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Tolerance of plasticulture strawberry to 2,4-D choline applied to row middles

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Research Article

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strawberry, *Fragaria ×ananassa* (Weston) Duchesne ex Rozier (pro nm.) 'Camarosa' 'Chandler'; 2,4-D

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Abstract

Field studies in strawberry grown on polyethylene-mulched raised beds were conducted from 2018 to 2019 and 2019 to 2020 in Clayton, NC, to determine 'Camarosa' and 'Chandler' strawberry tolerance to 2,4-D directed to the row middle between beds. Treatments included 2,4-D at 0, 0.53, 1.06, 1.60, and 2.13 kg ae ha^{-1} applied alone and sequential treatments (0.53 followed by [fb] 0.53 or 1.06 fb 1.06 kg ae ha^{-1}). Initial treatments were applied in winter (December 2018 or January 2020) during vegetative growth, and sequential applications were applied in spring (April 2019 or March 2020) during reproductive growth. No differences among treatments were observed for visual foliage injury, strawberry crop canopy, fruit yield, and fruit quality (pH, titratable acidity, and soluble solid content).

Introduction

More than 17,800 ha of strawberries were grown and harvested in 2019 in the United States, with a farm gate value of US$2.5 billion (USDA 2020). California (83% of farm gate value) and Florida (11% of farm gate value) are the largest strawberry-producing states in the United States, followed by North Carolina (1%) and Oregon (1%) (USDA 2020). Weed management practices in strawberry include fumigation, hand weeding, herbicides, and cover crops in row middles (area between polyethylene-mulched rows) (Fennimore and Daugovish 2018; Poling et al. 2005). Other cultural practices to limit weed interference are establishing healthy plants and field rotation. Fumigation is a critical foundation of a pest control program in some fields used for polyethylene-mulched strawberry production, reducing the weed, disease, and nematode pressure (Fennimore et al. 2003). Owing to the phaseout of methyl bromide and increasing regulatory restrictions on the use of alternative fumigants, such as 1,3-D or chloropicrin, nonfumigant alternatives have been increasingly researched in the past decades (Devkota and Norsworthy 2014; Gerik and Hanson 2011; Samtani et al. 2011; Samtani et al. 2012). Additionally, the use of multiple weed control measures is crucial in strawberry production (McWhirt et al. 2020). Hand weeding can be effective, but also expensive, with an estimated cost per hectare of US$3,180 (Bolda et al. 2016; Guan et al. 2017). Cover crops help suppress weeds between rows, but if cover crop establishment is slow, weeds can emerge and establish in this area (McWhirt et al. 2020). The use of herbicides to selectively control broadleaf weeds POST between rows in strawberry is limited to three registered chemicals (acifluorfen, carfentrazone, and clopyralid) (Melanson 2021).

Recent research has evaluated PRE herbicides applied to strawberry beds pretransplant. Yu and Boyd (2017) reported PRE herbicides applied through drip tape 7 and 14 d before transplant provided some weed control with limited crop injury. Yellow nutsedge (*Cyperus esculentus* L.) control was 36%, 51%, and 59% with fomesafen at 570 g ai ha^{-1}, EPTC at 2,940 g ai ha^{-1}, and napropamide at 3,585 g ai ha^{-1}, respectively. Flumioxazin at 105 g ai ha^{-1}, halosulfuron at 52 g ai ha^{-1}, and fomesafen at 570 g ai ha^{-1} suppressed black medic (*Medicago lupulina* L.) by 45%, 45%, and 48%, respectively. The greatest Carolina geranium (*Geranium carolinianum* L.) control was 14% with flumioxazin. With the exception of halosulfuron, which caused up to 46% injury to strawberry at the 35 d after transplanting rating, all other PRE herbicides caused ≤5% injury. Because weed control was inconsistent with these treatments in these studies, the authors suggested that POST herbicide application would be needed if these PRE herbicides applied through drip tape are utilized by growers. Another study concluded that drip-applied EPTC (229 and 458 g ai ha^{-1}), fomesafen (42 and 84 g ai ha^{-1}), and napropamide plus oxyfluorfen (448 + 56 g ai ha^{-1}) PRE did not injure strawberry or reduce yield when applied 1, 7, 15, and

Table 1. Year, planting date, harvest dates, strawberry cultivar, and soil characteristics for 2,4-D herbicide studies conducted in Clayton, NC in 2018 to 2020.

				Soil characteristics					
Year	Planting date	Harvest dates	Cultivar	pH	CEC	OM	Sand	Silt	Clay
						%			
2018–2019	17 Oct 2018	22 Apr–29 May 2019	Camarosa	6.0	1.5	0.5	86	12	2
2019–2020	8 Oct 2019	13 Apr–14 May 2020	Chandler	4.8	5.8	1.4	90	5	5

Figure 1. 2,4-D directed to row middle on both sides of polyethylene-mulched strawberry. Nontreated (left) and 2,4-D at 1.06 followed by 1.06 kg ha^{-1} (right) 8 wk after sequential application.

Figure 2. Strawberry canopy measurements determined by measuring the widest part of the plant canopy and then the width perpendicular.

30 d before transplanting (Boyd and Reed 2016). The study confirmed the same results for EPTC, fomesafen, halosulfuron (5 and 10 g ai ha^{-1}), EPTC plus *S*-metolachlor (229 + 107 g ai ha^{-1}), fomesafen plus *S*-metolachlor (42 + 107 g ai ha^{-1}), and napropamide plus oxyfluorfen when applied to the bed surface after fumigation and before plastic mulch was laid. Research has been conducted to evaluate clopyralid applied POST during fruiting to control weeds in the planting hole. Hunnicut et al. (2013) observed foliar injury <5% and up to 37% from clopyralid at 66 (maximum registered rate) and 261 g ha^{-1} POST, respectively. However, in the same study, marketable yield was 104% and 98% from strawberry treated with 66 (maximum registered rate) and 261 g ha^{-1} clopyralid, respectively, compared to the nontreated control. Clopyralid treatments were also compared to 2,4-D amine POST over strawberry grown on polyethylene mulch to determine efficacy on vetch and strawberry tolerance (McMurray et al. 1996). In these studies, strawberry exhibited ≤6% injury from all clopyralid treatments, and 2,4-D caused 5% and 12% injury when applied to strawberry in the 7- to 9- and 9- to 10-lf stages, respectively, and

73% injury when applied at the 5% to 10% bloom stage. These results indicate that 2,4-D amine can cause injury when applied POST-directed during reproductive stages but has limited effect on earlier vegetative stages.

2,4-D is a synthetic auxin (WSSA Group 4) that mimics indole acetic acid by disrupting nucleic acid metabolism and processes in the cell wall (Shaner 2014). Applied POST, 2,4-D affects cell division and growth in meristematic regions (Shaner 2014). The 2,4-D choline salt formulation is being considered for use in strawberry row middles because it has "ultra-low volatility," which lowers the potential for vapor movement (Anonymous 2012a). The choline salt formulation is less volatile than the amine salt formulation owing to higher stability and less disassociation from 2,4-D acid (Peterson et al. 2016). These characteristics should reduce the off-target movement from the row middles onto the planting row, lowering any potential injury effects. 2,4-D also provides effective control of annual and perennial broadleaf weeds common to strawberry production in the Southeast, including Carolina geranium, common lambsquarters (*Chenopodium album* L.), pigweed (*Amaranthus* spp.), annual sowthistle (*Sonchus oleraceus* L.), horseweed [*Conyza canadensis* (L.) Cronquist], vetch (*Vicia* spp.), cutleaf evening-primrose (*Oenothera laciniata* Hill), and curly dock (*Rumex crispus* L.) (Anonymous 2021). Fennimore and Boyd 2018). The addition of a 2,4-D choline registration in polyethylene-mulched strawberry would be another chemistry that controls problem weeds in the row middles. Currently, 2,4-D choline as Embed® Extra (Corteva, Indianapolis, IN, USA) is registered for use in select fruit crops, including apple (*Malus domestica* auct. non Borkh.), pear (*Pyrus communis* L.), stone fruit (*Prunus* spp.), and matted row strawberry, but not strawberry grown on polyethylene mulch (plasticulture) as an annual crop. In matted row strawberry, applications are limited to one per year during dormancy or after last harvest to reduce injury. Polyethylene-mulched strawberries differ in that they are never fully dormant, and therefore applications would be made during active growth. Questions remain whether 2,4-D choline affects active vegetative growth of strawberry plants that are grown in plasticulture systems.

Thus the objective of this study was to determine the effect of 2,4-D applied to row middles between polyethylene-mulched beds on strawberry vegetative growth, fruit yield, and quality.

Materials and Methods

Field studies were conducted at the Central Crops Research Station in Clayton, NC (35.668137°N, 78.506424°W and 35.668093°N, 78.505190°W), on a Wagram loamy sand (loamy, kaolinitic, thermic Arenic Kandiudults) or a Norfolk loamy sand (fine-loamy, kaolinitic, thermic Typic Kandiudults) (Table 1). 'Camarosa' and 'Chandler' strawberry cultivars were transplanted both years in October by hand into 0.9-m-wide raised beds covered in virtually impermeable film polyethylene mulch in a double-row planting spaced 0.3 × 0.3 m with a single line of drip tape and emitters spaced 30 cm apart (Table 1; Figure 1). The crop was managed through the season according to recommended practices (Poling et al. 2005) and then harvested the following April through May after fall planting (Table 1).

The experimental design was a randomized complete block with treatments replicated four times. Each replicate had 20 strawberry plants and consisted of two 3-m-long rows: the first a border row and the second row used for data collection. Treatments included 2,4-D (Embed® Extra) at 0.53 kg ae ha^{-1} alone or followed by (fb) 0.53 kg ae ha^{-1}, 1.06 kg ae ha^{-1} alone or fb 1.06 kg ae ha^{-1}, 1.6 kg ae ha^{-1}, and 2.13 kg ae ha^{-1}. Treatments were applied in winter (December 2018 or January 2020) during vegetative growth and spring (April 2019 or March 2020) during reproductive growth. A nontreated control was included for comparison. Strawberry beds were maintained weed-free by weekly hand removal of weeds from the planting hole. Weeds between beds were not controlled and were allowed to remain in the field. Chloropicrin with 1,3-dichloropropene (Pic-Clor 60, TriCal Inc., Hollister, CA, USA) (157 kg ha^{-1}) was applied as a preplant fumigant to the entire study. Treatments were directed between beds on both sides of the crop row, avoiding contact with strawberry foliage, using a CO_2-pressurized backpack sprayer calibrated to deliver 187 L ha^{-1} at 138 kPa with one TeeJet® 8003 EVS nozzle (TeeJet Technologies, Springfield, IL, USA).

Figure 3. Week 4 of 2020 strawberry harvest in Clayton, NC, with strawberry fruit sorted by nonmarketable (left) and marketable (right). Treatments from top to bottom: 0.53 followed by 0.53 kg ha^{-1} nontreated, 1.6 kg ha^{-1} alone, and 1.06 followed by 1.06 kg ha^{-1}.

Table 2. Effect of 2,4-D applied as a directed application in row middles on strawberry crop injury, combined over cropping years (2018 to 2019, 2019 to 2020), in Clayton, NC.[a,b]

	Herbicide rate		Strawberry stunting							
			Winter, WAT				Spring, WAT			
Treatment	Winter[c]	Spring[d]	1	2	4	8	1	2	4	6
	kg ae ha^{-1}		%							
Nontreated	0	0								
2,4-D	0.53	0	0	2	3	5	4	4	4	3
2,4-D	1.06	0	0	3	3	6	3	0	2	0
2,4-D	1.6	0	0	4	5	5	3	3	2	2
2,4-D	2.13	0	0	2	3	4	3	3	2	2
2,4-D	0.53	0.53	0	2	4	4	3	0	2	2
2,4-D	1.06	1.06	0	3	3	2	0	0	0	0
P value			NS	NS	NS	NS	NS	NS	NS	NS

[a]Strawberry crop injury was recorded on a scale of 0 (no injury) to 100 (plant death).
[b]Abbreviations: WAT, weeks after treatment; NS, not significant.
[c]Winter applications of 2,4-D were made in December 2018 or January 2020.
[d]Spring applications of 2,4-D were made in April 2019 or March 2020.

Table 3. Effect of 2,4-D applied as a directed application in row middles on strawberry canopy means (and standard error) in Clayton, NC, in 2019 and 2020.[a,b]

	Herbicide rate		Strawberry canopy			
			2019		2020	
Treatment	Winter[c]	Spring[d]	3 WATW	12 WATW	4 WATW	12 WATW
	kg ae ha^{-1}		cm^2			
Nontreated	0	0	277 (±11)	524 (±14)	533 (±41)	670 (±76)
2,4-D	0.53	0	295 (±23)	533 (±37)	479 (±20)	632 (±51)
2,4-D	1.06	0	255 (±28)	492 (±56)	541 (±36)	660 (±30)
2,4-D	1.6	0	240 (±31)	511 (±57)	490 (±37)	585 (±32)
2,4-D	2.13	0	277 (±15)	541 (±23)	477 (±42)	598 (±51)
2,4-D	0.53	0.53	226 (±39)	488 (±72)	501 (±53)	647 (±37)
2,4-D	1.06	1.06	271 (±27)	560 (±44)	517 (±76)	619 (±68)
P value			NS	NS	NS	NS

[a]Strawberry canopy was determined by measuring the widest part of the plant canopy and then the width perpendicular.
[b]Abbreviations: WATW, weeks after treatment, winter; NS, not significant.
[c]Winter applications of 2,4-D were made in December 2018 or January 2020.
[d]Spring applications of 2,4-D were made in April 2019 or March 2020.

Data recorded included visual crop injury 1, 2, 4, and 6 to 8 wk after each treatment (WAT) (both application timings). Crop injury was characterized by stunting or leaf chlorosis and necrosis rated on a scale of 0% (no injury) to 100% (crop death). Strawberry canopy was determined by measuring the widest part of the plant canopy and then the width perpendicular January through April (Figure 2). Measurements were multiplied together to obtain approximate canopy area.

Ripe fruit (at least 75% red) from the center 10 plants per plot were hand harvested once or twice a week for 6 wk beginning April 22, 2019, and April 13, 2020 (Table 1) (Gross et al. 2016; USDA 2006). Heavy rain during the sixth week of harvest in 2020 caused soggy fruit; therefore fruit were not harvested the sixth week in 2020. Fruit were separated into marketable (fully developed, uniform size, and free from decay and damage) and nonmarketable (not fully developed, not uniform in size, decay and/or damage) and then weighed separately (Gross et al. 2016; USDA 2006) (Figure 3). Ten marketable fruit from each plot were then placed in a −20 C freezer and held until fruit were analyzed. Frozen strawberry samples were thawed to room temperature for analyzing, then homogenized by hand crushing, and the juice was filtered through filter paper (Fisherbrand™ Filter Paper Qualitative P8, Fisher Scientific Co., Pittsburgh, PA, USA). Each homogenized sample was analyzed for total soluble solid content (SSC) (expressed in °Brix), titratable acidity (TA) (percent citric acid equivalents [v/v]), and pH. Soluble solid content and TA were determined by the PAL-BX|ACID F5 pocket Brix-acidity meter (Atago Co. Ltd., Bellevue, WA, USA) on setting 4 for strawberry. The pH of each fruit sample was measured using a PC800 pH meter (Apera Instruments, Columbus, OH, USA) calibrated to pH 4 and 7.

Response variables of crop injury, vegetative growth, yield, and fruit quality (SSC, TA, and pH) were subjected to analysis of variance and analyzed in SAS PROC MIXED (SAS 9.4, SAS Institute, Cary, NC, USA).

Results and Discussion

Crop injury was combined over years because there was no interaction between year and treatment. No difference in crop injury occurred across treatments (Table 2, not all data shown). Strawberry canopy data were separated by year because of different timings when canopy measurements were taken each year.

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Table 4. Effect of 2,4-D applied as a directed application in row middles on marketable, nonmarketable, and total strawberry fruit yield, pooled across cropping years in studies conducted in Clayton, NC, in 2018 to 2020.[a]

	Herbicide rate		Yield		
Treatment	Winter[b]	Spring[c]	Marketable	Nonmarketable	Total
	— kg ae ha^{-1} —		kg ha^{-1}		
Nontreated	0	0	21,349	3,330	24,679
2,4-D	0.53	0	20,054	2,738	22,792
2,4-D	1.06	0	21,238	3,219	24,457
2,4-D	1.6	0	19,832	2,627	22,459
2,4-D	2.13	0	19,610	2,738	22,348
2,4-D	0.53	0.53	21,090	2,849	23,939
2,4-D	1.06	1.06	20,683	3,145	23,828
P value			NS	NS	NS

[a]Abbreviation: NS, not significant.
[b]Winter applications of 2,4-D were made in December 2018 or January 2020.
[c]Spring applications of 2,4-D were made in April 2019 or March 2020.

Table 5. Effect of 2,4-D applied as a directed application in row middles on strawberry fruit pH, titratable acidity, and soluble solid content means (and standard errors) averaged across harvest timings, pooled across cropping years, in studies conducted in Clayton, NC, in 2018 to 2020.[a]

	Herbicide rate				
Treatment	Winter[b]	Spring[c]	pH	TA[d]	SSC[e]
	— kg ae ha^{-1} —				
Nontreated	0	0	3.67 (±0.13)	0.53 (±0.07)	7.0 (±0.6)
2,4-D	0.53	0	3.66 (±0.08)	0.56 (±0.08)	7.1 (±0.5)
2,4-D	1.06	0	3.70 (±0.11)	0.53 (±0.07)	7.0 (±0.7)
2,4-D	1.6	0	3.71 (±0.23)	0.56 (±0.05)	7.1 (±0.5)
2,4-D	2.13	0	3.72 (±0.23)	0.55 (±0.05)	7.1 (±0.5)
2,4-D	0.53	0.53	3.73 (±0.12)	0.57 (±0.07)	7.0 (±0.6)
2,4-D	1.06	1.06	3.74 (±0.12)	0.54 (±0.04)	6.9 (±0.4)
P value			NS	NS	NS

[a]Abbreviations: TA, titratable acidity; SSC, soluble solid content; NS, not significant.
[b]Winter applications of 2,4-D were made in December 2018 or January 2020.
[c]Spring applications of 2,4-D were made in April 2019 or March 2020.
[d]Measured in percent citric acid equivalents (v/v).
[e]Expressed in °Brix.

However, differences in strawberry canopy by treatment were not observed (Table 3, not all data shown).

Harvest data were combined every 2 wk to assess early, middle, and late harvest timing. In year 2, there were no data for week 6; only week 5 represented the late harvest. Yield was combined over years because there was no interaction between year and treatment. No significant difference was observed by treatment for yield (marketable, cull, or total fruit) by harvest timing (data not shown) or averaged across harvest timing (Table 4). Marketable yields from these studies were comparable to yields in breeding trials during the study years in North Carolina using 'Camarosa' and 'Chandler' (Fernandez 2021). Likewise, yields in the studies were similar to yield ranges expected on North Carolina farms (Anonymous 2012b).

Fruit quality data were also combined every 2 wk to assess pH, TA, and SSC by early, middle, and late harvest timings, with week 5 alone representing late harvest in year 2. No significant interaction was observed for fruit quality data, so data were combined over years. No significant difference was observed in pH, TA, and SSC of fruit at any of the harvest timings (data not shown) or when averaged across harvest timings by treatment (Table 5). The ranges for pH (3 to 4), TA (0.5 to 1.0), and SSC (6 to 9) in this study fall within the standard ranges for strawberry fruit produced in North Carolina (P. Perkins-Veazie, personal communication). Likewise, Basinger et al. (2019) found that herbicides did not affect fruit quality (pH, TA, and SSC) in grapes (*Vitis* spp.), and Peck et al. (2006) found that fruit quality (TA and SSC) was similar in conventional and organic apples ('Galaxy Gala'). Environment, genotype (Agüero et al. 2015; Samykanno et al. 2013), harvest dates, and management practices (Cayuela et al. 1997) can affect strawberry fruit quality characteristics. Although not as widely studied, it is important to evaluate the effect of herbicides on fruit quality. Wang et al. (2015) found that increasing strawberry fruit pH alters fruit color after harvest, describing fruit juice color at pH 2 as "strongest red" and at pH 5 as "pink." Titratable acidity and SSC (°Brix) determine the sour and sweet taste of fruit, respectively, which influence consumer preference. Jayasena and Cameron (2008) reported an increase in consumer acceptability for Crimson Seedless (*Vitis vinifera* L. 'Crimson Seedless') table grapes as the °Brix/acid ratio increased from 20 to 40.

The results of this study indicate that 2,4-D directed to the row middles of plasticulture strawberry does not cause visible injury to strawberry plants or an effect on fruit yield or fruit quality. The authors recommend a maximum rate of 1.06 kg ha^{-1} per application applied twice a year (once in the winter and again in the spring, 30 d before harvest) for a maximum of 2.13 kg ha^{-1} applied in a production year.

Future research should determine the effect of low-dose rates of 2,4-D, which would simulate misapplication or off-target movement, on strawberry vegetative growth, fruit yield, and fruit quality, specifically the effect on fruit development. Additionally, data should be collected on sequential applications of the higher rates (1.6 and 2.13 kg ha^{-1}) to assess any impact to growth, yield, and fruit quality.

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