others (CDPR 2019). DCPA was registered in 1958 and has, over time, acquired a long list of registered crops. However, concerns about groundwater contamination from a DCPA metabolite have raised regulatory concerns (Lohstroh and Koshlukova 2017). Although DCPA remains available for use in Brassica vegetables, there is no guarantee that it will be available in the long term; therefore, sustainable vegetable production will require alternatives to DCPA.

Weeds listed on the sulfentrazone label that are troublesome in California vegetables include common chickweed [*Stellaria media* (L.) Vill.], common purslane (*Portulaca oleracea* L.), little mallow (*Malva parviflora* L.), shepherd's-purse [*Capsella bursa-pastoris* (L.) Medik.], and many others (Anonymous 2019b). Therefore, widespread use of sulfentrazone on Brassica vegetables is possible. The objective of the study was to evaluate the potential for sulfentrazone to injure five vegetable crops planted at intervals of 3, 6, 9, and 12 mo after application so that accurate plant-back intervals can be listed on the product label.

Materials and Methods

Trial Series 2010–11

During 2010–11, four trials were conducted to measure sulfentrazone carryover to vegetables 3, 6, 9, and 12 mo after being applied. These trials were conducted at the Crop Improvement and Protection Research unit, which is operated by the U.S. Department of Agriculture–Agricultural Research Service (USDA-ARS) in Salinas, CA. The soil was Chualar loam (fine-loamy, mixed, superactive, thermic Typic Argixerolls), with 1.04% organic matter, pH 7.2. Each of the four studies was arranged as a randomized complete block design with four replicates. Each plant-back interval treatment included two rates of sulfentrazone, 112 and 224 g ai ha^{-1} (FMC, 1735 Market St. Philadelphia, PA), and a nontreated control. Each replicate consisted of two beds that were 2.0 m wide by 7.6 m long. The trial was hand weeded and mechanically cultivated throughout so that weed competition would not influence results.

On July 22, 2010, 30-d-old cabbage plants were transplanted into all plots, followed by sprinkler irrigation to set the transplants. Cabbage heads were harvested October 12, 2010, and remaining crop residues were incorporated into the beds. The herbicide applications in this trial series were made on two different dates. Sulfentrazone was applied at 112 and 224 g ai ha^{-1} on July 21, 2010, to the 9- and 12-mo plots and the rotational crops were planted April 20, 2011, and July 21, 2011, respectively. Sulfentrazone was applied at the same rates January 20, 2011, to the 3- and 6-mo plots, and the rotational crops were planted April 20, 2011, and July 21, 2011, respectively (Table 1). At each plant-back timing the beds were reformed after light tillage and rotational crops were planted: carrot, tomato, spinach, green bunch onion, and crisphead lettuce were seeded into each of the two-bed plots, three seed lines per bed, with 30-cm spacing between each line. When possible, the same vegetable varieties were used in all plantings, but the same varieties were not always available, and similar varieties were substituted as needed (Table 1). The crops were mechanically cultivated, hand weeded, fertilized, and sprinkler irrigated in accordance with local practices (Smith et al. 2011b). Crop stand evaluations were collected 14 to 25 d after planting (DAP). Estimates of crop injury were assessed at 54, 60, and 67 DAP in the 3- and 9-mo trials, and 19, 26, 75, and 88 DAP in the 6- and 12-mo trials. Fresh biomass samples for each crop were collected at 56 to 76 DAP, dried at 50 C for 5 d, and dry weights recorded (Table 1).

Trial Series 2012–13

During 2012–13, a second set of plant-back trials was conducted at the same USDA-ARS location described above for the 2010–11 trials. The experiments were conducted as four separate trials for each plant-back interval; 3, 6, 9, and 12 mo after sulfentrazone application as described for the 2010–11 trials. Within each planting interval, sulfentrazone at 112, 224, and 336 g ai ha^{-1} and a nontreated control were included. All treatments were replicated four times. Each replicate plot was set up and maintained as described above for the 2010–11 trials. The difference between this trial and the previous one is that there was only one sulfentrazone application date, May 9, 2012.

Snap beans 'Jade' were seeded into all plots May 8, 2012. Sulfentrazone was applied after planting but PRE on May 9, 2012, using the same methods described above for the 2010–11 trial. The day after the PRE application, the trial was sprinkler irrigated to activate the treatments and germinate the crop. The snap beans were mowed down and incorporated into the beds July 25, 2012, and allowed to decay for 2 wk.

Beds in each of the four trials were reformed August 9, 2012. In the 3-mo trial, carrot 'Nelson', bush tomato 'Early Girl', spinach 'Whale', green bunch onion 'Green Banner', and crisphead lettuce 'Corona' (Table 2) were seeded into each of the two-bed plots (three seed lines per bed, with 30-cm spacing between each line). The crops were cultivated, hand weeded, fertilized, and irrigated in accordance with local practices and rates. Crop stand counts and injury estimates were collected at 14 and 19 DAP, followed by fresh biomass samples collected at 36 to 54 DAP, dried at 50 C for 5 d, and then weighed (Table 2).

Beds in the 6-, 9-, and 12-mo trials were reformed October 19, 2012. In the 6-mo trial, the five vegetables were seeded and then cultivated, fertilized, and irrigated as described for the 3-mo trial. Crop stand and injury evaluations, respectively, were collected at 24 and 28 DAP (Table 2). Fresh biomass samples for each crop were collected 43 to 88 DAP, dried, and weighed; the stage at which carrot, lettuce, green bunch onion, and spinach were within the normal harvest range for these crops (Table 2; Koike et al. 2011; Nuñez et al. 2008; Smith et al. 2011a, 2011b). Tomato was the one exception; it was not cultivated until fruit maturity, because the design and crop densities did not permit maintaining tomato to normal maturity. However, tomato was cultivated long enough in the vegetative state to assess its susceptibility to herbicide injury.

Table 1. Application dates, plant-back intervals, planting dates, evaluation dates, and 10 C base growing degree-days during each planting cycle for carrot, lettuce, onion, spinach, and tomato at 3, 6, 9, and 12 mo after sulfentrazone application in 2010–11.

	Events			
Application dates	Jan. 20, 2011		July 21, 2010	
Plant-back intervals	3 mo	6 mo	9 mo	12 mo
Planting dates	Apr. 20, 2011: C,L,O,S,T[a]	July 21, 2011: C,L,O,S,T	Apr. 20, 2011: C,L,O,S,T	July 21, 2011: C,L,O,S,T
Evaluations				
Stand	May 9 (18 DAP[b]): L,S,T May 16 (25 DAP): C,O	Aug. 4 (14 DAP): S Aug. 8 (18 DAP): C,L,O,T	May 9 (18 DAP): L,S,T May 16 (25 DAP): C,O	Aug. 4 (14 DAP): S Aug. 8 (18 DAP): C,L,O,T
Injury	June 14 (54 DAP): S,T June 20 (60 DAP): C,L June 27 (67DAP): O	Aug. 9 (19 DAP): S Aug. 16 (26 DAP): L,T Oct. 4 (75 DAP): O Oct. 17 (88DAP): C	June 14 (54 DAP): S,T June 20 (60 DAP): C,L June 27 (67DAP): O	Aug. 9 (19 DAP): S Aug. 16 (26 DAP): L,T Oct. 4 (75 DAP): O Oct. 17 (88DAP): C
Dry weight	June 16 (56 DAP): S June 22 (62 DAP): L June 28 (68 DAP): T July 1 (71DAP): O July 6 (76DAP): C	Aug. 29 (39 DAP): S Sep. 21 (62 DAP): T Sep. 29 (70 DAP): L Oct. 4 (75DAP): O Oct. 17 (88DAP): C	June 16 (56 DAP): S June 22 (62 DAP): L June 28 (68 DAP): T July 1 (71DAP): O July 6 (76DAP): C	Aug. 29 (39 DAP): S Sep. 21 (62 DAP): T Sep. 29 (70 DAP): L Oct. 4 (75DAP): O Oct. 17 (88DAP): C
Growing degree days 10 C[c]	665	1,059	665	1,059

[a]Key to crops: C = carrot 'Nelson' (3- and 9-mo plots) and 'Mokum' (6- and 12-mo plots), L = lettuce 'Hallmark', O = onion 'EXP-1200', S = spinach 'Whale', T = tomato 'Quality 47'.
[b]DAP,days after planting.
[c]Growing degree-day calculator using 10 C as base temperature at the Salinas, CA, airport. http://ipm.ucanr.edu/WEATHER/ddcustom.php?CGIREF=%2Fcalludt.cgi%2FDDFILE1&USE=METHOD&UNITS=E&LOWTHRESHOLD=50&UPTHRESHOLD=&METHOD=SS&CUTOFF=H

Table 2. Application date, plant-back intervals, planting dates, evaluation dates and 10 C base growing degree-days during each planting cycle for carrot, lettuce, onion, spinach, and tomato at 3, 6, 9, and 12 mo after sulfentrazone application in 2012–13.

	Events			
Application date	May 9, 2012			
Plant-back intervals	3 mo	6 mo	9 mo	12 mo
Planting dates	Aug. 9, 2012: C,L,O,S,T[a]	Oct. 22, 2012: C,L,O,S,T	Feb. 11, 2013: L Mar. 5: C,O,S,T[b]	May 9, 2013: C,L,O,S,T
Evaluations				
Stand	Aug. 23 (14 DAP[c]): C,L,O,S,T	Nov.15 (24 DAP): C,L,O,S,T	Mar. 14 (31 DAP): L Apr. 1 (27 DAP): C,O,S,T	May 23 (14 DAP): S May 28 (19 DAP): L,T June 5 (27 DAP): C,O
Injury	Aug. 28 (19 DAP): C,L,O,S,T	Nov.19 (28 DAP): C,L,O,S,T	Apr. 8 (34 DAP): C,O,S,T Apr. 8 (56DAP): L	June 5 (27 DAP): C,L,O,S,T
Dry weight	Sep. 14 (36 DAP): S Sep. 25 (47 DAP): T Sep. 28 (50 DAP): L Oct. 2 (54DAP): C,O	Dec. 4 (43 DAP): L Dec. 7 (46 DAP): S Dec. 19 (58 DAP): T Jan. 17 (87DAP): O Jan. 18 (88DAP): C	Apr. 22 (48 DAP): S Apr. 22 (70 DAP): L Apr. 24 (50 DAP): C,T Apr. 26 (52DAP): O	June 27 (49 DAP): S July 3 (55 DAP): T July 5 (57 DAP): L July 17 (69DAP): C July 19 (71DAP): O
Growing degree days 10 C [d]	659	488	455	814

[a]Key to crops: C = carrot 'Nelson', L = lettuce 'Corona', O = onion 'Green Banner' (3-, 6- and 9-mo plots) and 'EXP-1200' (12-mo plot), S = spinach 'Whale', T = tomato 'Early Girl'.
[b]Carrots, onions, spinach, and tomatoes replanted on March 5 due to poor germination in all plots.
[c]DAP, days after planting.
[d]Growing degree-day calculator using 10 C as base temperature for the Salinas, CA, airport. http://ipm.ucanr.edu/WEATHER/ddcustom.php?CGIREF=%2Fcalludt.cgi%2FDDFILE1&USE=METHOD&UNITS=E&LOWTHRESHOLD=50&UPTHRESHOLD=&METHOD=SS&CUTOFF=H

The process of bed reshaping, crop planting, crop maintenance, and crop evaluations were repeated, as described above, for the 9- and 12-mo plots, with planting and evaluation dates listed in Table 2. One exception was the use of the 'EXP-1200' variety of green bunch onion in the 12-mo trial, due to unavailability of the 'Green Banner' seed used in the three earlier plantings.

Data Collection and Statistical Analysis

Crop injury was estimated at 0% = no injury and 100% = dead plants. The threshold of ≤20% crop injury was considered safe. Data were subjected to ANOVA, and when treatment effects were significant, mean separation was performed using Fisher's LSD test at the $\alpha = 0.05$ level using Agriculture Research Management 7 software (version 7.0.5, Gyllings Data Management, Inc., 405 Martin Blvd., Brookings, SD). Each of the planting intervals of 3, 6, 9, and 12 mo were analyzed as separate trials.

Results and Discussion

Vegetable crops like broccoli, cauliflower, and onion are grown year round in coastal California, and therefore the study of herbicide persistence in vegetables planted throughout the year is necessary information in order to develop plant-back restrictions for herbicide labels. Although the coastal California has a moderate climate, there are seasonal variations in temperature that may have influenced the results presented here, especially the dry weights (Table 3). The 3- and 9-mo plant-back cycles in 2010–11 took place from April to July, and the 6- and 12-mo cycles took place from

Table 3. Monthly precipitation and temperature averages at the study location July 2010 to October 2011, and May 2012 to July 2013.[a]

Month	Precipitation total	Average high	Average low
	mm	C	
July 2010	0.0	38.5	28.4
August	0.5	39.3	28.0
September	0.3	42.3	29.2
October	15.5	39.8	28.5
November	51.3	36.6	24.1
December	77.0	33.9	24.5
January 2011	40.4	35.3	22.2
February	31.0	33.8	20.8
March	74.4	35.1	24.3
April	6.9	36.7	24.1
May	19.1	37.0	25.7
June	4.8	38.0	28.1
July	0.0	39.2	29.1
August	0.0	38.2	28.3
September	0.8	41.3	29.3
October	32.3	41.2	27.4
May 2012	1.0	20.3	8.1
June	2.8	21.3	9.5
July	0.0	20.8	11.7
August	0.0	22.0	11.0
September	0.0	22.4	10.8
October	15.9	22.9	9.8
November	33.0	19.1	6.8
December	41.9	16.0	4.5
January 2013	54.6	16.4	4.9
February	60.1	17.2	6.0
March	60.4	18.1	6.9
April	21.4	19.4	7.9
May	6.6	20.1	10.0
June	1.5	21.4	11.6
July	0.0	21.8	12.7

[a]CIMIS weather data for the Salinas, CA, airport, which is 10 km from trial site. Available at: http://ipm.ucanr.edu/calludt.cgi/WXPCLISTSTNS?MAP=&COUNTY=&ACTIVE=1&NETWORK=&PATH=STNNAME&STN=salinas

July to October, during which 665 and 1,059 growing degree-days (GDD), respectively accumulated, at base temperature of 10 C (Tables 1 and 3). Growth in all the crops, including the nontreated, and all herbicide treatments were affected by the differing levels of GDD. In the 2012–13 trial, the 6-mo plant-back cycle took place from October to January, and the 9-mo cycle occurred from February to April. with 488 and 455 GDD, respectively, using a 10 C base temperature (Tables 2 and 3). Crop growth during the cool fall and winter months was slower compared with growth during the 3-mo cycle August to October, and the 12-mo cycle from May to July, with 659 and 814 GDD, respectively, at a base temperature of 10 C (Table 2). However, at each of the plant-back cycles, crop growth in plants that received sulfentrazone treatment was compared with that of the nontreated control for that cycle, and so the seasonal effects of temperature on crop growth within each plant-back interval are the same for all the sulfentrazone treatments and the nontreated. For each planting interval assessments of injury or no injury were made relative to the nontreated.

Carrot

Sulfentrazone at 112 and 224 g ai ha^{-1} caused minor injury (10% to 19%) to carrot at 3, 6, and 12 mo after application in the 2010–11 trial. Sulfentrazone at 336 g ai ha^{-1} caused significantly greater injury to carrot relative to the nontreated at 3, 6, and 9 mo after application in the 2012–13 trials. Carrot also had 23% injury from sulfentrazone at 224 g ai ha^{-1} at 9 mo after application (Table 4). The injury observed at the 9-mo planting in 2013 was likely exacerbated due to cool March and April temperatures (Tables 2 and 3). Injury symptoms were slight yellowing and stunting of foliage. Carrot stands and dry weights were not reduced at any plant-back interval in 2010–11 or 2012–13 trials (Table 4). The 2012–13 carrots in the 6- and 9-mo plantings were grown during the cool winter months and the low dry weights reflect the slow growth during those periods compared to the warmer 3- and 12-mo trials. However, the dry weights in the 6- and 9-mo timings in the nontreated controls were also reduced and so it can be assumed that these low weights were due to weather and not herbicide injury.

Lettuce

In the 2010–11 trial, sulfentrazone at 112 g ai ha^{-1} caused minor crop injury in the range of 20% to 24% at 3, 6, and 12 mo after application; and 224 g ai ha^{-1} caused 44% crop injury at 6 mo after application, and 26% to 28% injury 3 and 12 mo after application. Lettuce was injured in 2012–13 by all rates of sulfentrazone 3 mo after application. However, by 6 mo after application lettuce injury was on the decline and was within the acceptable injury threshold of 20% (Table 5). Injury symptoms included moderate stunting and slight yellowing of foliage. Relative to the nontreated, lettuce stands were not reduced by sulfentrazone at any plant-back interval in any of the trials (Table 5). Relative to the nontreated, sulfentrazone did not reduce lettuce dry weights at any plant-back interval during 2010–11. Compared to the nontreated, lettuce dry weights for all rates of sulfentrazone were reduced in the 3-mo plantings in 2012–13. Lettuce dry weights were very low for the 6-mo interval in 2012–13, but there were no differences relative to the nontreated. The lettuce dry weights were much higher for the 9- and 12-mo plantings, presumably the result of a combination of warmer weather and reduced sulfentrazone residues (Table 5).

Green Onion

Sulfentrazone at 112 g ai ha^{-1} caused 33% and 28% injury in the 2010–11 trial at 3 and 12 mo after application, respectively, and the 224 g ai ha^{-1} rate resulted in 24% injury at 6 mo and 15% injury at 12 mo after application (Table 6). All rates of sulfentrazone in 2012–13 resulted in 10% to 20% injury at 3, 6, and 12 mo after application. Crop injury at 9 mo was 10% or less. Green onion stands and dry weights were not reduced by sulfentrazone at any plant-back interval in the 2010–11 or 2012–13 trials (Table 6). Like carrot, the 2012–13 6- and 9-mo dry weights during cool weather were less than those of the 3- and 12-mo plantings grown during warmer weather.

Spinach

Sulfentrazone at 112 and 224 g ai ha^{-1} was highly injurious to spinach in the 2010–11 trial planted 3 to 12 mo after application with injury ranging from 15% to 88% (Table 7). Visual spinach injury from all sulfentrazone rates in the 2012–13 trials was severe (30% to 89%) 3 to 6 mo after application. Injury symptoms persisted in the 9- and 12-mo trials, ranging from 9% to 23% in 2012–13. Injury symptoms included moderate to severe stunting, cupping/crinkling, and slight yellowing/drying of foliage. Sulfentrazone did not reduce spinach stands in any of the 2010–11 or 2012–13 trials (Table 7). Spinach stands for all treatments in 2010–11 were lower in the 3- and 9-mo plant-back trials, most likely due to cool soils on the early spring

Table 4. Treatment effect on carrot injury estimates, stand and dry weights at 3, 6, 9, and 12 mo after sulfentrazone application.

		Injury[a]				Stand				Dry weight			
Treatment	Rate	3 mo[b]	6 mo	9 mo	12 mo	3 mo	6 mo	9 mo	12 mo	3 mo	6 mo	9 mo	12 mo
2010–11	g ai ha^{-1}	%				no. m^{-1}				g m^{-1}			
Sulfentrazone	112	10.0	14.0	4.0	18.0	50.2	37.6	55.4	36.0	315.9	289.4	272.4	296.9
Sulfentrazone	224	19.0	13.0	3.0	19.0	52.2	36.0	63.8	36.4	258.2	343.7	274.6	305.7
Nontreated	0.0	0.0	0.0	0.0	0.0	54.3	30.1	54.3	30.1	237.8	254.9	237.8	254.9
P-values		0.0583	0.2500	0.4219	0.1656	0.7855	0.6000	0.1421	0.5785	0.2686	0.1798	0.3280	0.4089
2012–13		%				no. m^{-1}				g m^{-1}			
Sulfentrazone	112	0.0 b[c]	3.0 b	11.0 ab	4.0	34.3	48.2	17.7	41.9	64.2	9.8	2.8	66.5
Sulfentrazone	224	3.0 b	6.0 b	23.0 a	0.0	38.6	47.1	13.6	48.9	68.1	10.8	2.0	69.2
Sulfentrazone	336	10.0 a	14.0 a	20.0 a	6.0	35.8	43.3	16.7	33.0	75.5	9.2	2.2	92.1
Nontreated	0.0	0.0 b	0.0 b	0.0 b	0.0	35.1	44.9	16.9	47.6	60.9	9.7	3.6	78.7
P-values		0.0009	0.0094	0.0266	0.6066	0.7467	0.6147	0.4472	0.1640	0.3198	0.9238	0.5396	0.0970

[a]Injury estimates were 0% = no injury and 100% = all plants dead. An injury estimate of ≤20% was considered safe.
[b]For the 2010–11 trial 'Nelson' was planted in 3- and 9-mo plots; 'Mokum' was planted in 6- and 12-mo plots.
[c]Means with the same letter within a column are not significantly different from each other according to Fisher's LSD test at P ≤ 0.05.

Table 5. Treatment effect on lettuce injury estimates, stand and dry weights at 3, 6, 9, and 12 mos after sulfentrazone application.

		Injury[a]				Stand				Dry weight			
Treatment	Rate	3 mo	6 mo	9 mo	12 mo	3 mo	6 mo	9 mo	12 mo	3 mo	6 mo	9 mo	12 mo
2010–11	g ai ha^{-1}	%				no. m^{-1}				g m^{-1}			
Sulfentrazone	112	20.0	24.0 b[b]	6.0	24.0 a	11.2	3.7	12.1	5.1	72.7	78.4	89.7	75.8
Sulfentrazone	224	26.0	44.0 a	0.0	28.0 a	11.2	3.5	10.8	4.7	55.7	82.2	95.3	89.4
Nontreated	0.0	0.0	0.0 c	0.0	0.0 b	11.2	4.1	11.1	4.1	109.1	75.8	109.1	75.8
P-values		0.0632	0.0046	0.2529	0.0016	1.000	0.5983	0.8514	0.3586	0.0947	0.8439	0.6847	0.6435
2012–13		%				no. m^{-1}				g m^{-1}			
Sulfentrazone	112	28.0 c[b]	5.0	10.0	0.0	9.1	11.8	7.4	15.1	16.6 b	0.5	52.5	50.5
Sulfentrazone	224	44.0 b	15.0	13.0	0.0	8.5	8.2	7.2	14.3	8.7 b	0.5	38.9	42.5
Sulfentrazone	336	56.0 a	20.0	18.0	0.0	8.7	7.7	7.4	11.2	1.5 b	0.3	55.4	40.9
Nontreated	0.0	0.0 d	0.0	0.0	0.0	8.7	10.4	7.8	14.1	38.6 a	0.5	44.0	57.7
P-values		<.0001	0.0832	0.3610	1.000	0.9982	0.3424	0.9856	0.2546	0.0024	0.8421	0.6936	0.2667

[a]Injury estimates were 0% = no injury and 100% = all plants dead. An injury estimate of ≤20% was considered safe.
[b]Means with the same letter within a column are not significantly different from each other according to Fisher's LSD test at P ≤ 0.05.

Table 6. Treatment effect on green onion injury estimates, and stand and dry weights at 3, 6, 9, and 12 mo after sulfentrazone application.

		Injury[a]				Stand				Dry weight			
Treatment	Rate	3 mo[b]	6 mo	9 mo	12 mo	3 mo	6 mo	9 mo	12 mo	3 mo	6 mo	9 mo	12 mo
2010–11	g ai ha^{-1}	%				no. m^{-1}				g m^{-1}			
Sulfentrazone	112	33.0	13.0	13.0	28.0 a[c]	74.5	49.5	89.9	51.5	24.5	130.8	63.4	87.9
Sulfentrazone	224	21.0	24.0	10.0	15.0 ab	68.1	38.3	71.2	53.7	32.2	87.5	48.2	100.6
Nontreated	0.0	0.0	0.0	0.0	0.0 b	72.1	42.8	72.1	42.8	31.3	143.2	31.3	143.2
P-values		0.0641	0.0961	0.2672	0.0270	0.8783	0.6045	0.1888	0.7283	0.7546	0.2726	0.3432	0.3875
2012–13		%				no. m^{-1}				g m^{-1}			
Sulfentrazone	112	10.0 b[c]	10.0	5.0	19.0 a	14.3	97.6	74.0	78.6	11.2	5.9	1.7	22.8
Sulfentrazone	224	15.0 ab	13.0	10.0	11.0 a	16.1	108.6	75.0	107.5	11.4	7.7	1.2	38.1
Sulfentrazone	336	20.0 a	14.0	8.0	10.0 a	16.9	110.2	74.1	105.0	9.8	6.4	1.8	32.2
Nontreated	0.0	0.0 c	0.0	0.0	0.0 b	14.3	98.8	67.9	76.6	12.8	6.9	1.5	43.3
P-values		0.0019	0.1902	0.4128	0.0094	0.8406	0.7498	0.6883	0.5781	0.8987	0.9127	0.1994	0.0595

[a]Injury estimates were 0% = no injury and 100% = all plants dead. An injury estimate of ≤20% was considered safe.
[b]For the 2012–13 trial 'Green Banner' was planted in 3-, 6-, and 9-mo plots; 'EXP-1200' was planted in the 12-mo plot.
[c]Means with the same letter within a column are not significantly different from each other according to Fisher's LSD test at P ≤ 0.05.

planting date (April 21), compared with the summer planting date (July 21) for the 6- and 12-mo plant-back treatments. Sulfentrazone did not reduce spinach dry weights at any plant-back interval in 2010–11. All rates of sulfentrazone reduced spinach dry weights in the 3- and 6-mo plantings in 2012–13 (Table 7). Spinach dry weights were not affected in the 9- and 12-mo plantings. Overall, the data suggest that spinach is highly sensitive to sulfentrazone.

Seeded Tomato

Sulfentrazone at 112 g ai ha^{-1} resulted in 8% to 15% tomato injury in 2010–11 at 3, 6, 9, and 12 mo after application, and was significantly higher relative to the nontreated at 6 mo. The 224 g ai ha^{-1} rate resulted in 15% to 39% injury 3, 6, and 12 mo after application, and injury was higher than the nontreated at 3 and 6 mo (Table 8). Little injury to tomato was observed at 9 mo after application in

Table 7. Treatment effect on spinach injury estimates, and stand and dry weights at 3, 6, 9, and 12 mo after sulfentrazone application.

		Injury[a]				Stand				Dry weight			
Treatment	Rate	3 mo	6 mo	9 mo	12 mo	3 mo	6 mo	9 mo	12 mo	3 mo	6 mo	9 mo	12 mo
2010–11	g ai ha^{-1}	%				no. m^{-1}				g m^{-1}			
Sulfentrazone	112	59.0 b[b]	48.0 a	15.0 b	40.0	1.8	19.0	3.8	26.2	14.7	47.6	52.2	48.6
Sulfentrazone	224	88.0 a	50.0 a	36.0 a	40.0	2.5	19.7	2.5	24.9	6.9	35.4	26.4	60.7
Nontreated	0.0	0.0 c	0.0 b	0.0 b	0.0	2.6	17.1	2.6	17.1	21.1	29.4	21.1	29.4
P-values		0.0006	0.0188	0.0080	0.1162	0.7798	0.9616	0.4433	0.5878	0.2924	0.6863	0.0609	0.4396
2012–13		%				no. m^{-1}				g m^{-1}			
Sulfentrazone	112	48.0 c	30.0 c	21.0	9.0 b	69.4	71.9	15.7	99.3	30.2 b	15.3 b	2.7	56.6
Sulfentrazone	224	74.0 b	49.0 b	23.0	21.0 a	56.4	72.5	16.7	104.9	5.4 c	11.0 b	3.8	48.4
Sulfentrazone	336	89.0 a	68.0 a	21.0	21.0 a	50.7	72.0	16.4	101.4	1.4 c	6.1 b	6.2	44.2
Nontreated	0.0	0.0 d	0.0 d	0.0	0.0 c	70.7	75.7	20.0	104.9	65.8 a	30.5 a	4.5	67.3
P-values		<.0001	<.0001	0.2570	<.0001	0.1415	0.9797	0.7261	0.8823	<.0001	0.0053	0.3338	0.0691

[a]Injury estimates were 0% = no injury and 100% = all plants dead. An injury estimate of ≤20% was considered safe.
[b]Means with the same letter within a column are not significantly different from each other according to Fisher's LSD test at $P \leq 0.05$.

Table 8. Treatment effect on tomato injury estimates, and stand and dry weights at 3, 6, 9, and 12 mo after sulfentrazone application.

		Injury[a]				Stand				Dry weight			
Treatment	Rate	3 mo	6 mo	9 mo	12 mo	3 mo	6 mo	9 mo	12 mo	3 mo	6 mo	9 mo	12 mo
2010–11	g ai ha^{-1}	%				no. m^{-1}				g m^{-1}			
Sulfentrazone	112	8.0 ab[b]	25.0 a	3.0	15.0	39.2	4.9	16.6 b	8.1	135.9	76.0	120.7	95.7
Sulfentrazone	224	25.0 a	39.0 a	0.0	15.0	41.2	3.7	71.6 a	7.4	96.1	59.4	166.5	114.0
Nontreated	0.0	0.0 b	0.0 b	0.0	0.0	28.5	3.3	28.5 b	3.3	81.8	49.5	81.8	49.5
P-values		0.0407	0.0205	0.1925	0.4334	0.8235	0.2201	0.0128	0.2946	0.5842	0.6963	0.1564	0.3514
2012–13		%				no. m^{-1}				g m^{-1}			
Sulfentrazone	112	5.0 ab	9.0	3.0	5.0	14.3	13.5	24.1	17.4	31.5	0.1	1.8	147.8
Sulfentrazone	224	13.0 a	5.0	13.0	10.0	10.7	15.0	20.9	22.8	27.1	0.2	1.2	149.3
Sulfentrazone	336	15.0 a	10.0	5.0	8.0	15.3	10.8	25.8	16.6	24.9	0.1	1.4	134.5
Nontreated	0.0	0.0 b	0.0	0.0	0.0	14.4	14.8	25.1	19.2	44.6	0.1	1.8	133.9
P-values		0.0408	0.1343	0.2056	0.4128	0.7064	0.4991	0.4163	0.8677	0.3223	0.8460	0.3967	0.8051

[a]Injury estimates were 0% = no injury and 100% = all plants dead. An injury estimate of ≤20% was considered safe.
[b]Means with the same letter within a column are not significantly different from each other according to Fisher's LSD test at $P \leq 0.05$.

2010–11. Tomato in 2012–13 exhibited minor (<15%) injury from sulfentrazone at all planting intervals. Where injury was observed, symptoms included stunting and slight yellowing of foliage. Sulfentrazone did not reduce tomato stand and dry weight at any plant-back interval in 2010–11 or 2012–13 (Table 8). Tomato growth during the cool winter months in 2012–13 was very slow in the 6- and 9-mo plantings as was reflected in the low dry weights. Seeded tomato was not sensitive to sulfentrazone soil residues ≥6 mo after application.

Pekarek et al. (2010) conducted a vegetable plant-back study in North Carolina to estimate the potential for injury following sulfentrazone application at 210, 420 and 840 g ai ha^{-1}. They planted vegetables approximately 1 yr following the sulfentrazone application. Their study, like ours, included onion and tomato. Their onion and tomato were transplants, whereas we direct-seeded those crops, and so their plants were likely more tolerant of sulfentrazone than ours. They found that onion and tomato tolerated sulfentrazone up to 420 g ai ha^{-1} with a 12-mo interval, which is comparable to our 12-mo results for tomato. The onion we tested was a seeded green onion that is likely more sensitive than the transplanted bulb onion that Pekarek et al. (2010) used. The onion data we report suggest greater sensitivity to sulfentrazone than Pekarek et al. (2010) found.

Many of these vegetables are very sensitive to herbicide residues in the soil. Some general trends are that the longer the period that elapses between application and planting, the less likely the injury. Flumioxazin at 211 g ha^{-1} applied 30 d before lettuce planting was highly injurious, whereas the same rate applied 90 d before lettuce planting was much less injurious (Fennimore et al. 2011). Herbicides such as imazosulfuron have long soil residuals and are capable of injuring crops such as broccoli, carrot, and onion for at least 2 yr after application (Felix et al. 2012). Clearly, verification of safe plant-back intervals is needed for herbicides used in rotation with vegetables and other sensitive crops.

Use rates for head and stem brassicas in coarse soils <1.5% organic matter on the sulfentrazone label are 32 to 42 g ha^{-1} (Anonymous 2020b). The sulfentrazone 112 g ha^{-1} rate was safe for use with carrot, onion, and tomato 12 mo after application (Tables 4, 6, and 8). Lettuce and spinach were injured by the sulfentrazone 112 g ha^{-1} rate at 12 mo after application, but the dry weights of both crops were not significantly reduced (Tables 5 and 7). This suggests that sulfentrazone at 32 to 42 g ha^{-1} will likely not cause carryover injury to carrot, onion, or tomato 3 mo after application. However, where overlap in the sulfentrazone spray pattern occurs and rates of 224 g ha^{-1} or higher result, then herbicide carryover injury is much more likely, especially to lettuce and spinach.

Recommendations

These recommendations should be considered for inclusion on a sulfentrazone product label. Carrot and tomato can be seeded any time >3 mo after sulfentrazone application at rates up to

336 g ai ha^{-1}. Lettuce and onion should not be planted within 9 mo of sulfentrazone application. Spinach should not be planted within 12 mo of sulfentrazone application and the safe interval beyond 12 mo was not determined. The sulfentrazone label requires a 24-mo interval before sugarbeet can be planted, a crop that closely resembles spinach in its sensitivity to herbicide residues in the soil (Anonymous 2019b). This study was based on direct-seeded vegetable crops. Generally, we have found that transplanted vegetables like lettuce are more tolerant to herbicides than seeded lettuce (Lati et al. 2015). Transplanted vegetables likely would have shorter sulfentrazone plant-back intervals than seeded vegetables.

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