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Total effects of contact and residual exposure of bifenthrin and λ-cyhalothrin on the predatory mite *Galendromus occidentalis* (Acari: Phytoseiidae)

Kelly A. Hamby · Jesse A. Alifano · Frank G. Zalom

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Abstract Pyrethroid insecticides are generally regarded as acutely toxic to predatory phytoseiid mites; however, persistence of hull split spray pyrethroid residues on almond trees and their effects on phytoseiids have not been quantified over time. Hull split, the separation of the almond hull along the suture, exposes the new crop nuts to infestation by *Amyelois transitella* (Walker) larvae, and is the preferred timing for insecticides applied for their control. *Galendromus occidentalis* (Nesbitt) is the most important phytoseiid biocontrol agent for web-spinning spider mites in California (USA) almond orchards, and the impact of bifenthrin and λ-cyhalothrin pyrethroid residue on their survival, fertility, and fecundity was determined. The total effects of direct contact with esfenvalerate, permethrin, bifenthrin and λ-cyhalothrin were also evaluated for comparison. The total effects (*E*) of direct contact treatments of the four pyrethroids ranged from 77.8 % for esfenvalerate to 98.8 % for bifenthrin. Both bifenthrin and λ-cyhalothrin twig residue would be considered harmful (IOBC class 4) following field application at hull split timing. Bifenthrin twig residue would be considered slightly harmful (IOBC class 2) for up to 3.5 months and harmless (IOBC class 1) after 6 months. λ-cyhalothrin residue would be considered moderately harmful (IOBC class 3) for up to 3.5 months following application and harmless (IOBC class 1) after 6 months. Bifenthrin and λ-cyhalothrin twig residue on treated trees significantly reduced *G. occidentalis* female survival for up to 6 months post-treatment, however total effects (*E*) classify these residues as harmless (IOBC class 1) after 6 months. Harmful effects of direct and residual exposure following application have implications for the use of these pyrethroids in an integrated mite management program for perennial crops.

Keywords Esfenvalerate · Permethrin · Lethal effects · Sub-lethal effects · Total effects · *Amyelois transitella*

K. A. Hamby (✉) · J. A. Alifano · F. G. Zalom
Department of Entomology and Nematology, University of California, Davis,
One Shields Avenue, Davis, CA 95616, USA
e-mail: kahamby@ucdavis.edu

Introduction

Successful conservation of predatory mite natural enemies in an integrated pest management framework is dependent, in part, on the ability of the predator mites to survive exposure to pesticides that may be directed at primary pests in a cropping system (Bower and Kaldor 1980; Sáenz de Cabezón Irigaray and Zalom 2006). Predators may be intrinsically more susceptible than their prey to pesticides based on reproductive success; therefore, examination of sub-lethal pesticide effects may be as important as acute effects as these may ultimately result in local extinction of the population (Hallam et al. 1993; Stark and Wennergren 1995; Stark et al. 1997).

Galendromus occidentalis (Nesbitt) (Acari: Phytoseiidae) is the main biocontrol agent regulating web-spinning spider mites, *Tetranychus* spp., in California almonds as well as other orchard and vine crops including apples, stone fruit, grapes and hops. An obligate predator, it is commercially available for augmentative release (Hoy et al. 1997; McMurtry and Croft 1997; Connell 2002; Gerson et al. 2003). *Galendromus occidentalis* overwinter in bark crevices or under buds as mated, diapausing females, although a small proportion do not enter diapause (Hoy and Flaherty 1975). They migrate onto leaves following budbreak and disperse throughout the tree searching for Acari prey (Lee and Davis 1968). Both acaricides and insecticides have been shown to have acute and sub-lethal effects that impact *G. occidentalis* populations associated with different cropping systems (Hoyt 1969; Sáenz de Cabezón Irigaray and Zalom 2006, 2007; Sáenz de Cabezón Irigaray et al. 2007; Bostanian et al. 2009).

Almonds, which are primarily grown in California, have become the largest tree crop in the USA in terms of acreage and farmgate value. *Amyelois transitella* (Walker) (Lepidoptera: Pyralidae), the navel orangeworm, is the key insect pest of almonds. It is controlled with insecticides applied at midsummer 'hull split'. Hull split, the separation of the almond hull along the suture, exposes the new crop nuts to infestation by *A. transitella* larvae. Regulations implemented during the last decade have resulted in a shift from organophosphates such as azinphospmethyl (Guthion, Bayer Cropsciences) and chlorpyrifos (Lorsban, Dow Agrociences) applied at hull split to pyrethroids (Connell 2002; Jones et al. 2009). Almond trees treated with the pyrethroid insecticides permethrin and esfenvalerate at hull split were found to have significantly more *Tetranychus* spp. spider mites and fewer predatory mites on leaves sampled during the remainder of the season (Bentley et al. 1987). In another study, bark residues from a dormant season application of either permethrin or esfenvalerate resulted in a significant reduction in survival of *G. occidentalis* for up to 7 months following treatment (Zalom et al. 2001). Pyrethroid insecticides are generally regarded as acutely toxic to phytoseiid mites (Aliniazee and Cranham 1980; Bostanian and Belanger 1985; Bostanian et al. 2009), however amount and toxicity of field residues of bifenthrin and λ-cyhalothrin remaining on tree bark following a hull split spray has not been evaluated on a phytoseiid.

We exposed gravid *G. occidentalis* females to permethrin, esfenvalerate, bifenthrin, and λ-cyhalothrin in a contact laboratory bioassay to determine and compare the direct effects of these pyrethroids on survivorship, fertility, and fecundity. Pyrethroids are classified into two types based on structural differences, differences in kinetic modification of the sodium channels, and two distinct syndromes of toxicity (Lautraite and Sargent 2009). Type I pyrethroids lack the α-cyano-3-phenoxybenzyl alcohol structure and induce whole body tremors (T-syndrome) in mammals, whereas Type II pyrethroids possess an α-cyano-3-phenoxybenzyl alcohol structure and produce sinuous writhing convulsions (choreoathetosis) and salivation (CS-syndrome) in mammals (Breckenridge et al. 2009; Burr and Ray

2004; Choi and Soderlund 2006; Weiner et al. 2009). To determine the residual impact of the currently favored Type I and Type II pyrethroids, almond trees were treated with either bifenthrin (Type I) or λ-cyhalothrin (Type II) at hull split and twig samples were collected up to 6 months post-treatment to quantify remaining surface residues and potential effects upon survivorship, fertility, and fecundity of female *G. occidentalis*. Bark surface residues are important in western USA orchard and vineyard cropping systems as *G. occidentalis* overwinter in concealed areas on the tree or vine itself (Caltagirone 1970).

Materials and methods

Contact bioassay

The origin of the *G. occidentalis* used in this study was a colony maintained on cotton seedlings (*Gossypium hirsutum* L.) infested with *Tetranychus urticae* Koch at 24 ± 1 °C, 75–85 % RH, and a 16:8 (L:D) photoperiod. The *T. urticae* were from a caged colony also maintained on cotton seedlings. Both colonies were maintained in the Zalom laboratory at the University of California, Davis, and they had not been previously exposed to pyrethroid insecticides.

Bifenthrin 0.240 g AI l^{-1} (Brigade WSB®, FMC Agricultural Products, Philadelphia, PA, USA), λ-cyhalothrin 0.479 g AI l^{-1} (Warrior CS®, Syngenta Crop Protection, Greensboro, NC, USA), esfenvalerate 0.120 g AI l^{-1} (AsanaEC®, DuPont Crop Protection, Wilmington, DE, USA), and permethrin 0.479 g AI l^{-1} (Ambush EC®, AMVAC Chemical, Los Angeles, CA, USA) were applied at the abovementioned typical field concentrations using a hand sprayer held 30 cm from whole cotton leaves inhabited by both *G. occidentalis* and their *T. urticae* prey that were removed from the laboratory colony described above. Control leaves were prepared in the same manner with distilled water being substituted for insecticide. The treated leaves were allowed to air dry for 5 min after application. Fresh leaf discs were cut from whole cowpea (*Vigna unguilata* L.) leaves excised from untreated and uninfested plants using a cork borer (20 mm diameter). The discs were placed on moistened filter paper in a Petri dish (90 mm diameter), with three leaf discs per Petri dish. One gravid *G. occidentalis* female from a treated leaf was then transferred to each untreated leaf disc with no fewer than 10 untreated *T. urticae* eggs provisioned as food for the predator. Seven dishes were used for each treatment in the trial (35 total dishes), and all treatments were applied on the same day. The cover of the Petri dish had three 10 mm holes covered with No Thrips Insect Screen® 150 × 150 μm (International Greenhouse Company, Danville, IL, USA) to provide ventilation and control humidity. The Petri dishes were placed in a Percival biological incubator and held at 24 ± 1 °C, 75–85 % RH, and a 16:8 (L:D) photoperiod during the experiment.

Number of surviving *G. occidentalis* females and number of eggs laid were counted at 72 h, as preliminary trials suggested that 72 h post application was appropriate for observing mortality effects. The eggs laid on each day were transferred to new leaf discs, and the number of those eggs that hatched was determined 72 h later, as *G. occidentalis* eggs have been reported to hatch within 3 days at 22 °C and 2 days at 28 °C (Stavrinides et al. 2010).

Field residue bioassay

The field pyrethroid trial was conducted at the Nickel's Soils Laboratory, Arbuckle, Colusa Co., CA, USA, in an almond orchard where no pyrethroid insecticides had ever been

applied. Four trees each of two common commercial cultivars, Nonpareil and Butte, were treated on 5 August, 2009 with registered field rates of bifenthrin (0.240 g AI l^{-1}) or λ-cyhalothrin (0.479 g AI l^{-1}) by handgun sprayer until runoff, while four trees of each variety remained untreated as a control (24 trees total). Treatments and varieties were assigned in a completely randomized design and an untreated tree was left as a buffer between each of the treated trees to limit drift. On the day following application, twigs approximately 2 cm in diameter and 6–8 cm in length were collected for bioassays and residue analysis. Samples were placed in 230 ml washed glass jars and frozen at −20 °C within 4 h of collection. A second sample was collected and frozen before leaf fall on 25 November, 2009, to coincide with the timing of natural predator movement from the foliage to bark and peduncles where they overwinter (Lee and Davis 1968; Caltagirone 1970). A final sample was taken and frozen after bloom on 16 February, 2010, corresponding to the time of predator movement back onto budding leaves following almond bloom. Twigs with smooth or green bark were excluded from sampling as this potentially indicates growth subsequent to application. Approximately 25 cm of winter rainfall was recorded onsite between application and final sample collection (http://ipm.ucdavis.edu/WEATHER). Most of this rainfall occurred between the second and third sample dates.

The frozen twigs were removed from the jars and thawed at room temperature the day prior to each predator bioassay. The twigs were cut into 3.0 cm lengths and split in half lengthwise. Groups of five split twigs were placed on top of a moistened filter paper in a 90 mm Petri dish for a total of 8 dishes for each treatment (λ-cyhalothrin, bifenthrin, control), cultivar (Butte or Nonpareil), and collection date (1, 111, and 194 days post application). Sufficient *T. urticae* eggs were transferred to each twig to serve as food and two gravid female *G. occidentalis* (from the same colony as the contact bioassay and kept at the same conditions) were transferred onto each twig for a total of 10 females per dish and dishes were prepared on the same day for each collection date (48 total dishes per collection date, 144 dishes total). The Petri dishes were placed in a Percival biological incubator and held at 24 ± 1 °C, 75–85 % RH, and a 16:8 (L:D) photoperiod during the experiment. Female survival and number of eggs laid were recorded at 72 h. Eggs laid were then transferred to an untreated cowpea leaf and hatch was determined 72 h later.

Residue analysis

Additional Nonpariel twigs were thawed on the same day as those used for the bioassays, and a random subset selected for analysis of bifenthrin and λ-cyhalothrin residues by Environmental Micro Analysis (Woodland, CA, USA). The diameter and length of three thawed Nonpareil twigs was measured and recorded to enable calculation of their surface area. Three replicate analyses were performed for each pyrethroid treatment at each sample date, and the untreated control was analyzed to ensure no contamination occurred during treatment or handling. The measured twig segments were placed into a 236.6 ml amber glass jar with a Teflon-lined screw cap, and 100 ml acetone was added. Contents were swirled for 1 h and then left to sit overnight. A 50 ml aliquot was removed from the jar into a 50 ml graduated test tube. Its contents were concentrated to dryness on a 45 °C N-evaporator and then reconstituted with hexane. The extract was cleaned using a 500 mg florisil SPE column followed by a carbon/amino SPE column and then concentrated just to dryness and increased back to 1 ml with toluene. Extracts were analyzed on a Varian 3400 gas chromatograph (Agilent Technologies, Folsom, CA, USA) equipped with dual columns and dual electron capture detectors. Amount of pyrethroid was calculated based on external standards and was reported with a 0.1 μg reporting limit. The amount was subsequently

adjusted for the total surface area of the twigs from the sample. Dibutyl chlorendate served as the surrogate standard for this analysis to quantify analyte loss during sample collection.

Statistical analysis

Survivorship was defined as percent of females alive 72 h post exposure to the laboratory contact sprays or the field residue samples. Fecundity was calculated as the total number of eggs laid in 72 h, and fertility was calculated as the percent of those eggs that hatched. The effect of the pesticide treatment on each of these variables was evaluated with analysis of variance (ANOVA) calculations using JMP® statistical software (JMP® Version 9.0.0, SAS Institute, Cary, NC). Data were transformed as necessary to meet assumptions of normality of residual errors (either logit or log transformed as described in the results) and homogeneity of variance (re-ran as a weighted least squares analysis using the reciprocal of the within treatment variance as the weighing factor). The Shapiro–Wilk test and the Levene's test were used to confirm the aforementioned assumptions. Means comparisons were performed using Dunnett's test to compare treatment means to the control. Total effects of pesticides (E) values were calculated by adjusting fertility-corrected values to the reproductive value using the equation:

$$E(\%) = 100\,\% - (100\,\% - M) \times R,$$

where M is the Abbotts-corrected mortality and R is the reproduction (eggs/female × % fecundity) per treated female over the reproduction per untreated female (Overmeer and Van Zon 1982).

Results

Contact bioassay

A one-way ANOVA ($F_{4,34} = 6.5132$, $P = 0.0007$) was performed of percent survival by pesticide. As the data passed a Shapiro–Wilk test for normality and a Levene's test for homogeneity of variance, the analysis was not transformed. A Dunnett's mean comparison versus the control was subsequently performed (Table 1). All of the pyrethroid treatments applied by direct contact to *G. occidentalis* caused a significant decline in survival relative to the control at 72 h post application.

A one-way ANOVA ($F_{4,34} = 30.9379$, $P < 0.0001$) was performed of total eggs laid in 72 h by pesticide. Data failed a Shapiro–Wilk test for normality of residual errors therefore data were log transformed. Data also failed a Levene's test for homogeneity of variance and the analysis was re-run as a weighted least squares analysis with the weighing factor being the reciprocal of the variance of the residual error of total eggs laid in 72 h. A Dunnett's mean comparison versus the control was subsequently performed (Table 1). Fecundity of surviving *G. occidentalis* females was significantly impacted by exposure to bifenthrin (Table 1), and indeed only a single egg was recorded. Females surviving treatment with esfenvalerate, permethrin, and λ-cyhalothrin also laid significantly fewer eggs than did females exposed to the water only control (Table 1).

A one-way ANOVA ($F_{4,17} = 17.7111$, $P < 0.0001$) was performed of percent eggs hatched by pesticide, excluding replicates where no eggs were laid. Data failed a Shapiro–Wilk test for normality of residual errors therefore data were logit transformed. Data

Table 1 Survivorship, fertility, fecundity and total effects (*E*) for *Galendromus occidentalis* females 72 h after each direct contact treatment

Treatment	Survival[a] ± SE	*P*[b]	Fecundity[c] ± SE	*P*[b]	Fertility[d] ± SE	*P*[b]	*E*
Control	90.48 ± 9.52	–	7.71 ± 1.13	–	97.96 ± 2.04	–	
Bifenthrin	42.86 ± 9.52	0.013	0.43 ± 0.30	<0.0001	100.00 ± 0.00[e]	0.0058[e]	98.8
λ-cyhalothrin	47.62 ± 14.29	0.028	1.57 ± 0.87	0.0014	77.78 ± 11.11	0.0003	83.9
Esfenvalerate	42.86 ± 11.98	0.013	2.00 ± 0.79	0.0051	76.67 ± 10.00	<0.0001	77.8
Permethrin	14.29 ± 6.73	<0.0001	0.43 ± 0.43	<0.0001	66.67 ± 0.00	0.0028	96.5

N = 7 Petri dishes (3 female mites per dish)

[a] Percent females alive after 72 h

[b] Dunnett's means comparison with control

[c] Eggs laid in 72 h

[d] Percent of eggs laid in 72 h that hatched

[e] Only one egg was laid by the surviving females and it hatched

passed a Levene's test for homogeneity of variance. A Dunnett's mean comparison versus the control was then performed (Table 1). All treatments significantly reduced fertility when compared to the water-only control (Table 1). The total effects of the pyrethroids ranged from 77.8 % for esfenvalerate to 98.8 % for bifenthrin.

Field residue bioassay

Residue analysis conducted on twigs sprayed with either bifenthrin or λ-cyhalothrin revealed detectable levels of both pyrethroids for over 6 months following hull split application (Table 2). A marked decrease in bifenthrin and λ-cyhalothrin residue concentration was documented between each successive sample date, indicating a half-life on almond bark of 2–3 months for bifenthrin and approximately 1.5 months for λ-cyhalothrin following the hull split application. No pyrethroid residue was detected on the control twigs. A two-way ANOVA ($F_{5,18} = 13.7861$, $P < 0.0001$) of pesticide residue was performed with days post application, pesticide, and the interaction of days post application*pesticide. The data passed a Shapiro–Wilk test. Due to the fact that the analysis failed a Levene's test for homogeneity of variance for the days after treatment factor, the analysis was re-run as a weighted least squares analysis with the weighting factor being the reciprocal of the variance of the residual errors of days after treatment. Days post application ($F_{2,18} = 18.9697$, $P = 0.0001$), pesticide ($F_{1,18} = 19.5126$, $P = 0.0007$), and the interaction of days after treatment*pesticide ($F_{2,18} = 6.1844$, $P = 0.013$) were all found to be significant. Therefore, a separate ANOVA was used for each day after treatment for the mite effect parameters.

At 1 day post application, data were pooled across almond variety as it was found to be non-significant for both survival and fecundity effect parameters. Percent survival data (one-way ANOVA $F_{2,47} = 19.9520$, $P < 0.0001$) passed a Shapiro–Wilk test for normality and a Levene's test for homogeneity of variance, the analysis was not transformed. A Dunnett's mean comparison versus the control was subsequently performed (Table 3). Both bifenthrin and λ-cyhalothrin exhibited significantly less survival than the water only control. Total eggs laid in 72 h (one-way ANOVA $F_{2,47} = 24.3223$, $P < 0.0001$) passed the Shapiro–Wilk test but failed a Levene's test therefore the analysis was re-run as a weighted least squares analysis with the weighting factor being the reciprocal of the

Table 2 Mean (± SE) pyrethroid residue (μg cm^{-2}) remaining on twigs collected from field-treated Nonpareil almond trees for each sample date

Sampling date	Days post application	Treatment	Pyrethroid residue (μg cm^{-2}) ± SE
8/6/09	1	Bifenthrin	0.110 ± 0.010
		λ-cyhalothrin	0.051 ± 0.010
11/25/09	111	Bifenthrin	0.046 ± 0.009
		λ-cyhalothrin	0.007 ± 0.003
2/16/10	194	Bifenthrin	0.017 ± 0.006
		λ-cyhalothrin	0.008 ± 0.002

Treatments were applied on 5 August, 2009. N = 3 twigs

variance of the residual errors of total eggs. A Dunnett's mean comparison versus the control was then performed (Table 3). Both bifenthrin and λ-cyhalothrin exhibited significantly lower fecundity than the water only control 1 day post application. For percent eggs hatched, the almond variety was determined to be significant, however data were pooled across almond variety (as this was the only instance of varietal significance) and a one-way ANOVA ($F_{2,45} = 2.3785$, $P = 0.10$) was performed of fecundity and found to be non-significant at 1 day post application.

Three and a half months post application (111 days post application), the almond variety was determined to be non-significant for all effect parameters and data were pooled across almond variety. Data for all effect parameters passed the Shapiro–Wilk test and the Levene's test, therefore no transformations were performed. Percent survival (one-way ANOVA $F_{2,47} = 19.9520$, $P < 0.0001$) and fecundity (one-way ANOVA $F_{2,47} = 24.3223$, $P < 0.0001$) showed a significant impact of pesticide, though fertility did not (one-way ANOVA $F_{2,47} = 1.8001$, $P = 0.18$). A Dunnett's mean comparison versus the control was

Table 3 Survival, fertility, fecundity and total effects (*E*) for *Galendromus occidentalis* females exposed to treatment residues on twigs collected from field-treated Nonpareil and Butte almond trees (pooled) for each sample date

Days post application	Treatment	Survival[a] ± SE	*P*[b]	Fecundity[c] ± SE	*P*[b]	Fertility[d] ± SE	*E*
1	Control	73.13 ± 2.54	–	17.56 ± 1.25	–	78.86 ± 4.34	
	Bifenthrin	42.50 ± 3.71	<0.0001	8.88 ± 0.96	<0.0001	77.09 ± 4.51	50.0
	λ-cyhalothrin	20.63 ± 3.35	<0.0001	2.87 ± 0.40	<0.0001	56.19 ± 9.59	87.0
111	Control	75.63 ± 3.98	–	15.50 ± 0.89	–	92.71 ± 1.40	
	Bifenthrin	54.38 ± 4.74	0.0014	10.25 ± 1.07	0.0004	90.99 ± 2.38	34.1
	λ-cyhalothrin	38.75 ± 3.64	<0.0001	6.50 ± 0.76	<0.0001	94.69 ± 2.21	58.9
194	Control	62.50 ± 2.96	–	14.63 ± 0.72	–	93.55 ± 1.31	
	Bifenthrin	48.75 ± 3.28	0.0071	11.13 ± 0.83	0.0063	94.11 ± 1.49	7.8
	λ-cyhalothrin	48.75 ± 3.28	0.0071	10.5 ± 0.84	0.0013	88.16 ± 2.57	19.9

Treatments were applied on 5 August, 2009. N = 16 Petri dishes (10 female mites per dish)

[a] Percent females alive after 72 h

[b] Dunnett's means comparison with control

[c] Eggs laid in 72 h

[d] Percent of eggs laid in 72 h that hatched

performed for survival and fecundity and both bifenthrin and λ-cyhalothrin residues exhibited reduced survival and fecundity relative to the control at 111 days post application (Table 3).

Six months post application (194 days), the almond variety was determined to be non-significant for all effect parameters and data were pooled across almond variety. Data for all effect parameters passed the Shapiro–Wilk test and the Levene's test, therefore no transformations were performed. Percent survival (one-way ANOVA $F_{2,47} = 6.2586$, $P = 0.0040$) and fecundity (one-way ANOVA $F_{2,47} = 7.7787$, $P = 0.0013$) showed a significant impact of pesticide, though fertility did not (one-way ANOVA $F_{2,47} = 2.1402$, $P = 0.13$). A Dunnett's mean comparison versus the control was performed for survival and fecundity and both bifenthrin and λ-cyhalothrin residues exhibited reduced survival and fecundity relative to the control at 194 days post application (Table 3).

Discussion

Bioassays conducted on the field-collected twigs showed significantly reduced *G. occidentalis* survival and fecundity relative to the control for both bifenthrin and λ-cyhalothrin on all sample dates (Table 3), though the number of individuals surviving did increase concomitant with the lower residual concentrations detected in the latter samples (Table 2) at 6 months after application when only 15.5 % (0.017 μg cm^{-2}) of the original bifenthrin deposit remained and when only 15.7 % (0.008 μg cm^{-2}) of the original λ-cyhalothrin twig residue remained. Fertility was not significantly impacted at any sample date (Table 3).

When considering total effects of the insecticides (*E*), bifenthrin residue on twigs would be considered slightly harmful (IOBC class 2) on the late November sample date when *G. occidentalis* females would have begun moving to the bark to overwinter and harmless (IOBC class 1) by almond bloom (Sterk et al. 1999). Total effects of λ-cyhalothrin residue on twigs would be considered harmful (IOBC class 4) following application, moderately harmful (IOBC class 3) later in the fall, and harmless (IOBC class 1) by almond bloom (Sterk et al. 1999).

The contact bioassay was a proxy for exposure to a spray at the time of almond hull split and suggests that all of these insecticides are highly toxic to *G. occidentalis* females. This would likely impact the ability of an exposed predator population to regulate web-spinning spider mites for some time thereafter. The 24 h, 3.5, and 6 months post-treatment residue assays do not capture the potential harmful direct effects ($E > 75$; IOBC class 4) on the predator population due to contact by the spray or to leaf residue post-treatment, but are an indicator of potential longer-term population effects. At the hull split spray timing, predatory mites are expected to be near their *T. urticae* prey on the leaves, as *Galendromus* spp. are considered good searchers and respond to volatiles resulting from *T. urticae* infestation (Hoy et al. 1997; McMurtry and Croft 1997). One might surmise that the *G. occidentalis* population would not quickly recover from the hull split treatment, but females that successfully escaped the spray or moved into the treated orchard later in the season might overwinter and produce offspring the following spring.

The late November (3.5 months post treatment) sample captured residue levels on almond bark that would be present when the females move from leaves to the bark to overwinter. At this time total effects (*E*) of bifenthrin residue would be considered slightly harmful (IOBC class 2) and λ-cyhalothrin moderately harmful (IOBC class 3) (Sterk et al. 1999). Although survival was significantly different from the control for both insecticides

6 months post treatment (corresponding with the time predators return to leaves following almond bloom), total effects of residues of either pyrethroid would be considered harmless (IOBC class 1) (Sterk et al. 1999). We found the pyrethroid residue half-life on almond bark to be 2–3 months for bifenthrin and approximately 1.5 months for λ-cyhalothrin following the midsummer hull split application. Our findings are corroborated by other studies that report bifenthrin to have an aerobic half-life of 65–125 days, and λ-cyhalothrin to have a shorter half-life, ranging from 24 to 53 days (He et al. 2008; Fecko 1999). We expected the longer half-life of bifenthrin to have greater impact on *G. occidentalis* as bifenthrin was shown to exhibit long residual activity to another phytoseiid, *Phytoseiulus persimilis* Athias-Henriot and was highly active against both *Neoseiulus californicus* (McGregor) and *Neoseiulus womersleyi* (Schicha) (Cote et al. 2002; Amano et al. 2004). Despite the shorter half-life, λ-cyhalothrin exhibited more harmful total effects at the late November residue levels. Another study showed that λ-cyhalothrin was highly active against the predatory Anystid mite *Anystis baccarum* (Linnaeus), with the label rate being 26 times greater than the estimated LC_{50} of 0.0007 g AI l^{-1} (Laurin and Bostanian 2007). It is possible that the modest differences in toxicity to *G. occidentalis* observed between bifenthrin and λ-cyhalothrin in the residual twig sample is due to the different pyrethroid types that they represent, or the higher concentration of the latter that was applied.

Consideration should be given to *G. occidentalis* longevity and progeny development following treatment as these measures relate to population recovery. Reproductive effects on individual females have been observed far longer than 3 days following exposure, and insecticide applications that did not have a significant effect on adult *G. occidentalis* survival have been shown to impact larval survival from eggs laid on acaricide treated surfaces (Sáenz de Cabezón Irigaray and Zalom 2006; Bostanian et al. 2009). Similar results were reported with *P. persimilis* females that survived treatment but lost fitness since their progeny ultimately died (Kim and Yoo 2002). If direct female mortality as well as indirect sub-lethal effects impact a predator population then suppression may be more severe than is indicated by the measure of acute mortality alone. Consideration must be given to a pesticide's persistence and the effects of remaining residue over time in order to appropriately predict its impact on a predator population. Insecticide residues remaining on treated surfaces can have a deleterious effect on phytophagous mite populations and can result in their long-term suppression, even into the following season on a perennial crop (Hoyt 1969; Bentley et al. 1987).

The inimical effects of pesticides have proven to be more complex than envisioned in the past, yet determining their effect on natural enemy populations is critical to enhancing biological control in integrated pest management programs (Jones et al. 2009). However, there are a number of insecticides registered that are both effective and nontoxic to predatory mites, and these should be used instead of more toxic chemicals such as pyrethroids to conserve biological control agents in almonds and other crops. For example, the Laurin and Bostanian (2007) study that documented toxic effects of λ-cyhalothrin to *A. baccarum* also showed that methoxfenozide, an ecdysone receptor agonist, and spinosad, a nicotinic acetylcholine receptor allosteric activator, were nontoxic to the predator. Bostanian et al. (2009) confirmed that indeed methoxyfenozide and spinosad were not toxic to *G. occidentalis*. Both of these insecticides are registered for use on almonds and other orchard and vine crops, and effectively suppress *A. transitella* on almonds at hull split (Higbee and Sieg 2012) and many other key Lepidoptera pests as well. Their use as an alternative to the pyrethroid insecticides would enable an integrated mite control program founded on stable predaceous mite populations.

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