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Flumioxazin soil persistence under plastic mulch and effects of pretransplant applications on strawberry

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Research Article

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Abstract

Weeds are managed in Florida strawberry production systems with plastic mulches, fumigants, and herbicides. There are limited post-transplant options to control weeds that emerge in the planting holes in the plastic-covered beds, but flumioxazin at 107 g ai ha^{-1} can be applied pretransplant under the plastic mulch to control broadleaf and grass weeds. Three research trials were conducted in Balm and Dover, FL, in 2017 and 2018 to evaluate tolerance of the strawberry cultivar 'Radiance' to flumioxazin rates ranging from 54 to 6,854 g ha^{-1} and to estimate herbicide persistence under the plastic mulch. Shoot damage was observed at 428 to 857 g ha^{-1} (4× and 8× the label rate, respectively), but a significant increase in the number of dead plants was not observed until the treatment rate was 857 g ha^{-1} at one site and 3,427 g ha^{-1} at a second site (8× and 32× the label rate, respectively). Berry yields were unaffected by rates lower than 857 g ha^{-1}. Flumioxazin persisted throughout the growing season (approximately 150 d) with no reduction in soil concentration. We conclude that applied at the label rate, flumioxazin is a safe pretransplant weed management option for season-long weed control in strawberry with no yield reduction at rates below 8× the label rate. Caution is recommended for growers who plant a second crop on the same bed.

Introduction

Strawberries are an important horticultural crop for Florida, with a total production value of US $282 million produced on 3,966 ha (USDA 2020). Florida strawberries are typically grown using a fumigated, raised-bed, plasticulture system. Beds are fumigated in late August, strawberries are transplanted in late September to mid October, and berries are harvested from December through early to mid March (Whitaker et al. 2019). Plasticulture crop protection changed dramatically with the phaseout of methyl bromide in 2005, in accordance with the Montreal Protocol (Ozone Secretariat 2019). The alternative fumigants that were adopted do not control as many pests as methyl bromide does and tend to have inconsistent weed control. To overcome this limitation, growers rely on fumigant combinations or pretransplant (PRETR) herbicide applications (Hanson and Shrestha 2006).

Flumioxazin is an important broad-spectrum, Weed Science Society of America Group 14, PRE herbicide used in strawberry production (Anonymous 2017). Group 14 chemistry inhibits protoporphyrinogen oxidase, which results in protoporphyrin IX buildup (Matringe et al. 1989), subsequent photo-oxidative reactions, and membrane damage (Matringe and Scalla 1988).

It has moderate persistence in soils; a half life of 21 d is reported for Tennessee soils (Mueller et al. 2014). Flumioxazin is frequently applied between raised beds and, in Florida vegetable fields, it tends to outperform and be more consistent than other PRE herbicides (Boyd 2016). It can also be safely applied over the top of some strawberry cultivars such as 'Selva' at low rates immediately after transplant if no foliage is present (Manning and Fennimore 2001). However, flumioxazin is typically applied PRETR under the plastic mulch, and safety has been demonstrated for several strawberry cultivars for this application timing (Samtani et al. 2012). Yu and Boyd (2017) also found that it could be safely applied through drip irrigation 7 to 14 d before transplant, but only variable control of black medic (*Medicago lupulina* L.) and goosegrass [*Eleusine indica* (L.) Gaertn.] was demonstrated, and Carolina geranium (*Geranium carolinianum* L.) was not controlled.

Flumioxazin is registered for control of several problematic broadleaf and grass species found in Florida strawberry production, including goosegrass, common lambsquarters (*Chenopodium album* L.), Florida pusley (*Richardia scabra* L.), common purslane (*Portulaca oleracea* L.), and smooth crabgrass [*Digitaria ischaemum* (Schreb.) Schreb. ex Muhl.] (Anonymous 2017). It is a recommended management option for growers in Florida (Whitaker et al. 2019), but in 2016

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and 2017, localized crop damage after flumioxazin applications was reported on several commercial farms (NS Boyd, personal communications). A relatively new strawberry cultivar, 'Radiance,' had become popular, and it was unknown if the observed damage was due to application error or increased sensitivity in the new cultivar. In addition, it was unknown if flumioxazin applications applied PRETR to strawberry would affect the subsequent vegetable crops in fields where relay crops were grown (Sandhu et al. 2020).

Weed management in Florida strawberry is complicated by the long growing season, the use of overhead irrigation for transplant establishment, and subtropical weed emergence patterns. In addition, commonly planted cultivars such as Sensation™ 'Florida127' have a growth habit that allows for better fruit visualization (Whitaker et al. 2015) but also limits competitiveness for light. PRE herbicides are applied at bed formation (in August) but strawberries are not transplanted until September or October, at which time overhead irrigation is applied for evaporative cooling and establishment. Overhead irrigation has been linked to reduced fomesafen persistence when applied under the plastic mulch at bed formation (Reed et al. 2018). Some broadleaf weeds emerge mid November during strawberry establishment, including black medic (Sharpe and Boyd 2018a) and Carolina geranium (NS Boyd, unpublished data), but others emerge much later in the season. Currently, the persistence of flumioxazin when applied under plastic mulch is unknown, but weed emergence in the late season suggests a lack of persistence.

Early research on herbicide persistence focused on computer modeling using rainfall and temperature as field-based inputs, which affected the laboratory-derived herbicide degradation rate via microbes and chemical-mediated pathways (Walker 1976; Walker and Barnes 1981). The presence of plastic mulch and drip irrigation should alter the applicability of such established models because evaporation and rainfall penetration are affected. Research in Georgia demonstrated more rapid dissipation of halosulfuron and *S*-metolachlor when applied to bare ground versus under a plastic mulch, with no difference in dissipation rate for sulfentrazone (Grey et al. 2007). It is well known that flumioxazin hydrolysis and photolysis occur within buffered solutions and pH has a substantial impact on their rates (Kwon et al. 2004). However, microbial degradation was shown to be the critical process affecting flumioxazin persistence in Georgia soils (Ferrell and Vencill 2003), and it is possible that fumigation within the strawberry production system could extend flumioxazin persistence beyond nonplasticulture settings if the overhead irrigation during plant establishment does not remove the herbicide from the bed (Reed et al. 2018).

Our objectives for this study were to evaluate strawberry tolerance to multiple doses of flumioxazin and to evaluate flumioxazin persistence under plastic mulch in the Florida strawberry production system.

Materials and Methods

Field Setup

Three field trials were conducted to evaluate strawberry tolerance to flumioxazin applied PRETR as well as flumioxazin persistence under plastic mulch. Trials 1 and 2 occurred at the Gulf Coast Research and Education Center (27°N, 82°W) in Balm, FL, from August 2017 to March 2018 (Trial 1) and August 2018 to March 2019 (Trial 2). Soils at the site are a Myakka fine sand (sandy, siliceous, hyperthermic Oxyaquic Alorthod) with a pH of 6.8, 0.8% organic matter, and 98%, 1%, and 1% sand, silt, and clay, respectively. Trial 3 occurred at the Florida Strawberry Growers Association research facility (28°N, 82°W) in Dover, FL, during the same period as Trial 2. The soil type in Trial 3 was characterized as Zolfo fine sand (sandy, siliceous, hyperthermic Oxyaquic Alorthod) with a pH of 6.4, less than 1% organic matter, and with 92% sand, 2% silt, and 6% clay. All sites had a history of purple nutsedge (*Cyperus rotundus* L.) infestation.

All experiments were arranged as a randomized complete block design with four blocks. Each plot consisted of 7.6 m within a single raised bed. There was 1.22 m between beds and each bed had a height of 30.5 cm, base width of 81 cm, and a bed-top width of 66 cm. Raised beds were formed with standard bed-pressing equipment and the soil was fumigated with 336 kg ha^{-1} of 63.4% 1,3-dichloropropene plus 34.7% chloropicrin (Telone C-35; Dow AgroSciences LLC, Indianapolis, IN) on August 15, 2017 (Trial 1) and August 20, 2018 (Trials 2 and 3). A single drip tape was installed in the center of the bed and the beds were covered with virtually impermeable film (aka, plastic mulch; Trial 1) and totally impermeable film (Trials 2 and 3) (Berry Plastics Corp., Evansville, IN). Drip tape contained emitters every 30 cm, and a flow rate of 0.95 L min^{-1} 30.5 m^{-1} was used (Jain Irrigation Inc., Haines City, FL).

The treatment list is provided in Table 1. Multiple rates of flumioxazin (Valent, Walnut Creek, CA) were applied to the bed top immediately after fumigation (see dates in the previous paragraph) and immediately before laying the plastic mulch. Throughout this article, herbicide dosages are discussed in reference to the label rate. All herbicide treatments were applied in 187 L ha^{-1} of water with a backpack sprayer (Bellspray Inc., Opelousas, LA) equipped with a single 8002EVS nozzle (Teejet Technologies, Wheaton, IL) at a pressure of 0.24 MPa. Two rows of strawberry (cv 'Radiance') were transplanted per bed with 38-cm spacing between plants on October 10, 2017 (Trial 1) and October 5, 2018 (Trials 2 and 3). All plots were irrigated and fertilized throughout the growing season per industry standards (Whitaker et al. 2019).

Data Collection

Strawberry crop injury was evaluated in Trial 1 (on November 6 and 15, 2017) and Trial 3 (on November 6 and 29, 2018), but not in Trial 2. Injury was evaluated on a percentage scale, where 0% was no injury and 100% represented complete shoot death. In trial 1, the number of living strawberry plants was counted on January 19, 2018, in each plot and percent crop kill calculated. On January 25, 2018, five strawberry shoots were harvested from each plot, berries removed, and the shoot was dried and weighed. In Trials 2 and 3, the number of living shoots was counted on January 2 and 3, 2019, respectively, and used to calculate percent kill. Shoot biomass data were not collected. In all trials, berries were harvested twice weekly from December to late February.

Soil Extraction and Analysis

Soil samples were collected from Trials 2 and 3. At each site, three soil cores, each 10 cm deep with a diameter of 2.5 cm, were taken from the center of the plot under the plastic mulch where the label rate (107g ha^{-1}) was applied. All three samples were placed in a single bag, thoroughly mixed, and immediately placed on ice for transport back to the laboratory, where they were frozen at −40 C until analysis. Samples were taken the day of herbicide application, at crop transplant (29–32 d after application [DAA]), immediately after the overhead irrigation used for crop establishment was turned off (50–53 DAA), mid-season (121 DAA), and at the end of the season (181 DAA).

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Table 1. Herbicide treatments in field experiments conducted at the Gulf Coast Research and Education Center in Balm, FL.

Flumioxazin rate	Comparison to label rate[a]
g ai ha^{-1}	
0	NA
53	0.5×
107	1×
214	2×
428	4×
857	8×
1,714	16×
3,427	32×
6,854	64×

Abbreviation: NA, not applicable.

Table 2. Effects of multiple flumioxazin rates on strawberry damage ratings in field experiments conducted at the Gulf Coast Research and Education Center in Balm, Florida, in 2017 and Dover, Florida, in 2018.

	Balm (Trial 1 date)[a]		Dover (Trial 2 dates)[a b]			
Flumioxazin rate	Nov. 15, 2017		Nov. 29, 2018		Nov. 29, 2018	
g ai ha^{-1}	%					
	Mean	SE	Mean	SE	Mean	SE
0	0 c	0.0	0 c	0	0 c	0
54	3 c	0.0	0 c	0	0 c	0
107	0 c	0.4	2 c	2	0 c	0
214	5 c	2.3	0 c	0	0 c	0
428	10 c	7.6	5 c	2	18 b	8
857	54 b	8.7	1 c	1	47 a	3
1,714	96 a	0.6	–	–	–	–
3,427	95 a	1.0	–	–	–	–
6,854	100 a	0.0	–	–	–	–

[a] Means within columns followed by the same letter are significantly different at $p<0.05$ based on Tukey adjusted mean comparisons.

[b] Abbreviation: –, no data collected.

For analysis, the soil sample in each bag was allowed to thaw for approximately 30 min and was thoroughly homogenized by hand while still inside the plastic bag. Then, a 10-g subsample was transferred to a 50-ml polypropylene centrifuge tube (Thermo Fisher Scientific, Waltham, MA). Herbicide was extracted from the subsample by adding 1 ml of 100% acetonitrile (ACN) g^{-1} of soil and shaking for 1 h on a reciprocating shaker at 200 rpm. After shaking, the soil and extractant suspension was centrifuged at 5,000 rpm for 15 min. A 1-ml aliquot was taken from the supernatant of each sample.

The flumioxazin content in each aliquot was determined by high-performance liquid chromatography (HPLC). A Thermo Fisher Scientific HPLC system was used to analyze the samples. The analytical system consisted of a quaternary pump with low-pressure mixing, an automated sample injector capable of 1- to 100-µl injections, a thermally controlled column compartment, and a variable wavelength ultraviolet (UV) detector. Aliquots from the extraction were directly injected without concentrating, and the separation was accomplished using a C18 column (150 mm long and 3 µm diam fitted with a guard column; Thermo Fisher Scientific). The column temperature was 35 C. The mobile-phase for the analysis used an ACN and water mixture (all solvents were HPLC grade). Water was fortified with 50 mM ammonium formate (Sigma-Aldrich, St. Louis, MO). Flumioxazin was detected at a UV wavelength of 280 nm. The retention time for the flumioxazin was 5.9 min. A recovery test from fortified, untreated soil samples indicated that recovery was approximately 100% for flumioxazin (data not shown). The limit of detection for flumioxazin was approximately 1,000 parts billion^{-1} in soil.

Data Analysis

Data were analyzed in SAS, version 9.2 (SAS Institute Inc., Cary, NC) using the mixed procedure with block as the random factor. Data were checked for normality and constant variance before analysis. Means were separated using the least-squares means statement in SAS with the Tukey adjustment at $P = 0.05$. Data collected on multiple dates, such as strawberry damage percentages, were analyzed using the repeated statement.

Results and Discussion

Strawberry Injury and Berry Yields

In Trial 1, the first injury ratings (27 d after transplant [DAT], November 6, 2017) were highly variable and, as a result, were not significantly different (data not shown). This can likely be explained by the fact that many of the older leaves on the transplants began to senesce shortly after establishment, including in the nontreated controls. By 35 DAT (November 15, 2017), injury levels were significantly different between flumioxazin rates ($P < 0.0001$) (Table 2). Flumioxazin rates greater than 4× the label rate caused injury, whereas at the highest flumioxazin rate (64× the label rate), all plants were dead (Table 3). Mid-season plant biomass only decreased with application rates well above the label rates. Biomass at 2× and 4× rates was not different from the nontreated control. At the 8× rate, biomass was 37% less than the nontreated control; at the highest rates, there was zero biomass, because none of the plants survived.

In Trial 2, injury data were lost, unfortunately, due to technical errors. However, plant survival results were similar to those of Trial 1, with no differences in plant survival between the nontreated control and 16× the label rate. At 32× and 64× the label rate, 75% and 84% of the strawberry plants died, respectively.

In Trial 3, the interaction between the herbicide rate and the date of the injury rating was significant ($P = 0.0046$) for strawberry injury and, as a result, the strawberry injury data are presented for each date (Table 2). On November 6, 2018, none of the herbicides evaluated caused significant strawberry injury, but on November 29, 2018, rates above 214 g ha^{-1} (2× the label rate) caused significant injury. No differences in plant survival were noted (Table 3).

These results verify the safety of PRETR flumioxazin applications in strawberry at label rates for the 'Radiance' cultivar. Samtani et al. (2012) found less than 5% shoot damage with seven strawberry cultivars when flumioxazin was applied up to 210 g ha^{-1}, which is slightly less than double the label rate in Florida (Anonymous 2017). In our trials, no injury was observed with 214 g ha^{-1} flumioxazin at one site and 428 g ha^{-1} at the second site when applied PRETR (Table 3). Manning and Fennimore (2001) found that flumioxazin at 125 g ha^{-1} applied shortly after transplant to transplants with no foliage had variable damage, with up to 12% damage on 'Selva' and 46% damage on 'Camerosa' cultivars. Combined, these results suggest that post-transplant applications should not be recommended and, although strawberry cultivars may differ in susceptibility, PRETR applications up to 2× the labeled rate can be safely applied. Strawberries have also demonstrated a broader tolerance to Group 14 chemistry, with fomesafen and oxyfluorfen tolerance demonstrated elsewhere (Boyd and Reed 2016; Reed et al. 2018).

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Table 3. Effects of flumioxazin rate on strawberry shoot biomass and shoot death in field experiments conducted at the Gulf Coast Research and Education Center in Balm, FL, in 2017-2018 and 2018-2019 (Trial I and II respectively) and at Dover, Florida in 2018-2019 (Trial III).

	Biomass[a]		Dead strawberry[a]					
	Trial 1		Trial 1		Trial 2		Trial 3	
Flumioxazin rate	Mean	SE	Mean	SE	Mean	SE	Mean	SE
g ai ha^{-1}	g $plant^{-1}$		%					
0	38 a	8.0	9 c	6.2	23 bc	9.7	10	4.0
54	38 ab	3.3	3 c	3.6	16 bc	6.1	0	0
107	44 a	1.1	6 c	2.7	18 bc	6.3	8	3.9
214	47 a	8.9	15 c	7.5	12 c	2.8	5	2.1
428	36 ab	3.2	6 c	2.1	18 bc	2.5	4	2.0
857	24 bc	3.5	25 b	13.9	18 bc	10.9	6	3.3
1,714	12 cd	2.5	60 b	6.2	34 b	2.8	–	–
3,427	9 d	6.3	77 a	8.6	75 a	8.1	–	–
6,854	0 d	0.0	100 a	0.0	84 a	6.2	–	–
P value	<0.0001		<0.0001		<0.0001		0.1946	

[a]Means within columns followed by the same letter are significantly different at p<0.05 based on Tukey adjusted mean comparisons.
Abbreviation: –, no data collected.

Table 4. Effects of flumioxazin rate on berry yield adjusted to account only for living plants present in the plots at the Gulf Coast Research and Education Center in Balm, FL, in 2017–2018 and 2018–2019 (Trials 1 and 2, respectively) and at Dover, Florida in 2018-2019 (Trial 3).[a]

Flumioxazin rate	Trial 1	Trial 2	Trial 3
g ai ha^{-1}	kg ha^{-1}		
0	18,480 a	13,430 ab	10,140
54	19,620 a	12,800 ab	10,300
107	16,750 ab	13,830 ab	9,280
214	16,340 ab	14,520 a	10,280
428	17,650 a	10,460 bc	10,670
857	11,020 b	10,450 bc	8,180
1,714	2,160 c	8,150 cd	–
3,427	2,080 c	8,820 cd	–
6,854	0 c	5,16 d	–
P value	<0.0001	0.0004	0.5652

[a]Means within columns followed by the same letter are significantly different at P < 0.05 based on Tukey adjusted mean comparisons.
Abbreviation: –, no data collected.

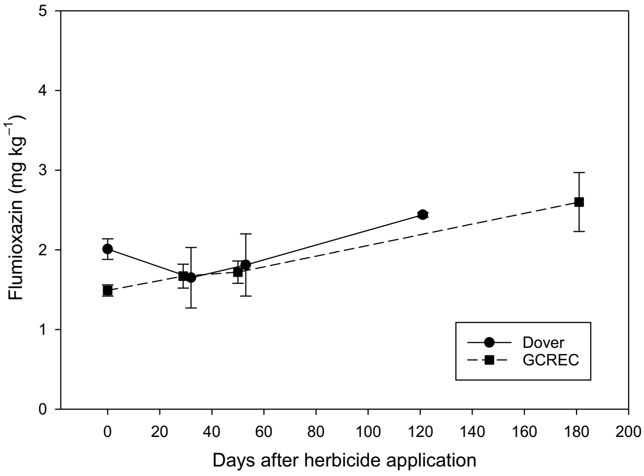

Figure 1. Persistence of flumioxazin in the soil under the plastic mulch in a strawberry crop over time when applied at 107 g ai ha^{-1} at the Gulf Coast Research and Education Center (GCREC) (Trial 2), and Dover (Trial 3) in 2018–2019.

Strawberry yields were affected by flumioxazin rate in Trials 1 and 2 but not Trial 3 (Table 4). In Trials 1 and 3, yields were unaffected by flumioxazin rates less than 857 g ha^{-1} (8× the label rate). Yields were lower at all other application rates in Trial 1. In Trial 2, similar results were observed, with no differences in yields after flumioxazin applications at rates lower than 1,714 g ha^{-1} (16× the label rate). Samtani et al. (2012) also reported that flumioxazin had no consistent effect on berry yields up to 210 g ha^{-1}. Our results clearly confirm strawberry tolerance to flumioxazin with no yield loss at rates as high as 8× and 16× the label rate. They also suggest it is possible for strawberry plants to recover from damage levels as high as 47% at 8× the label rate with no reduction in berry yield.

Flumioxazin Residue

Flumioxazin soil concentration was consistent over time (Figure 1). Flumioxazin half-life within a buffer solution (pH 7), linked to photolysis and hydrolysis, was 4.9 and 9.1 h, respectively (Kwon et al. 2004). However, black plastic mulch restricts much of the light penetration from reaching flumioxazin within plasticulture production (Lament 1993). Microbial degradation was estimated to be the dominant factor in flumioxazin persistence within Tifton and Greenville soils, where 99% of flumioxazin was recovered after 16 d in heat-treated soils (Ferrell and Vencill 2003). Those authors also found that flumioxazin mineralization was only 2% in both soils. Within the Florida strawberry plasticulture system, fumigation is a common and necessary practice for nematode control (Rosskopf et al. 2005; Zasada et al. 2010). It is possible that fumigation may reduce soil bacteria numbers and, consequently, restrict herbicide degradation. Flumioxazin persistence may also be partially explained by the low soil temperatures that occur during the winter months when Florida strawberry production occurs, versus the summer.

The demonstrated flumioxazin persistence within Florida strawberry production offers a promising solution for growers who struggle with broadleaf and grass weeds that emerge late in the growing season. Flumioxazin was still present within the bed at 120 to 180 DAA (Figure 1). This time frame corresponds to mid to late December (120 d) or mid to late February (180 d), which is either the beginning of strawberry harvest or the end of the season (Whitaker et al. 2019). This confirms that overhead irrigation did not remove flumioxazin from the bed, as was observed with fomesafen (Reed et al. 2018) and that flumioxazin is likely to persist throughout the entire season. Use of flumioxazin applied

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PRETR is a better weed management solution compared to POST applications of clopyralid, due to concerns about spray penetration, canopy shielding, and variable growth rates of target weeds, such as black medic (Sharpe and Boyd 2018b; Sharpe et al. 2018). Goosegrass was previously not controlled with the labeled flumioxazin dose (105 g ha^{-1}) applied through the drip irrigation (Anonymous 2017; Yu and Boyd 2017), but it was likely not a consequence of persistence within the bed but rather location within the soil profile and dilution after application with the drip irrigation. It is worth noting that grasses such as goosegrass and broadleaf weeds emerge primarily in the planting holes. The process of transplanting the strawberry crop or subsequent strawberry plant uptake could reduce flumioxazin availability and efficacy at the planting hole, but this requires additional study.

Flumioxazin applied at rates up to 4× the label rate did not injure strawberry plants, increase plant death, or reduce berry yields. Flumioxazin also persists throughout the production season and should provide season-long weed control. We conclude that flumioxazin is a safe herbicide for use under plastic mulch in plasticulture strawberry production in Florida and could be an important component of an integrated weed management program. The reported damage to 'Radiance' was not due to differential cultivar tolerance; field observations suggest it was most likely due to application error.

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References

Anonymous (2017) Chateau Herbicide SW Label. Walnut Creek, CA: Valent U.S.A. LLC

Boyd NS (2016) Pre- and post-emergence herbicides for row middle weed control in vegetable plasticulture production systems. Weed Technol 30:949–957

Boyd NS, Reed T (2016) Strawberry tolerance to bed-top and drip-applied preemergence herbicides. Weed Technol 30:492–498

Ferrell JA, Vencill WK (2003) Flumioxazin soil persistence and mineralization in laboratory experiments. J Agri Food Chem 51:4719–4721

Grey TL, Vencill WK, Mantripagada N, Culpepper AS (2007) Residual herbicide dissipation from soil covered with low-density polyethylene mulch or left bare. Weed Sci 55:638–643

Hanson B, Shrestha A (2006) Weed control with methyl bromide alternatives. CAB Rev: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources 1:1–13

Kwon JW, Armbrust KL, Grey TL (2004) Hydrolysis and photolysis of flumioxazin in aqueous buffer solutions. Pest Manag Sci 60:939–943

Lament WJ (1993) Plastic mulches for the production of vegetable crops. HortTechnology 3:35

Manning GR, Fennimore SA (2001) Evaluation of low-rate herbicides to supplement methyl bromide alternative fumigants to control weeds in strawberry. HortTechnology 11:603–609

Matringe M, Camadro JM, Labbe P, Scalla R (1989) Protoporphyrinogen oxidase as a molecular target for diphenyl ether herbicides. Biochem J 260: 231–235

Matringe M, Scalla R (1988) Studies on the mode of action of acifluorfen-methyl in nonchlorophyllous soybean cells. Plant Physiol 86:619–622

Mueller TC, Boswell BW, Mueller SS, Steckel LE (2014) Dissipation of fomesafen, saflufenacil, sulfentrazone, and flumioxazin from a Tennessee soil under field conditions. Weed Sci 62:664–671.

Ozone Secretariat (2020) The Montreal Protocol on substances that deplete the ozone layer. https://ozone.unep.org/treaties/montreal-protocol#nolink

Reed TV, Boyd NS, Wilson PC, Dittmar PJ, Sharpe SM (2018) Persistence and movement of fomesafen in Florida strawberry production. Weed Sci 66: 773–779

Rosskopf EN, Chellemi DO, Kokalis-Burelle N, Church GT (2005) Alternatives to methyl bromide: a Florida perspective. Plant Health Prog 6:19

Samtani JB, Weber JB, Fennimore SA (2012) Tolerance of strawberry cultivars to oxyfluorfen and flumioxazin herbicides. HortScience 47:848–851

Sandhu RK, Boyd NS, Sharpe S, Guan Z, Qiu Q, Luo T, Agehara S (2020) Management of relay-cropped strawberry and eggplant to maximize yield and economic return. HortScience 55:1083–1089

Sharpe SM, Boyd NS (2018a) Black medic (*Medicago lupulina*) emergence and emergence predictors within Florida strawberry fields. Weed Sci 67:253–260

Sharpe SM, Boyd NS (2018b) Black medic (*Medicago lupulina*) germination response to temperature and osmotic potential, and a novel growing degree-day accounting restriction for heat-limited germination. Weed Sci 67:246–252

Sharpe SM, Boyd NS, Dittmar PJ, MacDonald GE, Darnell RL, Ferrell JA (2018) Spray penetration into a strawberry canopy as affected by canopy structure, nozzle type, and application volume. Weed Technol 32:80–84

[USDA] U.S. Department of Agriculture, National Agricultural Statistics Service (2020) Quick stats. https://quickstats.nass.usda.gov/results/4ACCBD1C-FCD2-3C8E-BD74-FF0DAD7D373E. Accessed: April 24, 2020

Walker A (1976) Simulation of herbicide persistence in soil. I. Simazine and prometryne. Pestic Sci 7:41–49

Walker A, Barnes A (1981) Simulation of herbicide persistence in soil; a revised computer model. Pestic Sci 12:123–132

Whitaker VM, Boyd NS, Peres NA, Desaeger J, Noling JW, Lahiri S (2019) Strawberry production. Pages 311–332 in Dittmar P, Freeman J, Matthews P, Smith H, eds. Vegetable Production Handbook of Florida 2019-2020. Gainesville, FL: University of Florida

Whitaker VM, Chandler CK, Peres N, Cecilia M, Nunes N, Florida S, Avenue EF, Pierce F, Sims CA (2015) Sensation TM ' Florida127 ' Strawberry. HortScience 50:1088–1091

Yu J, Boyd NS (2017) Weed control with and strawberry tolerance to herbicides applied through drip irrigation. Weed Technol 31:870–876

Zasada IA, Halbrendt JM, Kokalis-Burelle N, LaMondia J, McKenry MV, Noling JW (2010) Managing nematodes without methyl bromide. Annu Rev Phytopathol 48:311–328

https://doi.org/10.1017/wet.2020.115 Published online by Cambridge University Press