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Tree Nut Crop Response to Simulated Florpyrauxifen-benzyl and Triclopyr Herbicide Drift

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Keywords. almond, herbicide symptomology, multiple exposures, off-target movement, pistachio, walnut

Abstract. **California is the nation's primary producer of almonds, pistachios, and walnuts, and an important producer of rice. Because of California's diverse cropping systems, off-target herbicide drift can be a considerable problem, particularly from aerial applications that are commonly used in flooded rice production systems. Triclopyr is an auxin-mimic type herbicide that has been commonly used in rice for many years for control of broadleaf weeds and the industry is familiar with symptoms of off-target triclopyr drift. Florpyrauxifen-benzyl is a newly registered auxin-mimic herbicide in California rice with activity on key weeds and is being rapidly adopted. Although symptoms typically are similar among auxinic herbicides, it is important to understand subtle differences and risks among these herbicides as stewardship for newly registered products. This research was conducted in 2020 and 2021 to determine the relative sensitivity of almond, pistachio, and walnut trees to simulated drift rates of florpyrauxifen-benzyl and triclopyr as well as characterize and compare symptoms caused by these two herbicides. The fractional herbicide rates tested were 1/200X, 1/100X, 1/33X, and 1/10X of the florpyrauxifen-benzyl use rate of 29.4 g·ha^{-1} a.i. and 1/200X, 1/100X, and 1/33X of the triclopyr use rate of 420.3 g·ha^{-1} a.e. Florpyrauxifen-benzyl and triclopyr herbicides were applied directly to one side of the canopy of 1- to 2-year-old almond, pistachio, and walnut trees. The general symptoms of florpyrauxifen-benzyl and triclopyr were chlorosis, chlorotic spots, leaf curling, leaf narrowing, leaf distortion, leaf malformation, leaf crinkling, shoot curling, stem coloring, stunting, terminal bud death, and twisting. The florpyrauxifen-benzyl and triclopyr injury symptoms were compared at the same fractional rates and found to be similar to each other. The herbicide injury was observed on the entire pistachio canopy, particularly on developing leaves and terminal buds. In contrast, injury symptoms on almond and walnut were more apparent on the side of the canopy to which the herbicides were applied. Symptom severity peaked at 14 days after treatment with the 1/10X florpyrauxifen-benzyl rate, when the visible injury was 16%, 48%, and 78% on almond, walnut, and pistachio, respectively. Although almond and walnut symptoms from the 1/10X florpyrauxifen-benzyl rate remained visible longer than all other treatments, all trees gradually recovered throughout the growing season. In contrast, pistachio trees did not recover fully and had injury symptoms that persisted for the remainder of the treatment year and at leaf-out the following spring. When drift occurs, it is typically at rates below 1/100X up to 1/33X of herbicide use rates. This research suggested that proper herbicide drift management practices and application precautions are likely to minimize the risk of significant injury from florpyrauxifen-benzyl drift to almond and walnut because of low injury symptoms at the typical drift rates. However, extra precautions may be needed if there are nearby pistachio orchards.**

California is the major producer of almonds [*Prunus dulcis* (Mill.) D.A. Webb], pistachios (*Pistacia vera* L.), and walnuts (*Juglans regia* L.) in the United States, where they are grown on 1M hectares (ha) in the Sacramento and San Joaquin Valleys and added more than $11.5B to the US economy in 2021 [US Department of Agriculture-National Agricultural Statistics Service (USDA-NASS) 2024]. Tree nuts are mostly produced in the Sacramento and San Joaquin Valleys and among these crops, almond is particularly important and accounts for 85% of the global production and $4.6B in export value in California [California Department of Food and Agriculture (CDFA) 2024].

The Sacramento Valley is also the second-largest rice (*Oryza sativa* L.) production region in the United States with more than 200,000 ha (Galvin et al. 2022) and a farmgate value of nearly $1B (CDFA 2024). California rice systems benefit from a Mediterranean climate with high solar radiation and relatively cool nighttime temperatures, which helps lead to 20% higher rice yields than the average of all other rice-producing regions in the United States (Hill et al. 2006). Approximately 97% of California rice fields are water-seeded, where pregerminated rice seeds are aerially spread onto fields with 10 to 15 cm standing water, and the fields are continuously flooded throughout the growing season (Hill et al. 2006; Inci and Al-Khatib 2024). This unique water-seeded and continuously flooding growing practice was adopted to suppress weedy grasses (Kennedy 1923). In the diverse cropping systems of the Sacramento Valley, rice is often grown in close proximity to almond, pistachio, and walnut orchards.

Weeds are a major problem in California rice production (Brim-DeForest et al. 2017). Weed competition may reduce yield by 90% in water-seeded rice systems (Brim-DeForest et al. 2017; Hill et al. 2006) if weeds are left uncontrolled. Alongside cultural management methods such as using certified weed-free seed, land leveling to maintain uniform water depth, and water depth management, herbicides are critical components of rice weed management [University of California Agriculture and Natural Resources (UCANR) 2023]. Water-seeded rice cropping systems in California highly favor aerial applications of herbicides (Espino et al. 2024), where off-target rice herbicide drift is a growing concern for tree nut crops (Galla et al. 2019). Most California rice weed management programs rely on herbicides applied at the day-of-seeding or within up to two-leaf-rice growth stage and followed by at least one application of post-emergence herbicides later in the growing season (Hill et al. 2006), generally from May to mid-July (UCANR 2023).

At this time, almond trees are actively growing from terminal and lateral buds, spurs, and shoots are emerging, and photosynthates are translocating from leaves to kernels (Micke 1996). Likewise, pistachios are vigorously growing from shoots and buds, when apical and terminal buds are developing about from late May to early July (Ferguson and Haviland 2016). Similarly, walnuts are initiating and differentiating buds, developing leaves, hull, and the shell size are increasing between late May and early July as well as accumulation of assimilates and proteins in kernels are developing (Galla et al. 2018a, 2018b, 2019; Ramos 1998). Because a substantial portion of rice herbicide applications in California coincide with vigorous and susceptible growth stages of almond, pistachio, and walnut, there is significant risk of tree crop injury from rice herbicide exposure.

During the herbicide application process, high wind speed, low relative humidity, high air temperature, and small droplet size may result in the physical movement of herbicides to off-target areas [UC Integrated Pest Management (UCIPM) 2016]. Under most herbicide application circumstances, non-target plant

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exposure to off-target herbicide drift is low with actual rates estimated from below 1/100X up to 1/33X of the field use rates (Al-Khatib and Peterson 1999; Al-Khatib et al. 2003). However, even at these low exposure levels, herbicide can injure or kill highly sensitive plants depending on the species, herbicide, actual rate, and growth stage (Egan et al. 2014). Therefore, concerns over the exposure of herbicides to off-target crops by either drift or accidental direct application are common among growers, crop consultants, and researchers in the diverse cropping systems of California's Sacramento Valley (UCANR 2023).

Florpyrauxifen-benzyl [benzyl 4-amino-3-chloro-6-(4-chloro-2-fluoro-3-methoxyphenyl)-5-fluoropyridine-2-carboxylate; CAS: 1390661-72-9] is a new synthetic auxin (HRAC/WSSA Group IV) herbicide with a novel site of action for selective post-emergence grass, sedge, and broadleaf weed control in rice. The 6-aryl-picolinate auxin herbicides such as florpyrauxifen-benzyl have a carboxylic acid functional group, which allow them to pass through the lipophilic walls of the phloem, be concentrated, and translocated (Epp et al. 2016). Moreover, the carboxylic acid functional group of florpyrauxifen-benzyl involves a key binding interaction at the site of action and mimics indole-3-acetic acid (IAA) to fill between the receptor and the corepressor proteins in the cell nucleus (Grossmann 2010).

Triclopyr [2-(3,5,6-trichloropyridin-2-yl) oxyacetic acid; CAS: 55335-06-3] is another auxin herbicide widely used to control sedges and broadleaf weeds in rice fields. Triclopyr is a pyridyloxy-carboxylate auxin-type herbicide available as in triethylamine salt and butoxyethyl ester formulations. Similar to other synthetic auxins, triclopyr interacts with the auxin receptor complex and binds to Aux/IAA proteins. Inherently, synthetic auxins are much more stable than natural auxins in plants (Epp et al. 2016) and show a strong auxin effect in susceptible plants, stimulating plant cell elongation even at a concentration as low as 1 μM (Taiz et al. 2022). Synthetic auxins have been used as herbicides to manage dicotyledonous weeds for more than 80 years (Grossmann 2010; Peterson et al. 2016). In susceptible plants, synthetic auxins can deregulate normal patterns of growth through distorted cell division and expansion. This abnormal growth can lead to leaf epinasty, tissue swelling, stem curling, chloroplast damage, membrane and vascular system damage, wilting, and necrosis, which can ultimately cause plant death (Grossmann 2010).

Synthetic auxins can be active and cause visible injury symptoms on sensitive broadleaf plants at very low exposure levels. Particularly with the commercialization of auxin-tolerant broadleaf crops, off-target injuries from auxin-mimic herbicides have been widely reported across the United States in recent years on vegetables, fruit and nut trees, field and forage crops, ornamentals, and vines (Egan et al. 2014; Haring et al. 2022; Warmund et al. 2022; Wells et al. 2019). A new auxin-type herbicide, florpyrauxifen-benzyl, was recently registered for use in rice. Given the importance of tree nuts in the Sacramento Valley where rice is widely grown, it is important to elucidate relative sensitivity of tree nuts to florpyrauxifen-benzyl simulated drift and compare the florpyrauxifen-benzyl injury symptoms with triclopyr injury symptoms, which have been widely used in California rice for many years. Therefore, the overall objective of this research was to characterize the symptoms of florpyrauxifen-benzyl at simulated drift rates on young almond, pistachio, and walnut trees and evaluate growth responses to florpyrauxifen-benzyl. We also evaluated almond, pistachio, and walnut responses, including herbicide symptomology and growth response to triclopyr simulated drift rates for comparison purposes.

Materials and Methods

Study sites. Four simulated off-target drift experiments were conducted in 2020 and 2021 in newly planted almond (lat. 38°32′18.8″N, long. 121°47′40.3″W), pistachio (lat. 38°32′19.5″N, long. 121°47′37.5″W), and walnut (lat. 38°32′19.6″N, long. 121°47′38.9″W) orchards (elevation 18 m) in UC Davis Plant Sciences Field Facility Orchards near Davis, CA, USA; and in an established walnut (lat. 38°30′27.4″N, long. 121°58′17.2″W, elevation 44 m) orchard at the UC Davis Wolfskill Experimental Orchard near Winters, CA, USA. The Davis orchards were established in Mar 2020 with 'Nonpareil' almond scion on 'Empyrean 1' rootstock, 'Kerman' pistachio scion on 'UCB 1 rootstock', and 'Chandler' walnut scion on 'clonal RX1' rootstock. Almonds and walnuts were planted with 6 m intrarow spacing and 4.2 m between rows, and pistachios were planted with 6 m intrarow spacing and 7 m between rows in Davis. The Winters orchard was established in Feb 2018 with 'Chandler' walnut scion on 'clonal Vlach' rootstock, with trees planted 5.4 m apart within the row and with 5.1 m between rows. At the time of the first application, all trees were 1 to 1.5 m tall in Davis orchards and walnut trees were 3 to 3.5 m tall in Winters orchard.

The soil was classified as Yolo silt loam with NO_3-N: 56 ppm, Olsen-P: 25 ppm, K: 348 ppm, Na: 15 ppm, Ca: 8 meq/100 g, Mg: 10 meq/100 g, CEC: 19 meq/100 g, organic matter (OM): 2.7%, and pH: 6.7 in the Davis orchards, and as Yolo silt loam with NO_3-N: 38 ppm, Olsen-P: 44 ppm, K: 447 ppm, Na: 29 ppm, Ca: 9 meq/100 g, Mg: 10 meq/100 g, CEC: 21 meq/100 g, OM: 2.7%, and pH: 7.3 in the Winters orchard. All trees were maintained free of diseases and insects as recommended by the UCIPM Guidelines (Ferguson and Haviland 2016; Strand 2002, 2003). In all experiments, weeds between rows were regularly mowed, and the intrarow strip was treated with a tank mix of rimsulfuron at 70 $g{\cdot}ha^{-1}$ a.i., indaziflam at 50 $g{\cdot}ha^{-1}$ a.i., oxyfluorfen at 560 $g{\cdot}ha^{-1}$ a.i., and glufosinate-ammonium at 450 $g{\cdot}ha^{-1}$ a.i. plus manufacturer recommended surfactants.

Herbicide applications. Florpyrauxifen-benzyl [Loyant® CA, 25 $g{\cdot}L^{-1}$ a.i., Corteva Agriscience, Indianapolis, IN, USA] and triclopyr [Grandstand™ CA, 359 $g{\cdot}L^{-1}$ acid equivalent (a.e.), Corteva Agriscience, Indianapolis, IN, USA] were applied on 9 Jun 2020 in the Davis orchards and on 18 Jun 2020 in the Winters orchard during calm weather conditions to avoid off-target movement to nearby trees. In all experiments, florpyrauxifen-benzyl was applied at four rates resembling a plausible drift rate of 1/200X (0.5% drift), 1/100X (1% drift), 1/33X (3% drift), and 1/10X (10% drift) of the use rate of 29.4 $g{\cdot}ha^{-1}$ a.i. (Galla et al. 2019). Due to the limited number of available trees, triclopyr was applied at only at three fractional rates of 1/200X, 1/100X, and 1/33X of the use rate of 420.3 $g{\cdot}ha^{-1}$ a.e. (Al-Khatib et al. 1992a). An untreated tree between treated plots was included as a buffer to reduce herbicide contamination in 2020. Four untreated check (UTC) plots also were included for comparison. Florpyrauxifen-benzyl spray mixtures included methylated seed oil (Super Spread MSO, Wilbur-Ellis, Fresno, CA, USA) at 584 $mL{\cdot}ha^{-1}$, and triclopyr spray mixtures included crop oil concentrate (MOR-ACT, Wilbur-Ellis, Fresno, CA, USA) at 1% v/v rate.

All herbicide treatments were applied to one side of the tree canopy as a single pass from top to bottom with a handheld, carbon dioxide-propelled backpack sprayer calibrated to deliver 187 $L{\cdot}ha^{-1}$ at 206 kPa pressure through AIXR8004 nozzle tip (TeeJet Technologies, Wheaton, IL, USA). The sprayer boom had two nozzle tips spaced 50 cm apart, and the spray treatments were calibrated based on a 3-second pass from top to bottom per tree. Environmental conditions at the time of application were 16 °C air temperature (temp), 58% relative humidity (RH), and 0.4 $m{\cdot}s^{-1}$ wind speed on 9 Jun 2020 in Davis; and 14 °C air temp, 65% RH, and 0.6 $m{\cdot}s^{-1}$ wind speed on 18 Jun 2020 in Winters. No in-season auxin-type herbicides were used to avoid the potential confusion with florpyrauxifen-benzyl and triclopyr drift symptoms on crops. Irrigation was made through a single-line drip irrigation system with surface emitters spaced every 30 cm in Davis and with microsprinklers in Winters during the growing seasons.

Studies were repeated on 31 May 2021 using the almond, pistachio, and walnut trees that were buffer trees during the 2020 experiments (1-year exposure study, where $n = 8$). In addition, the trees that were treated with florpyrauxifen-benzyl and triclopyr in 2020 were also retreated in 2021 with the same treatments as in the previous year's protocols to distinguish trees' 2-year exposure response (2-year exposure study, where $n = 4$) from 1-year exposure response (Bhatti et al. 1995). However, due to unavailability of trees, 2-year exposure treatments were not repeated during the 2022 growing season. The methodology for the 2-year exposure study was the same as previously described for the 1-year exposure study. Environmental conditions at the time of second-year application were 18 °C air temp, 50% RH, and 0.6 $m{\cdot}s^{-1}$

wind speed in Davis and 20 °C air temp, 50% RH, and 0.6 $m \cdot s^{-1}$ wind speed in Winters.

Data collection and experimental design. Experiments were conducted using a randomized complete block design with four replicates, where an individual tree was an experimental unit. Trees were observed for visible symptoms at 6, 12, 24, 48, and 72 h after herbicide treatment as well as 7, 14, 21, 28, 35, 42, and 90 d after treatment (DAT). Symptomology descriptions of the treated foliage were made according to the UCIPM Herbicide Symptoms guideline (UCIPM Herbicide Symptoms 2024). Injury was rated on a scale where 0 = no injury and 100 = death (Al-Khatib et al. 1992a; Bhatti et al. 1995) according to the following scale:

- 0% = Normal size growth; green pigmentation of all leaves; and identical appearance to UTC trees.
- 1%–4% = Normal-sized leaves; fewer than 5% of the leaves have only one discernible chlorotic spot, and the canopy has an overall appearance of faint but indistinct symptoms.
- 5%–9% = Slight reduction in leaf size; 2 to 5 diffuse chlorotic spots clearly visible on 5% to 10% of the leaves; adjacent chlorotic spots coalesce and result in puckering, usually at the leaf margin or interveinal areas; up to 5% of leaf curling and crinkling of only young leaves.
- 10%–29% = Reduction in leaf size up to 5%; growth restriction and chlorosis in interveinal tissues; symptoms moderate to severe on 10% to 30% of the leaves; less than 30% of the leaf surface chlorotic; from 5% to 10% necrosis, leaf curling, and crinkling of mostly young leaves; adjacent chlorotic areas merge and result in necrosis, usually at the interveinal areas; and shoot and stem curling up to 5% of the canopy.
- 30%–49% = Reduction in leaf size from 5% to 10%; shoot tip growth restricted; symptoms severe on 30% to 50% of the leaves; up to 50% of the leaves with chlorosis; from 10% to 25% necrosis, leaf curling, and crinkling; adjacent necrotic areas coalesce and result in holes, usually at the interveinal areas; and moderate to severe curling of shoots and stems from 5% to 10% of the canopy.
- 50%–69% = Reduction in leaf size from 10% to 25%; growth significantly restricted; symptoms very severe on 50% to 70% of the leaves; up to 70% of leaf surface chlorotic; from 25% to 50% necrosis, leaf curling, and crinkling; up to 10% stunting and irregular growth at the overall canopy; interveinal tissue-restricted and containing little green pigment; noticeable stem discoloring with dark red-brown spots up to 15% of the young branches; and terminal bud twisting and death.
- 70%–89% = Reduction in leaf size from 25% to 50%; growth severely restricted; symptoms very severe on 70% to 90% of the leaves; up to 90% of leaf surface chlorotic; from 50% to 75% necrosis, leaf curling, and crinkling; distinguishable leaf loss; from 10% to 50% stunting at the overall canopy; interveinal tissue-restricted and containing little green pigment; severe leaf distortion and malformation; very obvious stem discoloring with dark red-brown-black spots up to 50% of the young and old branches; and terminal bud malformation and death.
- 90%–99% = Almost no development of leaf and interveinal tissues; symptoms extremely severe on all the leaves; leaves 100% chlorotic; severe leaf curling, narrowing, distortion, malformation, and crinkling; necrosis at leaf margins and shoot tips dead; more than 50% of stunting overall; and extremely damaged appearance.
- 100% = Plant dead.

Florpyrauxifen-benzyl and triclopyr-treated sides of canopies from almond, pistachio, and walnut trees were compared with UTC trees at each observation time. Photos of trees were taken from the treated side of the canopy throughout the growing season to ensure consistency in evaluations. Furthermore, four randomly selected branches from the herbicide-treated side of each tree were measured to determine shoot growth. The number of nodes on the shoots were counted from the terminal buds through trunks before the simulated drift treatments and at 90 DAT. The number of nodes on the selected shoots on treated trees were compared with similar shoots on the UTC trees. In addition, tree trunks were marked and diameters were measured using a digital caliper with ± 25 μm accuracy (Fisherbrand™ Traceable™ Digital Calipers #06 to 664-16, Fisher Scientific, Waltham, MA, USA) at ~25 cm aboveground before the spring growth started in April (spring-data) and at the end of the summer (fall-data) ~140 DAT (Al-Khatib et al. 1992a; Gülci et al. 2023). Tree growth was expressed through trunk diameter change as a percent increase based on the following equation:

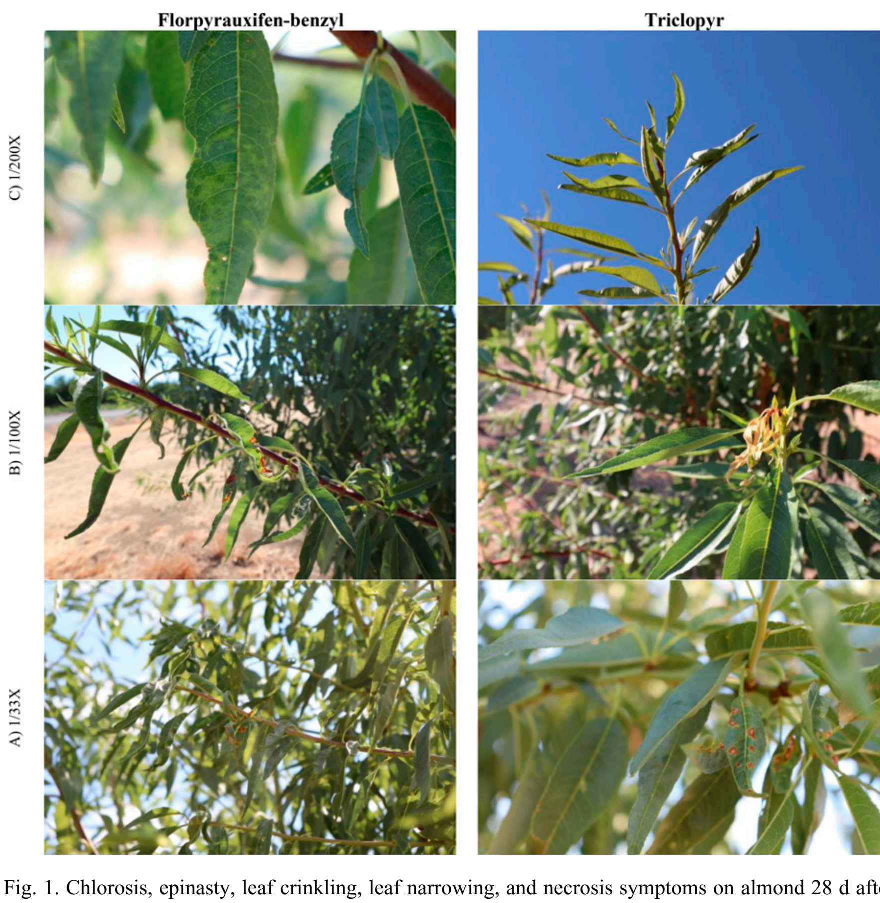

Fig. 1. Chlorosis, epinasty, leaf crinkling, leaf narrowing, and necrosis symptoms on almond 28 d after treatment with florpyrauxifen-benzyl and triclopyr at 1/200X, 1/100X, and 1/33X simulated drift rates. Florpyrauxifen-benzyl and triclopyr rice use rates are 29.4 $g \cdot ha^{-1}$ a.i. and 420.3 $g \cdot ha^{-1}$ a.e., respectively. Photos were taken on 28 Jun 2021, in the 2-year exposure study.

Table 1. Almond injury following simulated drift rates of florpyrauxifen-benzyl and triclopyr in 2020 and 2021.

Herbicide	Rate[ii]	One-yr exposure[i] 14 DAT[iii]	One-yr exposure 28 DAT	One-yr exposure 42 DAT	Two-yr exposure 14 DAT	Two-yr exposure 28 DAT	Two-yr exposure 42 DAT
		Visible injury (%)					
FPB	1/200X	1 a[iv]	2 b	1 a	1 b	3 b	2 b
FPB	1/100X	2 a	2 b	1 a	4 b	3 b	2 b
FPB	1/33X	2 a	4 b	2 a	4 b	7 b	2 b
FPB	1/10X	7 a	12 a	8 a	16 a	15 a	11 a
TRC	1/200X	1 a	3 b	1 a	1 b	3 b	1 b
TRC	1/100X	2 a	3 b	1 a	1 b	4 b	1 b
TRC	1/33X	2 a	3 b	1 a	4 b	3 b	2 b

[i] One-year exposure: Trees were treated in 2020 and the study was repeated on different trees in 2021, where sample size n = 8. Two-year exposure: The trees which were treated in 2020 were retreated in 2021, where sample size n = 4.

[ii] Florpyrauxifen-benzyl rate is expressed as a fraction of the rice use rate, 29.4 g·ha^{-1} a.i. Triclopyr rate is expressed as a fraction of the rice use rate of 420.3 g·ha^{-1} a.e.

[iii] DAT = days after treatment; FPB = florpyrauxifen-benzyl; TRC = triclopyr.

[iv] Means within a column not followed by the same letter are significantly different at $P \leq 0.05$ using Tukey's honestly significant difference test.

$$Y = \left[\left(\frac{X_f}{X_s}\right) - 1\right] \times 100,$$

where Y is the percent increase of trunk diameter, X_f = trunk diameter at the fall measurement, X_s = trunk diameter at the spring measurement. The relative change in herbicide treated tree trunk diameter was compared with UTC tree trunk diameter change.

Statistical analysis. Visual injury, number of nodes, and trunk diameter data for all trees were subjected to analysis of variance using 'agricolae', 'emmeans', and 'lme4' packages in RStudio Version 2024.04.2 + 764 (R Core Team 2024), and Tukey's honestly significant difference were used in the 'multcomp' package for means separation at α = 0.05, when applicable. Treatment by exposure interactions were analyzed and presented separately due to the different sample numbers (1-year exposure study n = 8 and 2-year exposure study n = 4). The herbicide and fractional drift rates were considered fixed factors, and year, block, and replication were considered random factors. The injury data for the walnut trees from the Davis and Winters orchards were combined because there was no significant interaction between site and treatment.

Results and Discussion

Because of no significant interactions occurred between year and treatment for the 1-year exposure study, the visible injury ratings data for the 2020 and 2021 were combined (n = 8). In general, florpyrauxifen-benzyl and triclopyr injury symptoms were apparent on all treated trees, and symptoms increased as herbicide rates increased. The initial florpyrauxifen-benzyl and triclopyr symptoms were observed similar on almond, pistachio, and walnut. However, the symptoms were more severe on pistachio compared with almond and walnut. In addition, the time required to develop symptoms was shorter with pistachio than with almond and walnut at all simulated drift rates.

Visible injury symptoms in both the 1-year exposure (n = 8) and 2-year exposure (n = 4) studies were observed at 7 DAT for almond, and generally peaked at 14 DAT (Fig. 1). Injury symptoms on almond were more noticeable on the treated side of the tree. However, slight injury symptoms were also observed on developing leaves on the nontreated side of the canopy. In addition, developing leaves and shoots showed more injury symptoms at all rates compared with developed leaves and shoots. Herbicide injury symptoms on almond from both herbicides were chlorosis, chlorotic spot, epinasty, leaf narrowing, leaf crinkling, necrosis, necrotic spots, shoot curling, terminal bud death, and twisting (Fig. 1). The initial chlorosis symptoms turned to necrosis within 7 to 14 d and eventually to necrotic spots. At the 1/10X florpyrauxifen-benzyl rate some necrotic spots turned to holes on the leaf surfaces. Leaf curling, necrosis, and necrotic spots were characteristic on almonds for both herbicides at higher rates. The 1/10X florpyrauxifen-benzyl drift caused the most severe symptoms on almond. Two-year treated almonds showed slightly more necrotic spots and leaf curling. However, even at this high simulated drift rate, these trees recovered from the initial injury symptoms and appeared normal at 90 DAT.

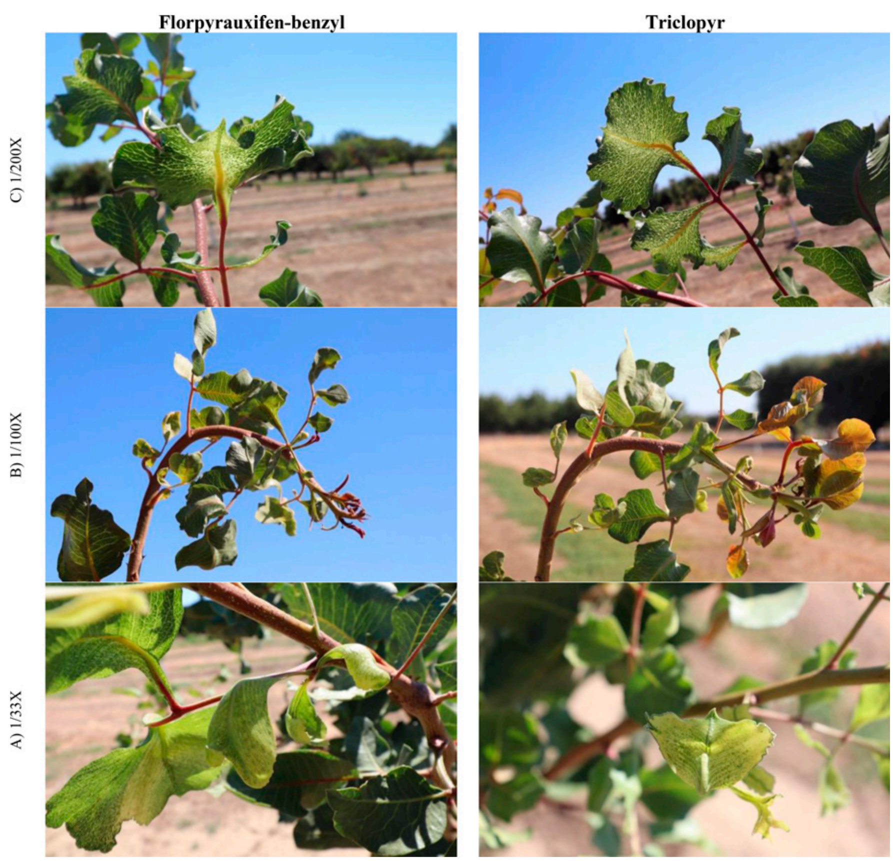

Fig. 2. Chlorosis, epinasty, leaf crinkling, leaf narrowing, shoot curling, and twisting symptoms on pistachio 28 d after treatment with florpyrauxifen-benzyl and triclopyr at 1/200X, 1/100X, and 1/33X simulated drift rates. Florpyrauxifen-benzyl and triclopyr rice use rates are 29.4 g·ha^{-1} a.i. and 420.3 g·ha^{-1} a.e., respectively. Photos were taken on 28 Jun 2021, in the 2-year exposure study.

Table 2. Pistachio injury following simulated drift rates of florpyrauxifen-benzyl and triclopyr in 2020 and 2021.

Herbicide	Rate[ii]	One-yr exposure[i]			Two-yr exposure		
		14 DAT[iii]	28 DAT	42 DAT	14 DAT	28 DAT	42 DAT
		Visible injury (%)					
FPB	1/200X	8 bc[iv]	8 b	10 b	19 b	20 bc	21 b
FPB	1/100X	13 bc	25 ab	23 ab	22 b	22 bc	29 b
FPB	1/33X	38 ab	38 ab	36 ab	55 a	36 b	34 b
FPB	1/10X	52 a	56 a	48 a	79 a	71 a	69 a
TRC	1/200X	3 c	5 b	10 b	3 b	6 c	8 b
TRC	1/100X	5 bc	8 b	10 b	9 b	10 c	12 b
TRC	1/33X	10 bc	10 b	20 ab	14 b	12 c	16 b

[i] One-year exposure: Trees were treated in 2020 and the study was repeated on different trees in 2021, where sample size n = 8. Two-year exposure: The trees which were treated in 2020 were retreated in 2021, where sample size n = 4.

[ii] Florpyrauxifen-benzyl rate is expressed as a fraction of the rice use rate, 29.4 $g \cdot ha^{-1}$ a.i. Triclopyr rate is expressed as a fraction of the rice use rate of 420.3 $g \cdot ha^{-1}$ a.e.

[iii] DAT = days after treatment; FPB = florpyrauxifen-benzyl; TRC = triclopyr.

[iv] Means within a column not followed by the same letter are significantly different at $P \leq 0.05$ using Tukey's honestly significant difference test.

Florpyrauxifen-benzyl visible injury on almonds in the 1-year exposure study (n = 8) was less than 8% at all rates at 14 DAT (Table 1). Similarly, triclopyr visible injury on almond was less than 3% at all rates at 14 DAT. The injury symptoms on almonds were visible through 42 DAT and florpyrauxifen-benzyl visible injury was less than 9% at all rates. Similarly, triclopyr visible injury was less than 2% at all rates 42 DAT. These results suggest that almond recovery from 1-year exposure of both herbicides was rapid with the exception of 1/10X florpyrauxifen-benzyl rate, which still had 8% injury 42 DAT. Florpyrauxifen-benzyl and triclopyr injury symptoms on almonds from the 2-year exposure study (n = 4) were similar to 1-year exposure study (n = 8) symptoms (Table 1). The greatest herbicide injury on almonds was 16% at 1/10X florpyrauxifen-benzyl rate 14 DAT, which gradually decreased throughout the growing season. Except florpyrauxifen-benzyl at 1/10X rate, all florpyrauxifen-benzyl and triclopyr visible injury ratings from 2-year exposure study were less than 3% at 42 DAT and statistically similar to one another.

Florpyrauxifen-benzyl and triclopyr injury symptoms on pistachios in both 1- and 2-year exposure studies were observed at 3 DAT, and generally peaked at from 14 through 28 DAT (Table 2). The injury was distinguishable at the entire pistachio canopy, but most notable on developing leaves and terminal buds. Injury symptoms on pistachio from both herbicides were similar to the injury symptoms on almond and initially appeared as chlorosis and leaf curling (Fig. 2). Florpyrauxifen-benzyl and triclopyr at 1/33X and higher rates resulted in some maroon-brown lesions on stems and stunting on pistachio (Fig. 2). By 14 DAT, leaf epinasty became more apparent and leaf epinasty symptoms became more severe through 42 DAT (data not shown). Stems developed dark color lesion spots on new branches and these lesions persisted throughout the growing season in trees treated with the 1/10X florpyrauxifen-benzyl rate (Fig. 2). The highest herbicide injury on pistachio was observed with florpyrauxifen-benzyl at 1/10X rate treatment as 56% injury at 28 DAT in the 1-year exposure study, whereas 2-year exposure study resulted in 79% injury with 1/10X florpyrauxifen-benzyl treatment at 14 DAT. Shoot curling, stem coloring, stunting, and twisting symptoms on pistachio were more apparent at higher rates of both florpyrauxifen-benzyl and triclopyr. Herbicide injury symptoms on pistachio gradually decreased, although injury symptoms from the 1/10X florpyrauxifen-benzyl treatment remained throughout the same growing season and were still present at leaf-out the following season (data not shown). In the following spring observations, stunting was the only symptom that remained from the 1/10X florpyrauxifen-benzyl drift treatments. In all other treatments, both florpyrauxifen-benzyl- and triclopyr-treated pistachio trees appeared normal at leaf-out in the following spring.

Florpyrauxifen-benzyl and triclopyr injury symptoms on walnut were initially observed at 7 DAT and generally peaked at 14 DAT (Table 3). Florpyrauxifen-benzyl at the 1/10X rate caused 45% and 49% injury on treated walnut trees at 14 DAT in the 1- and 2-year

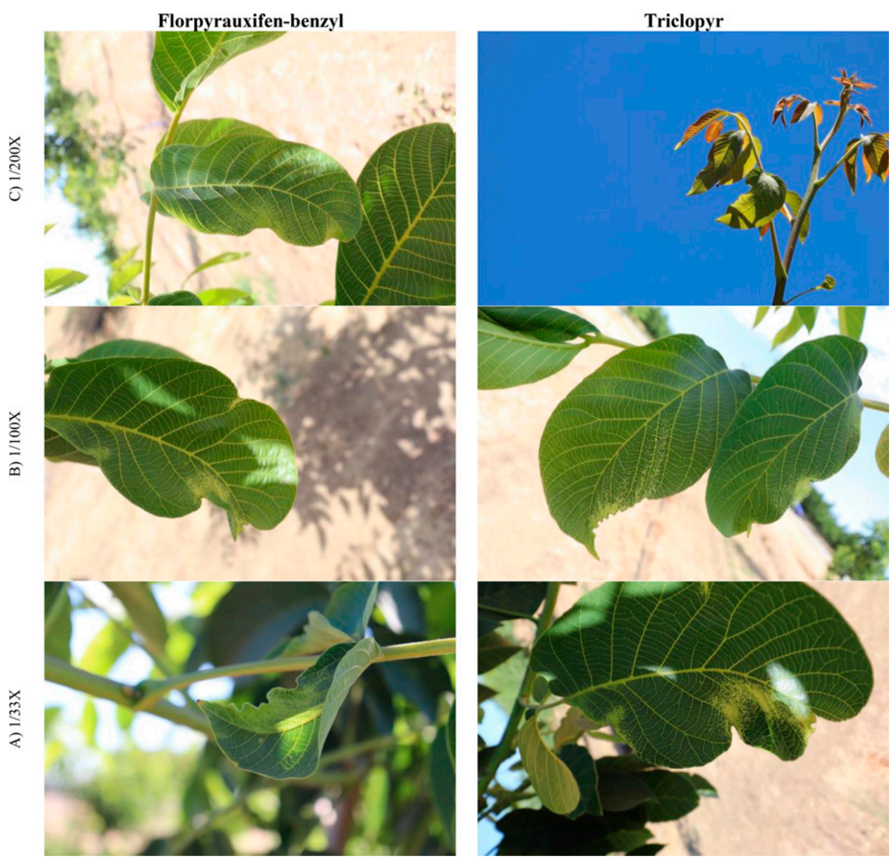

Fig. 3. Chlorosis, epinasty, leaf crinkling, leaf narrowing, and twisting symptoms on walnut 28 d after treatment with florpyrauxifen-benzyl and triclopyr at 1/200X, 1/100X, and 1/33X simulated drift rates. Florpyrauxifen-benzyl and triclopyr rice use rates are 29.4 $g \cdot ha^{-1}$ a.i. and 420.3 $g \cdot ha^{-1}$ a.e., respectively. Photos were taken on 28 Jun 2021, in the 2-year exposure study.

Table 3. Walnut injury following simulated drift rates of florpyrauxifen-benzyl and triclopyr in 2020 and 2021.

Herbicide	Rate[ii]	One-yr exposure[i] 14 DAT[iii]	28 DAT	42 DAT	Two-yr exposure 14 DAT	28 DAT	42 DAT
		Visible injury (%)					
FPB	1/200X	10 ab[iv]	22 a	5 a	7 b	22 ab	5 a
FPB	1/100X	12 ab	27 a	6 a	15 b	27 ab	5 a
FPB	1/33X	18 ab	30 a	7 a	21 b	29 ab	6 a
FPB	1/10X	45 a	40 a	8 a	49 a	46 a	10 a
TRC	1/200X	6 b	11 a	5 a	7 b	14 b	5 a
TRC	1/100X	8 ab	13 a	5 a	10 b	14 b	6 a
TRC	1/33X	17 ab	12 a	8 a	14 b	24 ab	6 a

[i] One-year exposure: Trees were treated in 2020 and the study was repeated on different trees in 2021, where sample size n = 8. Two-year exposure: The trees which were treated in 2020 were retreated in 2021, where sample size n = 4.
[ii] Florpyrauxifen-benzyl rate is expressed as a fraction of the rice use rate, 29.4 $g{\cdot}ha^{-1}$ a.i. Triclopyr rate is expressed as a fraction of rice use rate of 420.3 $g{\cdot}ha^{-1}$ a.e.
[iii] DAT = days after treatment; FPB = florpyrauxifen-benzyl; TRC = triclopyr.
[iv] Means within a column not followed by the same letter are significantly different at $P \leq 0.05$ using Tukey's honestly significant difference test.

exposure studies, respectively. Although, both florpyrauxifen-benzyl and triclopyr injury symptoms on walnuts were more severe on the treated side of the tree, symptoms on developing leaves could be observed through the entire canopy (Fig. 3). Symptoms of florpyrauxifen-benzyl and triclopyr injury on walnuts were similar to the symptoms on almond. However, compared with almond and pistachio, herbicide injury symptoms on walnut were only apparent on the developing leaves and no symptoms were observed on leaves that were fully developed before the herbicide treatments were applied. This is different from previous research which indicated that actively growing and developing walnut leaves and shoots are susceptible to acetolactate synthase (ALS) inhibitor herbicides bispyribac-sodium and bensulfuron-methyl exposure even at 1/200X field use rates (Galla et al. 2018a). ALS inhibitors can be lethal at a very low concentration (Zhou et al. 2007) and plant responses are likely to differ among modes-of-action such as auxin-mimics. Walnut recovery from injury symptoms was similar to almond recovery. At 42 DAT, herbicide injury symptoms on walnut were less than 11% at all rates with both florpyrauxifen-benzyl and triclopyr in the both 1- and 2-year exposure studies and statistically similar to one another.

In previous research, Serim and Patterson (2024) reported florpyrauxifen-benzyl and quinclorac at 1/32X rates caused 88% and 40% visible injury, respectively, on sunflower 28 DAT. Miller and Norsworthy (2018) reported that a 1/10X florpyrauxifen-benzyl rate caused 96% injury symptoms on soybeans 14 DAT and the injury increased to 99% at 28 DAT. Moreover, Schwartz-Lazaro et al. (2017) reported that injury from florpyrauxifen-benzyl was more severe on soybean compared with ALS inhibitors such as bispyribac-sodium, penoxsulam, halosulfuron, orthosulfamuron, and imazosulfuron at drift rates. The greater florpyrauxifen-benzyl injury in annual crops is likely due to their higher growth rate (Taiz et al. 2022). Moreover, the higher herbicide rate may injure the sensitive foliage more than the multiple exposures to lower rates. Galla et al. (2018b) reported that at least three exposures to a 1/200X rate of bispyribac-sodium was required to cause injury symptoms on 1-year-old walnut trees whereas a single 1/33X drift rate was enough. However, this phenomenon may vary with multiple factors such as herbicide, application method, drift rate, crop, maturity of crop, and environmental conditions.

The tree trunk diameter change for almond, pistachio, and walnut was variable and showed no significant interactions among herbicide treatment, exposure, and year. Results showed that the herbicide drift rates did not significantly affect relative trunk growth rate of any of the crop trees, despite foliar injury symptoms (data not shown). These results suggest that almond, pistachio, and walnut can recover from florpyrauxifen-benzyl and triclopyr herbicide drift rates.

Conclusions

The research showed that the newly registered rice herbicide, florpyrauxifen-benzyl, can cause visible injury on almond, pistachio, and walnut trees at simulated drift rates. As an auxin-mimic, florpyrauxifen-benzyl injury symptoms were very similar to symptoms from another registered auxin-mimic herbicide, triclopyr, on all crops. The 1/10X florpyrauxifen-benzyl treatment resulted in the greatest injury on all crops and delayed growth on pistachio, which suggests that pistachio was the most susceptible tree nut crop to florpyrauxifen-benzyl. Moreover, pistachio injury from the 1/10X florpyrauxifen-benzyl treatment was greater after 2 years of exposure, which suggests cumulative effects from repeated exposure.

The visible herbicide injury ratings from the simulated florpyrauxifen-benzyl and triclopyr drift rates differences among almond, pistachio, and walnut are not surprising because the absorption, translocation, and metabolism of herbicides are expected to vary among plant species (Al-Khatib et al. 1992b). Although the typical herbicide drift rates under normal field conditions generally are from 1/100X to 1/33X of the field use rates (Al-Khatib and Peterson 1999), the 1/10X florpyrauxifen-benzyl rate in this study was added to simulate a worst-case scenario, considering consecutive drift events in a short interval of time or an accidental herbicide application, events that are unlikely to commonly occur in a typical drift situation. This research suggests that almond and walnut have the potential for rapid recovery from florpyrauxifen-benzyl and triclopyr at the common drift rates.

Due to its selective grass activity and good control of broadleaves and sedges, florpyrauxifen-benzyl is expected to be widely used by growers (Inci and Al-Khatib 2024). California growers are familiar with management programs for triclopyr, which has been registered for use in rice for many years. Florpyrauxifen-benzyl and triclopyr herbicides can cause significant damage if they drift onto pistachio trees at sufficient amounts. The risk of off-target movement of rice herbicides is greatest for aerial applications (UCANR 2023). Although triclopyr drift mitigation strategies allow aerial applications, the current florpyrauxifen-benzyl label limits the herbicide to ground applications, which further reduces the risk of significant injury to nearby tree nut crops and imparts an extra level of precaution.

Off-target drift management programs in accordance with label for florpyrauxifen-benzyl applications are likely to be effective to reduce the risk of significant crop injury from florpyrauxifen-benzyl drift on almonds and walnuts in most cases, but extra precautions may be needed if there are nearby pistachio orchards. Further studies should investigate the impacts of off-target movement of auxinic herbicides such as florpyrauxifen-benzyl and triclopyr on the yield quality or quantity.

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