# Relative Toxicity and Residual Activity of Insecticides Used in Blueberry Pest Management: Mortality of Natural Enemies

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**ABSTRACT** A series of bioassays were conducted to determine the relative toxicities and residual activities of insecticides labeled for use in blueberry (*Vaccinium corymbosum* L.) on natural enemies, to identify products with low toxicity or short duration effects on biological control agents. In total, 14 insecticides were evaluated using treated petri dishes and four commercially available natural enemies (*Aphidius colemani* Viereck, *Orius insidiosus* [Say], *Chrysoperla rufilabris* [Burmeister], and *Hippodamia convergens* [Guérin-Menéville]). Dishes were aged under greenhouse conditions for 0, 3, 7, or 14 d before introducing insects to test residual activity. Acute effects (combined mortality and knockdown) varied by insecticide, residue age, and natural enemy species. Broad-spectrum insecticides caused high mortality to all biocontrol agents, whereas products approved for use in organic agriculture had little effect. The reduced-risk insecticide acetamiprid consistently caused significant acute effects, even after aging for 14 d. Methoxyfenozide, novaluron, and chlorantraniliprole, which also are classified as reduced-risk insecticides, had low toxicity, and along with the organic products could be compatible with biological control. This study provides information to guide blueberry growers in their selection of insecticides. Further research will be needed to determine whether adoption of a pest management program based on the use of more selective insecticides will result in higher levels of biological control in blueberry.

**KEY WORDS** natural enemy, reduced-risk insecticide, bioassay

Commercial production of highbush blueberry, *Vaccinium corymbosum* L., typically requires a number of agricultural inputs, including pesticides. Growers often contend with multiple insect, disease, and weed pests that call for active management to reduce economic losses. Insecticides are the primary means for suppressing blueberry insect pests that include direct pests of fruit and indirect pests of foliage, including virus-vectoring aphids (Hemiptera: Aphididae; Dorschner et al. 2009). One of the drawbacks of using insecticides is their toxicity to nontarget arthropods that provide biological control. Disrupting predator and parasitoid populations can result in pest resurgence and secondary pest outbreaks (Whalon and Elsner 1982, Croft 1990). Ideally, pesticides should be selective; that is, highly toxic to pests although being nontoxic to other organisms (Ripper et al. 1951). Restrictions on the use of some broad-spectrum insecticides have prompted the increasing availability of new products with more selective activity for use in fruit crops such as blueberry (Isaacs et al. 2006). For instance, azinphos-methyl, an organophosphate insecticide widely used for control of lepidopteran pests, is being phased out by the United States Environmental Protection Agency (US EPA) and replaced with products such as pyriproxifen, methoxyfenozide, acetamiprid, and indoxacarb (Wise et al. 2010). A number of new selective pesticides are classified as reduced-risk and therefore have an expedited review process for registration in the United States (US EPA 2012). This classification indicates that the insecticide has relatively low risk to beneficial insects, but this is not always the case (Biondi et al. 2012).

Many conventional insecticides are more toxic to beneficial organisms than they are to pests (Mullin and Croft 1985). Typically, much less is known about the effects of pesticides on natural enemies compared with herbivorous pests (Croft 1990), but it has been recognized as an important issue for >50 yr (Ripper 1956, van den Bosch and Stern 1962) and has been studied in many cropping systems. Naturally occurring predators and parasitoids make important contributions to pest control, and more recently, their value has been quantified in some systems (Losey and Vaughan 2006, Landis et al. 2008). Increased natural enemy abundance and activity could compensate for losses of control resulting from decreasing pesticide use in an integrated pest management (IPM) program (Epstein et al. 2000), but producers need to have a clear understanding of which insecticides allow nat-

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**Table 1. Insecticide treatments, classes, and rates used in laboratory bioassays to test insecticide effects on natural enemies**

| Active ingredient | Trade name | Class | IRAC[a] group | Manufacturer | Rate |
|---|---|---|---|---|---|
| *Bacillus thuringiensis* subsp. *kurstaki*[b] | DiPel | Microbial | 11 | Valent | 1.67 kg/ha |
| Pyrethrins[b] | PyGanic EC5.0 | Pyrethrin | 3A | MGK | 4.74 liters/ha |
| Methoxyfenozide[c] | Intrepid 2F | IGR | 18 | Dow | 0.89 liters/ha |
| Novaluron[c] | Rimon 0.83EC | Benzoylurea | 15 | Chemtura | 1.48 liters/ha |
| Chlorantraniliprole[c] | Altacor 35WDG | Diamide | 28 | DuPont | 0.22 kg/ha |
| Spinetoram[c] | Delegate 25WG | Spinosyn | 5 | Dow | 0.30 kg/ha |
| Indoxacarb[c] | Avaunt 30WDG | Oxadiazine | 22A | DuPont | 0.44 kg/ha |
| Acetamiprid[c] | Assail 30SG | Nicotinoid | 4A | UPI | 0.39 kg/ha |
| Imidacloprid[d] | Admire Pro | Nicotinoid | 4A | Bayer | 0.16 kg/ha |
| Zeta-cypermethrin | Mustang Max | Pyrethroid | 3A | FMC | 0.30 liters/ha |
| Esfenvalerate | Asana XL | Pyrethroid | 3A | DuPont | 0.71 liters/ha |
| Methomyl | Lannate LV | Carbamate | 1A | DuPont | 1.78 liters/ha |
| Phosmet | Imidan 70 WP | Organophosphate | 1B | Gowan | 1.48 kg/ha |
| Azinphos-methyl | Guthion 50WP | Organophosphate | 1B | MANA | 1.11 kg/ha |

[a] Insecticide Resistance Action Committee.
[b] Labeled for use in organic agriculture (www.omri.org/omri-lists).
[c] Reduced-risk (www.epa.gov/opprd001/workplan/reducedrisk.html).
[d] Provado 1.6 F (Bayer CropScience) at 0.29 liters/ha was used in the *A. colemani* bioassay.

ural enemies to persist to allow for informed product selection decisions.

Integration of biological and chemical control is the fundamental tenet on which IPM is based (Stern et al. 1959). Approaches to this integration include reducing pesticide use, use of selective pesticides, and modifying natural enemies to reduce their susceptibility to pesticides (Weinzierl 2008, Naranjo and Ellsworth 2009). In this study, we evaluated the selectivity of pesticides toward natural enemies in a blueberry production system, using four representative species: a parasitoid wasp, lady beetle, lacewing, and predatory hemipteran. The species used are all potential biological control agents of aphids (Völkl et al. 2007) and other insects in perennial fruit systems. These species are representative of the community of natural enemies active on blueberry fruit and foliage during the growing season, and therefore are expected to be most affected by foliar sprays of insecticides.

In the United States, there are >29,000 ha of cultivated blueberries (United States Department of Agriculture–National Agricultural Statistics Service [USDA–NASS] 2012). On average, between 80 and 90% of blueberries bearing hectares receive some insecticides each year to prevent infestation by insect pests (USDA–NASS 2010). Pesticide use is driven by the high value of fresh blueberries and consumer expectation for unblemished and uncontaminated fruit. In light of this, it is important to determine which insecticides have the potential to disrupt natural enemies; therefore, the goal of this study was to determine the relative risk to natural enemies from different insecticides. This information can be combined with pest control efficacy data for making recommendations and allowing informed decisions regarding the use of insecticides. Our objectives were to 1) evaluate the relative toxicities of selected insecticides registered for use in blueberry on natural enemy adults, and 2) compare residual activities of these insecticides.

## Materials and Methods

**Insects.** Four commercially available natural enemy species were used in the bioassays: *Aphidius colemani* Viereck (Hymenoptera: Braconidae), insidious flower bug (*Orius insidiosus* [Say] [Hemiptera: Anthocoridae]), green lacewing (*Chrysoperla rufilabris* [Burmeister] [Neuroptera: Chrysopidae]); (all three purchased from Rincon-Vitova Insectaries, Inc., Ventura, CA), and convergent lady beetle (*Hippodamia convergens* [Guérin-Menéville] [Coleoptera: Coccinellidae; Gardening Zone, Camarillo, CA]). These species were selected to represent taxonomic diversity and a range of feeding types. Weekly fresh shipments were used for each residue age so that insects were used within 3 d of being received. The insects were chilled briefly to facilitate transferring them from shipping cages to test arenas.

**Laboratory Experiment.** Insecticides and rates used in this experiment are listed in Table 1. In addition to these chemicals, an untreated control (deionized water) was included for 15 treatments in total, except for trials with *A. colemani*, which omitted novaluron, chlorantraniliprole, and spinetoram. Treatments were applied to the inner surfaces of 47-mm-diameter plastic petri dish bottoms (Fisher, Pittsburgh, PA) by using a Potter precision spray tower (Burkard Scientific, Uxbridge, United Kingdom) with an output equivalent to 468 liters/ha (50 gallons/acre) spray volume (Wise et al. 2010). Residues were allowed to dry before insects were placed in the dishes. For each experiment, all petri dishes were treated at the same time and then aged in a greenhouse (23 ± 2°C, 70% RH) for 0, 3, 7, or 14 d after treatment (DAT), for a total of 10 replicates per treatment for each residue age. Dishes were placed on trays on a workbench in a greenhouse and inverted so that treated surfaces were not directly exposed to the air. They were arranged to avoid shading and exposed to sunlight filtered through the glass of the greenhouse. After residues aged for the appro-

priate amount of time, adult insects (mix of females and males) were added to each petri dish (10 *A. colemani*, 10 *H. convergens*, 5 *O. insidiosus*, or 5 *C. rufilabris*). A smear of honey water (10% by volume) was added to the untreated lid of each dish, along with a 2-cm long piece of damp cotton dental wick to serve as a water source. Once the dishes were sealed shut, they were inverted so the treated surface was on the bottom. Dishes with insects were placed on the middle shelves of a reach-in environmental chamber (20 ± 2°C and a photoperiod of 16:8 [L:D] h). All insects from each experiment were placed in the same chamber. Insect mortality was measured at 24-, 48-, and 72-h exposure time. Insects that were moving but could not right themselves or moved only when touched with a probe were considered knocked down. Insects that were not moving and did not move when touched with a probe were considered dead.

**Statistical Analysis.** Percent mortality and percent knockdown were combined and analyzed as acute effects. We considered knocked-down insects to be functionally dead because, unless they are able to recover, they do not provide biological control services. Because the bioassays for the different species were conducted at different times, separate analyses were conducted for each species and we did not make direct comparisons among species. Values were arcsine square-root transformed before analysis, and untransformed means and standard errors are reported in the figures. In the tables and figures, insecticides were grouped as organic, reduced-risk, or broad-spectrum, based on the US EPA and Organic Materials Review Institute (www.omri.org) classifications. Imidacloprid, which is classified as an organophosphate alternative by the EPA, was included in the reduced-risk group for analysis.

Experimental designs were a 12 by 4 by 3 (insecticide treatment, residue age, exposure time) factorial for the *A. colemani* experiment, and a 15 by 4 by 3 factorial for the other three experiments. Differences in acute effects among treatments and residue ages were determined using repeated-measures analysis of variance (ANOVA) with exposure time as the repeated factor (PROC MIXED; SAS Institute 2009). Degrees of freedom were adjusted using the Satterthwaite option and means separation tests were performed using Tukey's HSD ($\alpha = 0.05$) to control for experiment-wise error rates (SAS Institute 2009). Simple effect comparisons of insecticide groups by residue age and exposure time were made using linear contrasts.

## Results

For each natural enemy species, the insecticide treatment, residue age, exposure time, and interactions significantly affected the combined mortality and knockdown (Table 2). Of all insecticides evaluated, methomyl, phosmet, and azinphos-methyl consistently caused the highest acute effects in the natural enemies tested.

**Table 2. Analysis of variance results from laboratory bioassays testing the effects of treatment, DAT, time, and interactions on natural enemy acute effects (combined mortality and knockdown) from insecticide exposure**

| Species | Factor | df | *F* | *P* |
|---|---|---|---|---|
| *A. colemani* (covariance: heterogeneous autoregressive) | | | | |
| | Treatment | 11,1147 | 106.68 | <0.0001 |
| | DAT | 3,1147 | 232.48 | <0.0001 |
| | Time | 2,977 | 267.17 | <0.0001 |
| | Treatment × DAT | 33,1147 | 12.34 | <0.0001 |
| | Treatment × time | 22,977 | 15.69 | <0.0001 |
| | DAT × time | 6,977 | 22.14 | <0.0001 |
| | Treat × DAT × time | 66,977 | 3.90 | <0.0001 |
| *O. insidiosus* (covariance: unspecified structure) | | | | |
| | Treatment | 14,1617 | 467.53 | <0.0001 |
| | DAT | 3,1617 | 158.50 | <0.0001 |
| | Time | 2,1617 | 418.85 | <0.0001 |
| | Treatment × DAT | 42,1617 | 16.43 | <0.0001 |
| | Treatment × time | 28,1617 | 16.58 | <0.0001 |
| | DAT × time | 6,1617 | 7.93 | <0.0001 |
| | Treat × DAT × time | 84,1617 | 2.58 | <0.0001 |
| *H. convergens* (covariance: compound symmetry) | | | | |
| | Treatment | 14,1620 | 1577.53 | <0.0001 |
| | DAT | 3,1620 | 102.68 | <0.0001 |
| | Time | 2,1620 | 38.96 | <0.0001 |
| | Treatment × DAT | 42,1620 | 33.98 | <0.0001 |
| | Treatment × time | 28,1620 | 28.51 | <0.0001 |
| | DAT × time | 6,1620 | 2.23 | 0.0376 |
| | Treat × DAT × time | 84,1620 | 2.82 | <0.0001 |
| *C. rufilabris* (covariance: unspecified structure) | | | | |
| | Treatment | 14,1620 | 1520.93 | <0.0001 |
| | DAT | 3,1620 | 303.02 | <0.0001 |
| | Time | 2,1620 | 70.69 | <0.0001 |
| | Treatment × DAT | 42,1620 | 74.54 | <0.0001 |
| | Treatment × time | 28,1620 | 10.52 | <0.0001 |
| | DAT × time | 6,1620 | 15.15 | <0.0001 |
| | Treat × DAT × time | 84,1620 | 5.97 | <0.0001 |

For *A. colemani*, at 24-h exposure time, indoxacarb and the broad-spectrum treatments caused the highest acute effects (Fig. 1). Most affected wasps were killed rather than knocked down. Pyrethrins caused high mortality at 0 and 3 d of aging, but at 7 and 14 d, acute effects were no different from the control. Zeta-cypermethrin lost some toxicity at 14 DAT. By insecticide group, organic and reduced-risk treatments were not significantly different at 3 and 14 DAT, and both had lesser acute effects than broad-spectrum products (Table 3). At 0 and 7 DAT, all contrasts among insecticide groups were significant.

Mortality of *O. insidiosus* was high for acetamiprid and for the broad-spectrum treatments at the 24-h exposure time (Fig. 2). Spinetoram was highly toxic at 0 DAT but lost toxicity after aging in the greenhouse. Treatments with lowest toxicity were *Bacillus thuringiensis* (*B.t.*), pyrethrins, methoxyfenozide, novaluron, and chlorantraniliprole. Knockdown of this species was low for all treatments, except for acetamiprid and imidacloprid at 7 DAT. All contrasts among insecticide groups were significant, with acute effects lowest for organic treatments and highest for broad-spectrum treatments (Table 3).

For *H. convergens*, indoxacarb, acetamiprid, imidacloprid, and the broad-spectrum insecticides caused significant acute effects (Fig. 3), but imidacloprid lost toxicity when aged for 14 d. Esfenvalerate, zeta-cypermethrin, imidacloprid, acetamiprid, and indoxacarb

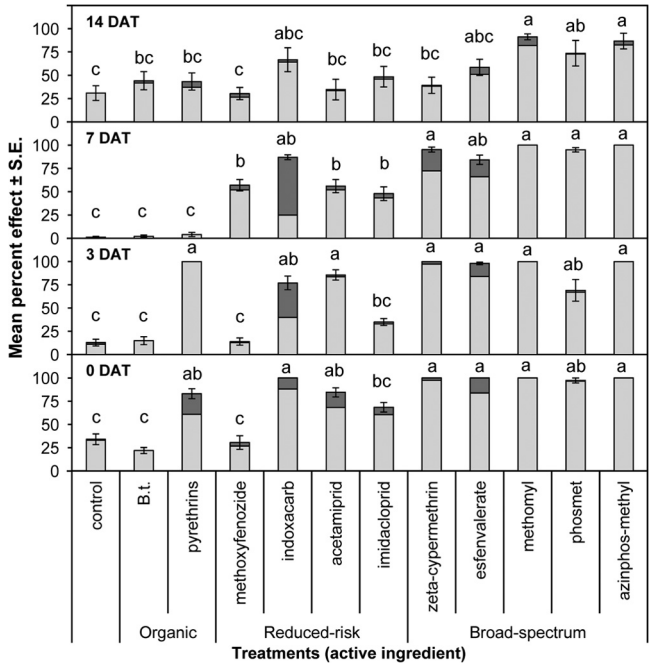


**Fig. 1.** Mean percent effect ± SE of insecticides on *A. colemani* after 24-h exposure to residues aged 0, 3, 7, and 14 DAT. Dark portions of bars represent percent knockdown; light portions represent percent mortality. Bars with the same letter are not significantly different at $P < 0.05$.

knocked down 33–90% of beetles (Fig. 3). Indoxacarb, in particular, caused low mortality but very high knockdown. All contrasts among insecticide groups were significant, with acute effects lowest for organic treatments and highest for broad-spectrum treatments (Table 3).

The pattern of susceptibility for *C. rufilabris* was similar to that for *H. convergens.* Treatments with low toxicity included *B.t.*, pyrethrins, methoxyfenozide, novaluron, and chlorantraniliprole (Fig. 4). Spinetoram, imidacloprid, and methomyl lost toxicity when residues were aged for 14 d. Indoxacarb and

**Table 3. Analysis of variance results from laboratory bioassays to compare the effects of different insecticide groups on natural enemies**

| Species | 0 DAT | | | 3 DAT | | | 7 DAT | | | 14 DAT | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | df | *F* | *P* | df | *F* | *P* | df | *F* | *P* | df | *F* | *P* |
| *A. colemani* | | | | | | | | | | | | |
| ORG vs RR | 1 | 20.74 | <0.0001 | 1 | 2.06 | 0.1542 | 1 | 273.87 | <0.0001 | 1 | 0.13 | 0.7184 |
| ORG vs BS | 1 | 219.24 | <0.0001 | 1 | 63.07 | <0.0001 | 1 | 765.30 | <0.0001 | 1 | 12.55 | 0.0006 |
| RR vs BS | 1 | 158.47 | <0.0001 | 1 | 138.24 | <0.0001 | 1 | 172.62 | <0.0001 | 1 | 15.61 | 0.0001 |
| Error | 108 | | | 108 | | | 108 | | | 108 | | |
| *O. insidiosus* | | | | | | | | | | | | |
| ORG vs RR | 1 | 10.49 | 0.0015 | 1 | 34.47 | <0.0001 | 1 | 48.27 | <0.0001 | 1 | 24.78 | <0.0001 |
| ORG vs BS | 1 | 169.98 | <0.0001 | 1 | 372.14 | <0.0001 | 1 | 454.51 | <0.0001 | 1 | 357.66 | <0.0001 |
| RR vs BS | 1 | 200.55 | <0.0001 | 1 | 381.22 | <0.0001 | 1 | 438.87 | <0.0001 | 1 | 408.31 | <0.0001 |
| Error | 134 | | | 135 | | | 135 | | | 135 | | |
| *H. convergens* | | | | | | | | | | | | |
| ORG vs RR | 1 | 51.90 | <0.0001 | 1 | 148.33 | <0.0001 | 1 | 113.74 | <0.0001 | 1 | 91.11 | <0.0001 |
| ORG vs BS | 1 | 379.82 | <0.0001 | 1 | 633.76 | <0.0001 | 1 | 488.90 | <0.0001 | 1 | 985.77 | <0.0001 |
| RR vs BS | 1 | 319.96 | <0.0001 | 1 | 372.27 | <0.0001 | 1 | 288.68 | <0.0001 | 1 | 1010.7 | <0.0001 |
| Error | 135 | | | 135 | | | 135 | | | 135 | | |
| *C. rufilabris* | | | | | | | | | | | | |
| ORG vs RR | 1 | 817.68 | <0.0001 | 1 | 432.67 | <0.0001 | 1 | 539.73 | <0.0001 | 1 | 84.67 | <0.0001 |
| ORG vs BS | 1 | 2601.3 | <0.0001 | 1 | 1203.7 | <0.0001 | 1 | 1532.0 | <0.0001 | 1 | 709.72 | <0.0001 |
| RR vs BS | 1 | 1137.1 | <0.0001 | 1 | 444.82 | <0.0001 | 1 | 581.55 | <0.0001 | 1 | 648.50 | <0.0001 |
| Error | 135 | | | 135 | | | 135 | | | 135 | | |

ORG, organic; RR, reduced-risk; BS, broad-spectrum.

Insecticide group contrasts for acute effects (combined mortality and knockdown) at 24 (*A. colemani* and *O. insidiosus*) or 72 h (*H. convergens* and *C. rufilabris*).

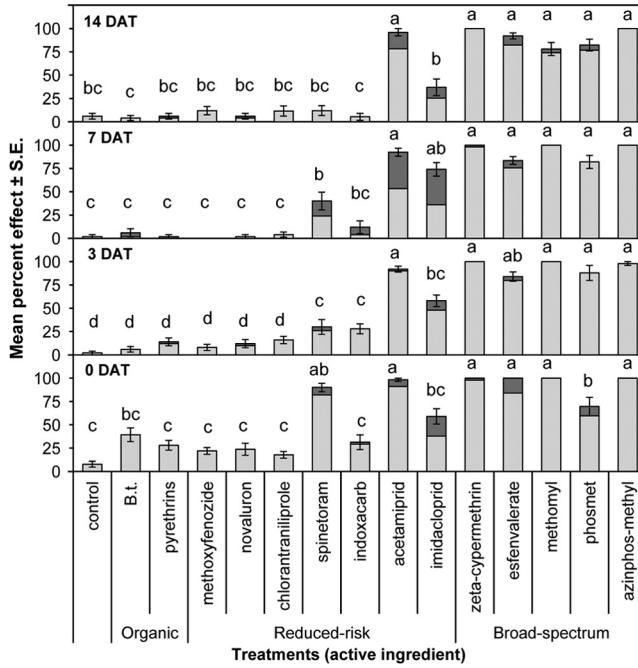


**Fig. 2.** Mean percent effect ± SE of insecticides on insidious flower bug, *O. insidiosus*, after 24-h exposure to residues aged 0, 3, 7, and 14 DAT. Dark portions of bars represent percent knockdown; light portions represent percent mortality. Bars with the same letter are not significantly different at $P < 0.05$.

imidacloprid knocked down a higher percentage of *C. rufilabris* than those that were killed by these treatments (Fig. 4). All contrasts among insecticide groups were significant, with acute effects lowest for organic treatments and highest for broad-spectrum treatments (Table 3).

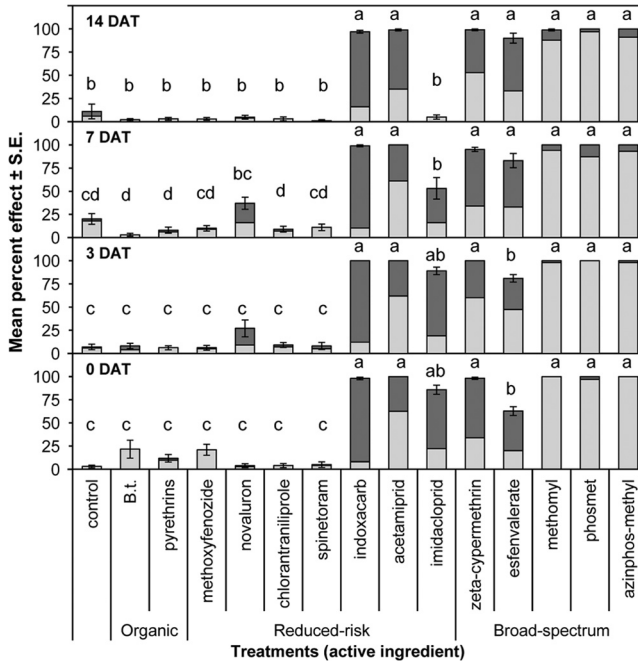


**Fig. 3.** Mean percent effect ± SE of insecticides on convergent lady beetle, *H. convergens*, after 72-h exposure to residues aged 0, 3, 7, and 14 DAT. Dark portions of bars represent percent knockdown; light portions represent percent mortality. Bars with the same letter are not significantly different at $P < 0.05$.

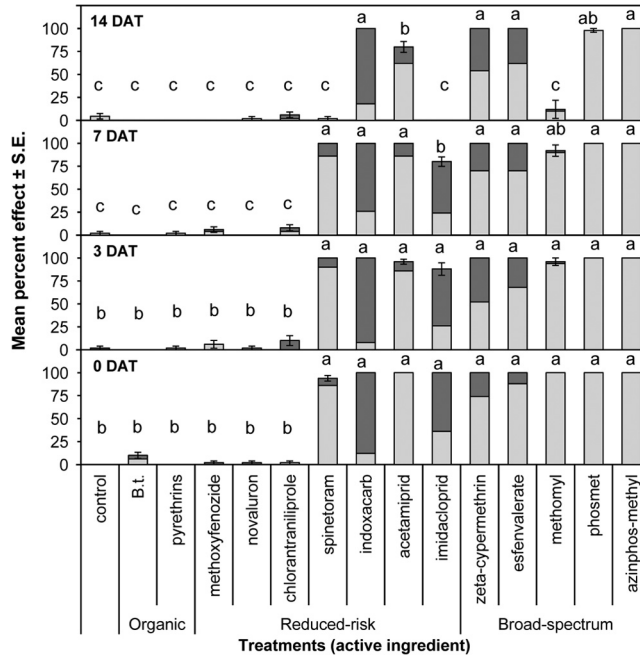


**Fig. 4.** Mean percent effect ± SE of insecticides on green lacewing, *C. rufilabris*, after 72-h exposure to residues aged 0, 3, 7, and 14 DAT. Dark portions of bars represent percent knock-down; light portions represent percent mortality. Bars with the same letter are not significantly different at $P < 0.05$.

## Discussion

In this study, we found that contact residual activity of insecticides on natural enemies common in blueberry fields is variable both among natural enemy species and among insecticides. In addition, the residual effect of different insecticides varied, suggesting that growers have options for products that control pests and minimize negative effects on natural enemies. The natural enemy species used in this study represent different orders, life histories, and feeding types; therefore, differences in their reactions to the insecticides were expected. The products evaluated also cross a range of insecticide classes with active ingredients varying in their sensitivity to different environmental conditions (Tomlin 2009); therefore, differences in residual activity also were expected. Although acute effects were recorded up to 72 h for all species, we only report results for 24-h posttreatment for *A. colemani* and *O. insidiosus* because of high control mortality after 24 h. These species can survive for longer periods of time under laboratory conditions (Kalule and Wright 2005, Wong and Frank 2013); therefore, this was likely a result of stress during shipping and lack of food throughout the experiments. Therefore, we used the shorter exposure time because the effects of insecticides and starvation could not be separated beyond the 24-h exposure time. All species of natural enemies were used as shipped from the commercial supplier; hence, ages of individuals could not be determined. This adds another source of variability to the results, but we would expect natural populations in blueberry fields to also have a mix of age ranges.

As predicted, we observed that the broad-spectrum insecticides used in our bioassays were more toxic than the reduced-risk insecticides, which in turn were more toxic than the organic products (Table 3). However, there were exceptions in each case. The reduced-risk products, acetamiprid and spinetoram, were as toxic as some of the broad-spectrum insecticides. Acetamiprid, which is classified as a reduced-risk product, was more toxic to *O. insidiosus* than imidacloprid, another neonicotinoid. In addition, acetamiprid remained highly toxic when residues were aged >7 d, whereas imidacloprid lost some toxicity over time. This difference may be because of the effect of sunlight, which accelerates the breakdown of imidacloprid but has little effect on acetamiprid (Tomlin 2009). Acetamiprid has been shown to reduce populations of some predatory arthropods in Arizona cotton fields (Naranjo and Akey 2005). Sohrabi et al. (2013), using a leaf dipping method, observed that imidacloprid was highly toxic to *Eretmocerus mundus* Mercet, a parasitoid of *Bemisia tabaci* (Gennadius), in both preimaginal and adult stages. The impact of neonicotinoids on natural enemies in greenhouse environments has been reviewed by Cloyd and Bethke (2010), who identified several natural enemies, including *Orius* spp., *H. convergens*, and *Chrysoperla carnea* (Stephens), which have shown negative reactions to this insecticide class. When considering knockdown in addition to mortality, the broad-spec-

trum insecticides affected 100% of the insects in most cases. A few individuals that were knocked down did recover, but in the process they would have been vulnerable to predation and their ability to provide biocontrol services would be reduced.

Insecticides approved for use in organic agriculture are not necessarily safer than synthetic conventional products (Johnson and Krugner 2004, Bahlai et al. 2010), but in our bioassays the organic insecticides were safest for natural enemies, particularly after residues were aged for ≥3 d. The organic products we used, pyrethrins and *B.t.*, are particularly sensitive to degradation in the presence of sunlight and UV light (Tomlin 2009). The lack of residual activity, however, may also apply to target pests, requiring multiple applications for effective control. Repeated applications could mean that natural enemies end up receiving higher chronic doses of insecticides.

Other studies using the natural enemy species evaluated in this study produced results that were similar to ours, but there were also some differences. Stara et al. (2011) observed that *A. colemani* was highly sensitive to most products tested in their residue toxicity experiments. Similar to our results, acetamiprid and indoxacarb caused high mortality (Stara et al. 2011), but the results differed for methoxyfenozide, which was less toxic in our experiment. In a contact bioassay, indoxacarb was toxic to *A. colemani* but did not show negative effects on reproductive capacity when treated wasps were allowed to parasitize aphids (Bostanian and Akalach 2004). Indirect exposure to indoxacarb through treated hosts also affects different parasitoid species differently with no significant reduction observed in *A. colemani* emergence from aphids (Bostanian and Akalach 2004), but significantly lower survival of *Trichogramma minutum* Riley from cranberry fruitworm eggs (Wise et al. 2010).

In a residue toxicity bioassay, Gradish et al. (2011) observed that chlorantraniliprole was not toxic to *O. insidiosus* adults, consistent with our results. Elzen et al. (1998) also performed laboratory bioassays by using treated leaves and showed that imidacloprid and azinphos-methyl had low toxicity to *O. insidiosus* (<10% mortality). Conversely, we found that azinphos-methyl and both neonicotinoids, imidacloprid and acetamiprid, were highly toxic to *O. insidiosus.* These differences are likely because of the different substrates used (leaves versus petri dishes), which can affect pesticide exposure (Studebaker and Kring 2003).

Fewer studies have explored the responses of *H. convergens* or *C. rufilabris* to the newer products and formulations included in our bioassays. Early experiments using imidacloprid showed that it was toxic to *H. convergens* and *C. rufilabris* in laboratory bioassays (Mizell and Sconyers 1992). Our results are consistent with previous studies using broad-spectrum insecticides: *H. convergens* adults were highly susceptible to organophosphate, carbamate, and pyrethroid insecticides (Mizell and Schiffhauer 1990, Bayoun et al. 1995). Mizell and Schiffhauer (1990) observed that *C. rufilabris* adult mortality was low for pyrethroids, azinphos-methyl, and methomyl in residue bioassays, and in general, *Chrysoperla* species were tolerant to these pesticide classes. Our results indicated that *C. rufilabris* was negatively affected by pyrethroids, although we used different products from the earlier study. Amarasekare and Shearer (2013) found that lacewing adults were very sensitive to chlorantraniliprole and spinetoram, but they included direct contact as well as residual exposure. Novaluron caused very low mortality in our experiments, but in direct contact assays, Zotti et al. (2013) showed that it is highly toxic to lacewing larvae.

Observed susceptibility to insecticides can vary based on bioassay methods. In this study, we considered only one route of exposure, residual uptake from treated surfaces. This was sufficient for comparing acute effects on adults among insecticides. The parasitoid and predators used in this study likely spend a considerable amount of time walking on plant surfaces searching for host or prey, mates, and oviposition sites; therefore, this exposure method is representative of a main exposure path for these insects. Insecticides can also have life-stage specific effects, but we included only adults in our bioassays in part because this is the critical stage for colonization of blueberry fields. Detrimental effects of insecticides on adults could prevent the spread of biological control across blueberry fields. In addition, a number of natural enemies, including the ones used in this study, are shipped from the supplier as adults, ready to be released into the field. Sublethal effects of pesticides such as reduced longevity, reduced fecundity, and changes in feeding behavior can also be detrimental to natural enemy populations and the services they provide (Desneux et al. 2007), but this was not a focus of our study. For the sake of screening as many insecticides as possible, we limited our observations to acute effects: mortality and knockdown (impaired movement).

Insecticides used in managing blueberry insect pests vary in their selectivity to natural enemies, and adoption of reduced-risk or organic products might help conserve natural enemies and enable higher levels of biocontrol (O'Neal et al. 2005). Conserving biocontrol agents in blueberries is becoming more challenging with the appearance of some key direct pests. One of these pests, *Drosophila suzukii* Matsumura, a recent invasive species (Hauser 2011, Lee et al. 2011), has forced growers to make frequent insecticide applications to keep infestation at acceptable levels.

This study provides information to guide growers' selection of insecticides based on the potential negative effects on natural enemies. Evaluating pesticide effects by using only a laboratory method may not accurately indicate how they would perform under field conditions; therefore, future studies should include multiple testing methods such as greenhouse, field trials, or both (Studebaker and Kring 2003), and other routes of exposure and sublethal effects should also be considered (Stark et al. 2007). In addition to managing insect pests, combining chemical and biological control also is expected to help minimize se-

lection for resistance (Gentz et al. 2010). Further research will be needed to determine whether adoption of an IPM program based on tactics that include use of inputs less detrimental to natural enemies enables higher levels of biological control, and therefore maintains lower pest populations in blueberry.

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## References Cited

**Amarasekare, K. G., and P. W. Shearer. 2013.** Comparing effects of insecticides on two green lacewings species, *Chrysoperla* johnsoni and *Chrysoperla carnea* (Neuroptera: Chrysopidae). J. Econ. Entomol. 106: 1126–1133.

**Bahlai, C. A., Y. Xue, C. M. McCreary, A. W. Schaafsma, and R. H. Hallett. 2010.** Choosing organic pesticides over synthetic pesticides may not effectively mitigate environmental risk in soybeans. PLoS ONE 5: e11250. doi: 10.1371/journal.pone.0011250.

**Bayoun, I. M., F. W. Plapp, Jr., F. E. Gilstrap, and G. J. Michels Jr. 1995.** Toxicity of selected insecticides to *Diuraphis noxia* (Homoptera: Aphididae) and its natural enemies. J. Econ. Entomol. 88: 1177–1185.

**Biondi, A., N. Desneux, G. Siscaro, and L. Zappalà. 2012.** Using organic-certified rather than synthetic pesticides may not be safer for biological control agents: selectivity and side effects of 14 pesticides on the predator *Orius laevigatus.* Chemosphere 87: 803–812.

**Bostanian, N. J., and M. Akalach. 2004.** The contact toxicity of indoxacarb and five other insecticides to *Orius insidiosus* (Hemiptera: Anthocoridae) and *Aphidius colemani* (Hymenoptera: Braconidae), beneficials used in the greenhouse industry. Pest Manage. Sci. 60: 1231–1236.

**Cloyd, R. A., and J. A. Bethke. 2010.** Impact of neonicotinoid insecticides on natural enemies in greenhouse and interiorscape environments. Pest Manage. Sci. 67: 3–9.

**Croft, B. A. 1990.** Arthropod biological control agents and pesticides, p. 703. Wiley, New York.

**Desneux, N., A. Decourtye, and J. M. Delpeuch. 2007.** The sublethal effects of pesticides on beneficial arthropods. Annu. Rev. Entomol. 52: 81–106.

**Dorschner, K., J. DeFrancesco, R. Isaacs, J. Wise, and D. Trinka. 2009.** The IR-4 Program: helping the US blueberry industry control high-priority insect, diseases and weed pests. Acta Hortic. 810: 293–297.

**Elzen, G. W., P. J. Elzen, and E. G. King. 1998.** Laboratory toxicity of insecticide residues to *Orius insidiosus, Geocoris punctipes, Hippodamia convergens,* and *Chrysoperla carnea.* Southwest. Entomol. 23: 335–342.

**Epstein, D. L., R. S. Zack, J. F. Brunner, L. Gut, and J. J. Brown. 2000.** Effects of broad-spectrum insecticides on epigeal arthropod biodiversity in Pacific Northwest apple orchards. Environ. Entomol. 29: 340–348.

**Gentz, M. C., G. Murdoch, and G. F. King. 2010.** Tandem use of selective insecticides and natural enemies for effective, reduced-risk pest management. Biol. Control 52: 208–215.

**Gradish, A. E., C. D. Scott-Dupree, L. Schipp, C. R. Harris, and G. Ferguson. 2011.** Effect of reduced risk pesticides on greenhouse vegetable arthropod biological control agents. Pest Manage. Sci. 67: 82–86.

**Hauser, M. 2011.** A historic account of the invasion of *Drosophila suzukii* (Matsumura) (Diptera: Drosophilidae) in the continental United States, with remarks on their identification. Pest Manage. Sci. 67: 1352–1357.

**Isaacs, R., K. S. Mason, M. Brewer, T. Noma, and M. O'Neal. 2006.** Does implementation of a reduced-risk blueberry insect control program enhance biological control? IOBC/WPRS Bull. 29: 7–11.

**Johnson, M. W., and R. Krugner. 2004.** Impact of legally compliant organic pesticides on natural enemies, pp. 69–75. *In* M. S. Hoddle (ed.), Proceedings, 4th California Conference on Biological Control, 13–15 July 2004, Berkeley, CA. Center for Biological Control, College of Natural Resources, University of California, CA.

**Kalule, T., and D. J. Wright. 2005.** Effect of cultivars with varying levels of resistance to aphids on development time, sex ratio, size and longevity of the parasitoid *Aphidius colemani.* BioControl 50: 235–246.

**Landis, D. A., M. M. Gardiner, W. van der Werf, and S. M. Swinton. 2008.** Increasing corn for biofuel production reduces biocontrol services in agricultural landscapes. Proc. Natl. Acad. Sci. U.S.A. 105: 20552–20557.

**Lee, J. C., D. J. Bruck, A. J. Dreves, C. Ioriatti, H. Vogt, and P. Baufeld. 2011.** In focus: spotted wing drosophila, *Drosophila suzukii,* across perspectives. Pest Manage. Sci. 67: 1349–1351.

**Losey, J. E., and M. Vaughan. 2006.** The economic value of ecological services provided by insects. BioScience 56: 311–323.

**Mizell III, R. F., and D. E. Schiffhauer. 1990.** Effects of pesticides on pecan aphid predators *Chrysoperla rufilabris* (Neuroptera: Chrysopidae), *Hippodamia convergens, Cycloneda sanguinea* (L.), *Olla v-nigrum* (Coleoptera: Coccinellidae), and *Aphelinus perpallidus* (Hymenoptera: Encyrtidae). J. Econ. Entomol. 83: 1806–1812.

**Mizell III, R. F., and M. C. Sconyers. 1992.** Toxicity of imidacloprid to selected arthropod predators in the laboratory. Fla. Entomol. 75: 277–280.

**Mullin, C. A., and B. A. Croft. 1985.** An update on development of selective pesticides favoring arthropod natural enemies, pp. 123–150. *In* M. A. Hoy and D. C. Herzog (eds.), Biological control in agricultural IPM systems. Academic, Orlando, FL.

**Naranjo, S. E., and D. H. Akey. 2005.** Conservation of natural enemies in cotton: comparative selectivity of acetamiprid in the management of *Bemisia tabaci.* Pest Manage. Sci. 61: 555–566.

**Naranjo, S. E., and P. C. Ellsworth. 2009.** Fifty years of the integrated control concept: moving the model and implementation forward in Arizona. Pest Manage. Sci. 65: 1267–1286.

**O'Neal, M. E., K. S. Mason, and R. Isaacs. 2005.** Seasonal abundance of ground beetles in highbush blueberry (*Vaccinium corymbosum*) fields and response to a reduced-risk insecticide program. Environ. Entomol. 34: 378–384.

**Ripper, W. E. 1956.** Effect of pesticides on balance of arthropod populations. Annu. Rev. Entomol. 1: 403–438.

**Ripper, W. E., R. M. Greenslade, and G. S. Hartley. 1951.** Selective insecticides and biological control. J. Econ. Entomol. 44: 448–459.

**SAS Institute. 2009.** SAS/STAT 9.2 user's guide, 2nd ed. SAS Institute, Cary, NC.

**Sohrabi, F., P. Shishehbor, M. Saber, and M. S. Mosaddegh. 2013.** Lethal and sublethal effects of imidacloprid and buprofezin on the sweetpotato whitefly parasitoid *Eretmocerus mundus* (Hymenoptera: Aphelinidae). Crop Prot. 45: 98–103.

**Stara, J., J. Ourednickova, and F. Kocourek. 2011.** Laboratory evaluation of the side effects of insecticides on *Aphidius colemani* (Hymenoptera: Aphidiidae), *Aphidioletes aphidimyza* (Diptera: Cecidomyiidae), and *Neoseiulus cucumeris* (Acari: Phytoseidae). J. Pest Sci. 84: 25–31.

**Stark, J. D., R. Vargas, and J. E. Banks. 2007.** Incorporating ecologically relevant measures of pesticide effect for estimating the compatibility of pesticides and biocontrol agents. J. Econ. Entomol. 100: 1027–1032.

**Stern, V. M., R. F. Smith, R. van den Bosch, and K. S. Hagen. 1959.** The integrated control concept. Hilgardia 29: 81–101.

**Studebaker, G. E., and T. J. Kring. 2003.** Effects of insecticides on *Orius insidiosus* (Hemiptera: Anthocoridae), measured by field, greenhouse and Petri dish bioassays. Fla. Entomol. 86: 178–185.

**Tomlin, C.D.S. 2009.** The pesticide manual, 15th ed. British Crop Production Council, Alton, United Kingdom.

**[USDA–NASS] U. S. Department of Agriculture–National Agricultural Statistics Service. 2010.** 2009 Fruit chemical use. (http://www.nass.usda.gov/Data_and_Statistics/Pre-Defined_Queries/2009_Fruit_Chem_Usage/index.asp).

**[USDA–NASS] U. S. Department of Agriculture–National Agricultural Statistics Service. 2012.** Non-citrus fruits and nuts 2011 summary. (http://usda01.library.cornell.edu/usda/current/NoncFruiNu/NoncFruiNu-07-06-2012.pdf).

**[US EPA] United States Environmental Protection Agency. 2012.** Guidelines for expedited review of conventional pesticides under the reduced-risk initiative and for biological pesticides. Pesticide Registration Notice 97-3 (4 Sept 1997, updated 9 May 2012). (http://www.epa.gov/pesticides/PR_Notices/pr97-3.html).

**van den Bosch, R., and V. M. Stern. 1962.** The integration of chemical and biological control of arthropod pests. Annu. Rev. Entomol. 7: 367–386.

**Völkl, W., M. Mackauer, J. K. Pell, and J. Brodeur. 2007.** Predators, parasitoids and pathogens, pp. 187–233. *In* H. F. van Emden and R. Harrington (eds.), Aphids as crop pests. CAB International, Oxfordshire, United Kingdom.

**Weinzierl, R. A. 2008.** Integrating pesticides with biotic and biological control for arthropod pest management, pp. 179–191. *In* E. B. Radcliffe, W. D. Hutchison, and R. E. Cancelado (eds.), Integrated pest management: concepts, tactics, strategies and case studies. Cambridge University Press, Cambridge, United Kingdom.

**Whalon, M. E., and E. A. Elsner. 1982.** Impact of insecticides on *Illinoia pepperi* and its predators. J. Econ. Entomol. 75: 356–358.

**Wise, J. C., P. E. Jenkins, R. Vander Poppen, and R. Isaacs. 2010.** Activity of broad-spectrum and reduced-risk insecticides on various life stages of cranberry fruitworm (Lepidoptera: Pyralidae) in highbush blueberry. J. Econ. Entomol. 103: 1720–1728.

**Wong, S. K., and S. D. Frank. 2013.** Pollen increases fitness and abundance of *Orius insidiosus* Say (Heteroptera: Anthocoridae) on banker plants. Biol. Control 64: 45–50.

**Zotti, M. J., A. D. Grutzmacher, I. H. Lopes, and G. Smagghe. 2013.** Comparative effects of insecticides with different mechanisms of action on *Chrysoperla externa* (Neuroptera: Chrysopidae): lethal, sublethal and dose-response effects. Insect Sci. 20(6): 743–752. (doi: 10.1111/1744-1917.12008.)

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