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IPM-compatibility of foliar insecticides for citrus: Indices derived from toxicity to beneficial insects from four orders

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Abstract

A series of compounds representing four major pesticide groups were tested for toxicity to beneficial insects representing four different insect orders: Coleoptera (Coccinellidae), Hemiptera (Anthocoridae), Hymenoptera (Aphelinidae), and Neuroptera (Chrysopidae). These materials included organophosphates (methidathion, esfenvalerate and phosmet), carbamates (carbofuran, methomyl and carbaryl), pyrethroids (bifenthrin, fenpropathrin, zeta-cypermethrin, cyfluthrin and permethrin) and the oxadiazine indoxacarb. Toxicity to coccinellid and lacewing species was assessed by treating 1st instar larvae with the recommended field rate of commercial products, and two 10 fold dilutions of these materials, in topical spray applications. Adult *Aphytis melinus* Debach and 2nd instar *Orius insidiosus* (Say) were exposed to leaf residues of the same concentrations for 24 h. ANOVA performed on composite survival indices derived from these data resolved significant differences among materials with respect to their overall toxicity to beneficial insects. Cyfluthrin, fenpropathrin and zeta-cypermethrin all increased the developmental time of the lacewing and one or more coccinellid species for larvae that survived topical applications. Bifenthrin increased developmental time for two coccinellid species and decreased it in a third. Indoxacarb (Avaunt® WG, DuPont Corp.) ranked highest overall for safety to beneficial insects, largely because of its low dermal toxicity to all species tested. Zeta-cypermethrin (Super Fury®, FMC Corporation) received the second best safety rating, largely because of its low toxicity as a leaf residue to *A. melinus* and *O. insidiosus*. Phosmet (Imidan® 70W, Gowan Co.) and methidathion (Supracide® 25W, Gowan Co.) ranked high for safety to coccinellid species, but compounds currently recommended for use in citrus such as fenpropathrin (Danitol® 2.4EC, Sumimoto Chem. Co.) and carbaryl (Sevin® XLR EC, Rhone Poulenc Ag. Co.) ranked very low for IPM-compatibility based on their relatively high toxicity to all species tested.

Keywords: Aphytis melinus, *Chrysoperla rufilabris*, *Curinus coeruleus*, *Cycloneda sanguinea*, *Harmonia axyridis*, insecticides, *Olla v-nigrum*, *Orius insidiosus*

Abbreviation:
FR field rate

Introduction

A potential problem arising from broadcast pesticide applications is the disruption of beneficial insect populations important in biological control processes. Such disruptions can lead to resurgence of secondary pests (Trumper & Holt, 1998) and 'pesticide treadmill' scenarios (Bellows *et al.*, 1985). The majority of citrus produced in Florida is destined for juicing and receives very few treatments with hard pesticides. Consequently, a myriad of acarine, homopteran and lepidopteran pests are usually held at sub-economic levels by a robust community of natural enemies. Nevertheless, periodic outbreaks of pests such as the Asian citrus psyllid, *Diaphorina citri* Kuwayama, and the citrus leafminer, *Phyllocnistis citrella* Stainton, have necessitated relatively widespread applications of foliar insecticides in recent years. Other pests such as the citrus root weevil, *Diaprepes abbreviatus* L., have remained a chronic problem in particular groves, with adult weevils becoming a perennial target of insecticide treatments during periods of new citrus growth. The net result is a need for evaluating insecticides, not only for efficacy against these target pests, but also for their safety to a range of beneficial insects that are relied upon to maintain biological control of many other citrus pests.

Since broadcast pesticide applications directed against foliage-feeding insects are most likely to disrupt foraging natural enemies, we compared the relative toxicity of a range of foliar materials to a number of beneficial insects that are all important in biological control of citrus pests. The objective was to construct a rating scale for materials representative of the major pesticide groups based on their respective toxicity to beneficial insects representative of four insect orders: Coleoptera: Hemiptera, Hymenoptera, and Neuroptera. Materials currently registered for foliar use in Florida citrus include various pyrethroids, organophosphates, and carbamates (2003 Florida Citrus Pest Management Guide). Some materials not currently registered for use in citrus were used that are under evaluation for efficacy against persistent pests, such as *D. abbreviatus*. In addition, several novel compounds with unique modes of action that are pending registration for use on citrus in Florida were also used. As citrus is a relatively minor crop in U.S. agriculture, documents provided online by the National Agricultural Statistics Service (http://www.usda.gov/nass) were consulted to ensure that materials were included with broad national usage patterns as well as those applied in citrus (Table 1). Between 1996 and 2000, more than 1,000,000 lbs. of methomyl and 800,000 lbs of permethrin were applied to fruits, nuts, vegetables and cotton in the United States. Forages, field and vegetable crops received 998,000 lbs. of carbofuran during 1997 and 1998, but this increased to 1,979,000 lbs. during 1999 and 2000. Between 1997 and 2001, the use of carbaryl in Florida citrus increased from 31,000 lbs. to 187,000, with national agricultural usage increasing from 195,000 lbs. to 485,000 lbs. Some 770,000 lbs. of phosmet and 142,000 lbs. of esfenvalerate were applied to fruits, nuts and vegetables in the U.S. between 1996 and 2000. Although agricultural use of bifenthrin is relatively limited, national usage tripled between 1997 and 2000. In Florida citrus, bifenthrin is used as a soil barrier against *D. abbreviatus* neonate larvae (McCoy *et al.*, 2001). Cyfluthrin, fenpropathrin and zeta-cypermethrin are all 'type II' pyrethroids that, although not used in large quanities prior to 2000, have seen expanded registration for use on a wider range of crops in recent years.

Among the Coleoptera, the Coccinellidae are especially important as generalist predators of many pests. Four species of Coccinellidae were available for testing, all maintained in continuous culture in our laboratory: *Curinus coeruleus* Mulsant, *Cycloneda sanguinea* L., *Harmonia axyridis* Pallas, and *Olla v-nigrum* Mulsant. These species are all common in Florida citrus groves where they contribute to control of aphids, psyllids and other homopteran pests (Michaud, 2000; 2001; 2002a). The order Hymenoptera includes many parasitic species important in biological control. *Aphytis melinus* DeBach (Hymenoptera: Aphelinidae) was selected for testing. It is a species widely recognized in citrus production as an effective parasitoid of California red scale, *Aonidiella aurantii* (Maskell), especially in regions where the scale has developed resistance to insecticides (Grafton-Cardwell *et al*., 2001). The order Hemiptera includes generalist predators in the families Anthocoridae, Nabidae and Reduviidae among others. The insidious flower bug, *Orius insidiosus* (Say) (Hemiptera: Anthocoridae), was selected for testing. It is a predator of thrips and other small insects (Funderburk et al., 2000; Mendes *et al.*, 2002). The order Neuroptera includes at least two families with species that contribute to biological control of citrus pests, Chrysopidae and Hemerobiidae. *Chrysoperla rufilabris* Burmeister (Neuroptera: Chrysopidae), a generalist predator of aphids, psyllids and leafminers (Inamullah & Morse, 1999; Michaud, 1999), was selected as a representative of this order. The latter three species are also readily available from commercial sources, rendering them practical candidate agents for use in augmentation biological control programs.

Materials and Methods

Insects

Adults of *A. melinus* were obtained by mail order from Biocontrol Network (www.biconet.com). Eggs of *O. insidiosus* were obtained by mail order from Entomos LLC (www.anbp.org/Entomos.htm). Eggs of *C. rufilabris* in citrus groves were obtained by mail order from Beneficial Insectary (www.insectary.com). Coccinellid species were reared in the laboratory at 24 ± 1º C under 'cool white' fluorsescent lighting (L:D = 16:8). The colonies were all initiated from adults that were field-collected from citrus groves in Polk County, Fl, in February, 2002, except for *C. coeruleus* that was collected in St. Lucie County, FL in August, 2001. Adult beetles were maintained in 1 liter, wide-mouth mason jars containing shredded wax paper and covered with muslin. While in the jars, beetles were fed a combination of bee pollen and frozen eggs of the flour moth *Ephestia kuehniella* Zeller (Lepidoptera: Pyralidae). Distilled water was made available continuously on a cotton wick. Sexually mature females were removed from jars for oviposition

Table 1. List of compounds, formulations and field rates of materials tested, assuming a field application volume of 1168 L / hectare (= 125 gallons per acre). [1]material registered for use on citrus; [2]registration for use on citrus pending.

Material	Trade Name	Formulation	Manufacturer	Field Rate (ppm)	Pesticide Group
indoxacarb[2]	Avaunt®	WG	DuPont	113	oxadiazine
bifenthrin[1]	Capture®	2 EC	FMC Corporation	500	pyrethroid
fenpropathrin[1]	Danitol®	2.4 EC	Valent	309	pyrethroid
zeta-cypermethrin	Super Fury®	0.8 EC	FMC Corporation	16	pyrethroid
cyfluthrin	Baythroid®	2 emulsifiable	Bayer	500	pyrethroid
permethrin	Pounce®	3.2 EC	FMC Corporation	384	pyrethroid
carbofuran	Furadan®	4F	FMC Corporation	880	carbamate
methomyl	Lannate®	LV	Dupont	870	carbamate
carbaryl[1]	Sevin XLR®	EC	Rhone Poulenc	8240	carbamate
methidathion	Supracide®	25W	Novartis	500	organophosphate
esfenvalerate	Asana®	XL	Dupont	42	organophosphate
phosmet	Imidan®	70 W	Gowan	1400	organophosphate

and isolated in plastic Petri dishes (5.5 cm diam. x 1.0 cm) where they were provided with frozen *Ephestia* eggs and water encapsulated in polymer beads (Entomos, LLC) as required. Eggs were harvested daily and held in a Plexiglass incubator until eclosion 3-4 days later (7-8 days for *C. coeruleus*). Newly eclosed larvae were reared in Petri dishes (as above) on a diet of frozen *Ephestia* eggs with water available in polymer beads.

Pesticides

The materials selected included representatives of three major classes of insecticides - organophosphates, carbamates and pyrethroids, and one oxadiazine (indoxacarb), a new class of compound with a novel mode of action (Table 1). Six materials (indoxacarb, bifenthrin, fenpropathrin, zeta-cypermethrin, carabaryl and methidathion) were tested on insects from all the four insect orders. These materials are either registered for use on citrus, have registration pending, or have shown promise in preliminary efficacy trials against *D. abbreviatus*. Another six materials (esfenvalerate, cyfluthrin, permethrin, carbofuran, methomyl and phosmet) were tested only on larvae of Coccinellidae and Chrysopidae because of logistic constraints. Experiments were repeated with three concentrations of each material beginning with the recommended field rate (FR), and proceeding to tenfold dilutions thereof (FR/10, and FR/100). A fourth concentration corresponding to FR/1000 was tested for some species-material combinations when survival at FR/100 was not high enough to permit comparison of developmental times.

Experiments - topical sprays

Predatory larvae of Coccinellidae and Chrysopidae 24 (± 6) h-old were placed into plastic Petri dishes (5.5 cm diameter x 1.0 cm) in groups of seven or eight for topical spray treatments. Larvae were sprayed with materials in a Potter Precision Spray Tower (Burkard Manufacturing Co. Ltd., http://pollenuk.worc.ac.uk/Burkard/Default.html). The tower was calibrated to deliver the smallest possible droplet size to achieve complete coverage of the treated area. Spray deposition was visualized by spraying 1 ml of distilled water onto water sensitive paper (Novartis Corp. www.novartis.com). Papers treated in the tower exhibited complete color-change and did not resolve individual droplets. Larvae in control groups (n = 20) were sprayed with 1 ml of distilled water; larvae in treatment groups (n = 20) were sprayed with 1 ml aqueous solution of the test material. Following these treatments, individual larvae were immediately isolated in individual Petri dishes (as above) and provisioned with *Ephestia* eggs and water beads. All larvae were reared to adults to determine the survival rate at each concentration and this value was corrected for control mortality using Abbott's formula (Abbott, 1925). Developmental time was calculated for each larva as the number of days from hatching to the formation of a prepupae. Data for developmental time was compared between treatment and control insects using a one-way ANOVA (SPSS, 1998).

Experiments – leaf residues.

Adults of *A. melinus* are active flyers and nymphs of *O. insidiosus* are fast-moving insects, rendering these species unsuitable for treatment by topical spray application in the tower. Therefore, the toxicity of materials to adult *A. melinus* (< 3 d old) and to 2nd instar nymphs of *O. insidiosus* was determined by exposing the insects to material residues on leaf disks. Freshly picked grapefruit leaves were washed in a 0.005% solution of Chlorox® bleach, rinsed in distilled water, and dried on paper towels. Leaf disks (3 cm in diameter) were punched from the leaves using a leaf punch. Leaf disks in treatment series (n = 20-25) were sprayed with 1 ml aqueous solution of the test material in the Potter Tower; leaf disks in control series (n = 20-25) were sprayed with 1 ml distilled water. Both treated and control leaf disks were placed into labeled plastic Petri dishes (3.5 cm x 1.0 cm). For *O. insidiosus* nymphs, a small measure of *Ephestia* eggs (ca. 0.05 g) was placed in the center of each disk so that insects would be induced to traverse the leaf to access the food. For *A. melinus* adults, a 1 μl droplet of diluted honey was smeared on the lid of each dish using a micropipette. Single insects were transferred individually to each dish and left for a period of 24 h. After this period, each insect was transferred to a clean dish and provisioned with fresh food (*Ephestia* eggs for *O. insidiosus*, diluted honey for *A. melinus*). Survival was calculated for *A. melinus* as the number alive on day three following treatment. Survival was calculated for *O. insidiosus* as the number molting to the adult stage. In both cases, survival data was adjusted for control mortality using Abbott's formula (Abbott, 1925).

Calculation of survival indices

For each insect-material combination, the corrected proportional survival was expressed as a decimal for each of the three material concentrations tested. Each value was then multiplied by the reciprocal of the corresponding dilution rate (100, 10, and 1 for FR, FR/10, and FR/100, respectively), and the resulting three values were averaged. Thus survival at higher concentrations was weighted proportionally more than survival at lower concentrations. In the case of Hemiptera, Hymenoptera and Neuroptera, the survival index for each compound represented that of the single species tested. In the case of Coleoptera, the survival index for each compound was averaged over the four species tested. This procedure yielded four survival indices for each of the six materials that were tested on all four insect orders, each corresponding to one insect order. These indices were then analysed by one-way ANOVA to detect any differences in overall toxicity of the materials, or in the overall sensitivity of insects. Since in the case of Coleoptera there were four survival indices for each compound corresponding to each of the four species, the mean toxicity of all twelve materials was compared across the four coccinellid species. Composite indices were then calculated for each of the six compounds tested on all species by averaging values across the four insect orders.

Results

The mortality data for all species tested with topical spray applications, corrected for control mortality, are given in Table 2. The corrected mortality data for all species tested with leaf residues are given in Table 3.

A comparison among coccinellid species of topical spray survival indices for all materials revealed no significant variation among species in their general sensitivity ($F = 0.852$; 3,44 df; $P = 0.473$). The overall comparison of coccinellid survival indices

Table 2. Corrected percent mortality of five insect species treated as first instar larvae with topical spray applications of twelve pesticides at each of three different concentrations. FR = field rate (refer to Table 1 for ppm).

	Order: Family →		Coleoptera: Coccinellidae				Neuroptera: Chrysopidae
Pesticide	Species →		*Curinus coeruleus*	*Cycloneda sanguinea*	*Harmonia axyridis*	*Olla v-nigrum*	*Chrysoperla rufilabris*
Group	Compound	Rate					
Pyrethroid	cyfluthrin	FR	100.0	100.0	100.0	100.0	100.0
		FR / 10	100.0	100.0	100.0	100.0	15.0
		FR / 100	100.0	9.7	0.0	15.3	0.0
	bifenthrin	FR	100.0	100.0	100.0	100.0	100.0
		FR / 10	100.0	100.0	100.0	100.0	6.7
		FR / 100	100.0	100.0	100.0	52.6	0.0
	fenpropathrin	FR	100.0	100.0	100.0	100.0	100.0
		FR / 10	100.0	100.0	100.0	100.0	55.0
		FR / 100	47.1	55.0	75.0	0.0	27.0
	zeta-cypermethrin	FR	100.0	100.0	100.0	100.0	100.0
		FR / 10	100.0	100.0	100.0	100.0	20.7
		FR / 100	100.0	100.0	100.0	17.6	10.5
	permethrin	FR	100.0	100.0	100.0	100.0	100.0
		FR / 10	100.0	100.0	100.0	100.0	100.0
		FR / 100	25.0	27.8	60.0	25.0	5.6
Carbamate	carbofuran	FR	100.0	100.0	100.0	100.0	100.0
		FR / 10	100.0	100.0	100.0	100.0	100.0
		FR / 100	100.0	100.0	100.0	85.0	11.8
	methomyl	FR	100.0	100.0	100.0	100.0	100.0
		FR / 10	100.0	100.0	100.0	61.1	100.0
		FR / 100	62.5	26.7	80.0	10.0	0.0
	carbaryl	FR	100.0	100.0	100.0	100.0	100.0
		FR / 10	100.0	100.0	100.0	100.0	100.0
		FR / 100	100.0	82.4	100.0	94.7	4.4
Organophosphate	esfenvalerate	FR	100.0	100.0	100.0	100.0	73.6
		FR / 10	100.0	100.0	100.0	100.0	10.0
		FR / 100	31.4	49.7	15.0	15.0	0.0
	methidathion	FR	100.0	100.0	100.0	100.0	15.0
		FR / 10	40.0	38.5	100.0	26.1	10.5
		FR / 100	0.0	0.0	10.0	0.0	0.0
	phosmet	FR	100.0	100.0	100.0	16.2	100.0
		FR / 10	100.0	26.7	85.0	0.0	5.6
		FR / 100	6.2	0.0	10.5		0.0
Oxadiazine	indoxacarb	FR	100.0	35.3	33.0	89.5	25.0
		FR / 10	5.2	0.0	0.0	5.0	0.0

Table 3. Corrected percent mortality of two insect species treated either as second instar nymphs (*O. insidiosus*) or adults < 3 days old (*A. melinus*) with 24 h exposures to leaf residues of six pesticides at each of three different concentrations. FR = field rate (refer to Table 1 for ppm).

			Orius insidiosus Hemiptera: Anthocoridae	*Aphytis melinus* Hymneoptera: Aphelinidae
Pesticide Group	Compound	Rate		
Pyrethroid	bifenthrin	FR	95.7	95.5
		FR / 10	72.7	52.3
		FR / 100	44.4	16
	fenpropathrin	FR	95.7	100
		FR / 10	63.6	12
		FR / 100	25	0
	zeta-cypermethrin	FR	56.2	64.8
		FR / 10	27.3	8.1
		FR / 100	7.1	0
Carbamate	carbaryl	FR	95.6	100
		FR / 10	86.4	14.3
		FR / 100	28.6	0
OP	methidathion	FR	100	100
		FR / 10	36.4	95.7
		FR / 100	14.3	26.7
Oxadiazine	indoxacarb	FR	38.1	65.7
		FR / 10	15.6	2
		FR / 100	4.1	1.2

among materials produced a marginally significant result ($F = 1.903$; 11,36 df; $P = 0.072$), and the LSD test resolved some significant differences ($P < 0.05$) among means (Fig. 1). Topical spray survival indices for *C. rufilabris* larvae are depicted in Fig. 2, and those for materials applied as leave residues to *A. melinus* and *O. insidiosus* in Figs. 3 and 4, respectively. When composite survival indices were calculated for each material and weighted equally for each of the four insect orders, there were significant differences among materials in their overall toxicity ($F = 7.161$; 5,18 df; $P < 0.001$; Fig. 5).

A number of materials had effects on the developmental time of predatory larvae in topical spray applications. *H. axyridis* larvae surviving methidathion at the field rate /100 had their developmental time extended by 0.54 days ($F = 17.277$; 1,34 df; $P < 0.001$). Similarly, *C. sanguinea* larvae surviving esfenvalerate at 1/100 the field rate had their developmental time extended by about 10%, or 0.94 days ($F = 6.485$; 1,23 df; $P = 0.018$). The pyrethroid insecticides, as a group, had the most effects on insect developmental time and those that had significant effects ($P < 0.05$) on two or more species are depicted in Fig. 6. No other effects on developmental time were significantly different between control and treatment in any other species-material combinations.

Discussion

Some disagreement exists with respect to how plant protection products should be tested for non-target effects on beneficial insects. The IOBC Working Group has recommended the testing of at least four different species in the laboratory under 'worst case' conditions (Vogt, 2000), and favored the use of the most sensitive 'indicator' species in order to err on the side of safety for non-targets. Their data provide evidence that far fewer materials emerge as harmful in semi-field trials compared to the number that appear harmful in the laboratory. In contrast, Hattingh *et al.* (2000) recommended the selection of indicator species that are neither extremely sensitive, nor extremely resistant. In the present study, we tested a range of taxonomically diverse species that are relevant to a particular cropping system, without any a priori assumptions regarding their relative sensitivity.

The objective of this study was not to compare the relative toxicities of active ingredients across a range of concentrations as would be the case with standard LC-50 determinations, but rather to compare their relative impact on populations of beneficial insects when applied at field rates recommended for citrus. A similar attempt to derive a comprehensive system for classifying pesticides for non-target impacts on beneficial insects in citrus was that of Hattingh *et al.* (2000). Their approach employed a series of insects from diverse taxonomic groups, as did ours, but also incorporated a component of field persistence for each compound, where our system did not. However, our approach incorporated mortality at three material concentrations, as opposed to only the field rate, and immature insects were held until they completed development to the adult stage, as opposed to having mortality measured only after 24-48 hours. Also, we selected to rank our ratings numerically, as opposed to grouping them in arbitrary impact categories. Direct comparison of results is not possible because ratings for particular materials

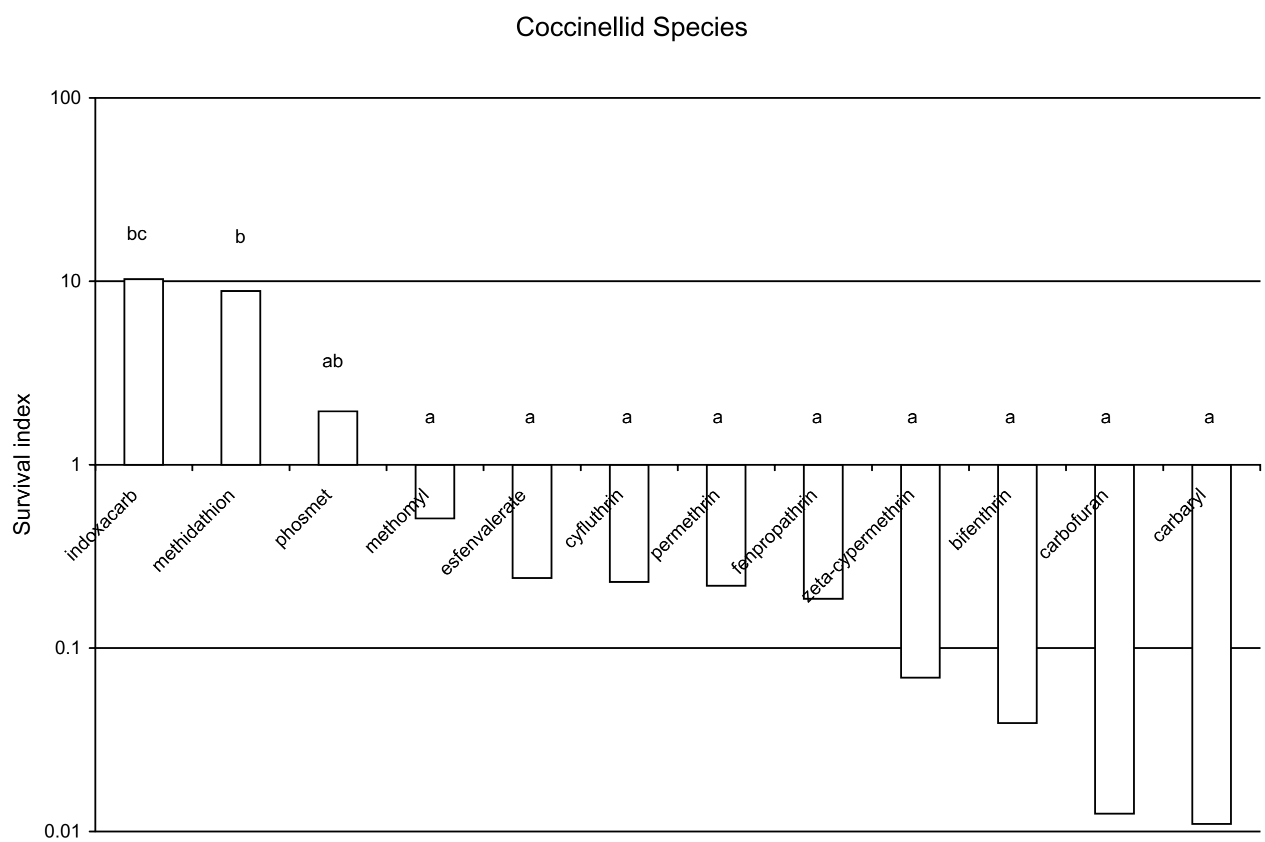

Figure 1. Mean survival indices calculated for four coccinellid species treated as first instar larvae with topical spray applications of 12 insecticides at three concentrations. Columns bearing the same letter were not significantly different in a one-way ANOVA followed by LSD ($\alpha \leq 0.05$).

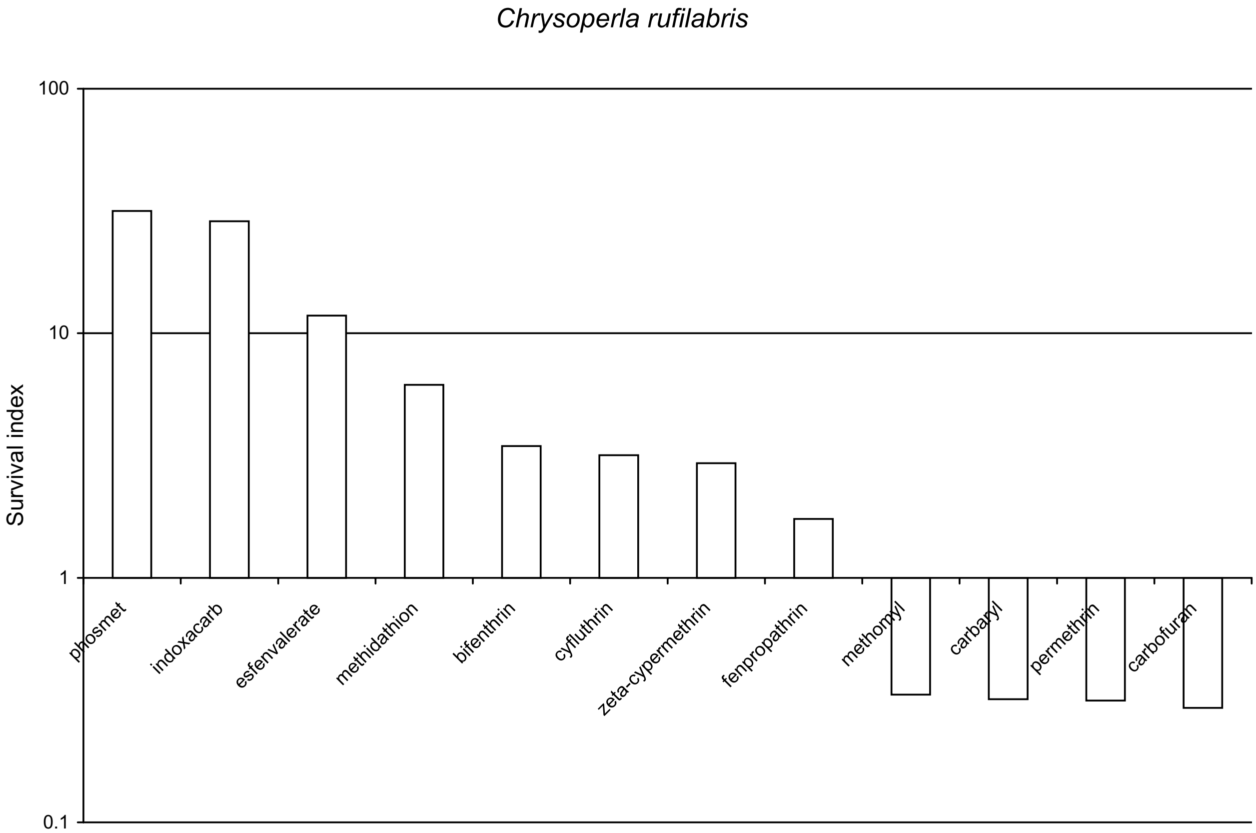

Figure 2. Mean survival indices calculated for *Chrysoperla rufilabris* treated as first instar larvae with topical spray applications of 12 insecticides at three concentrations.

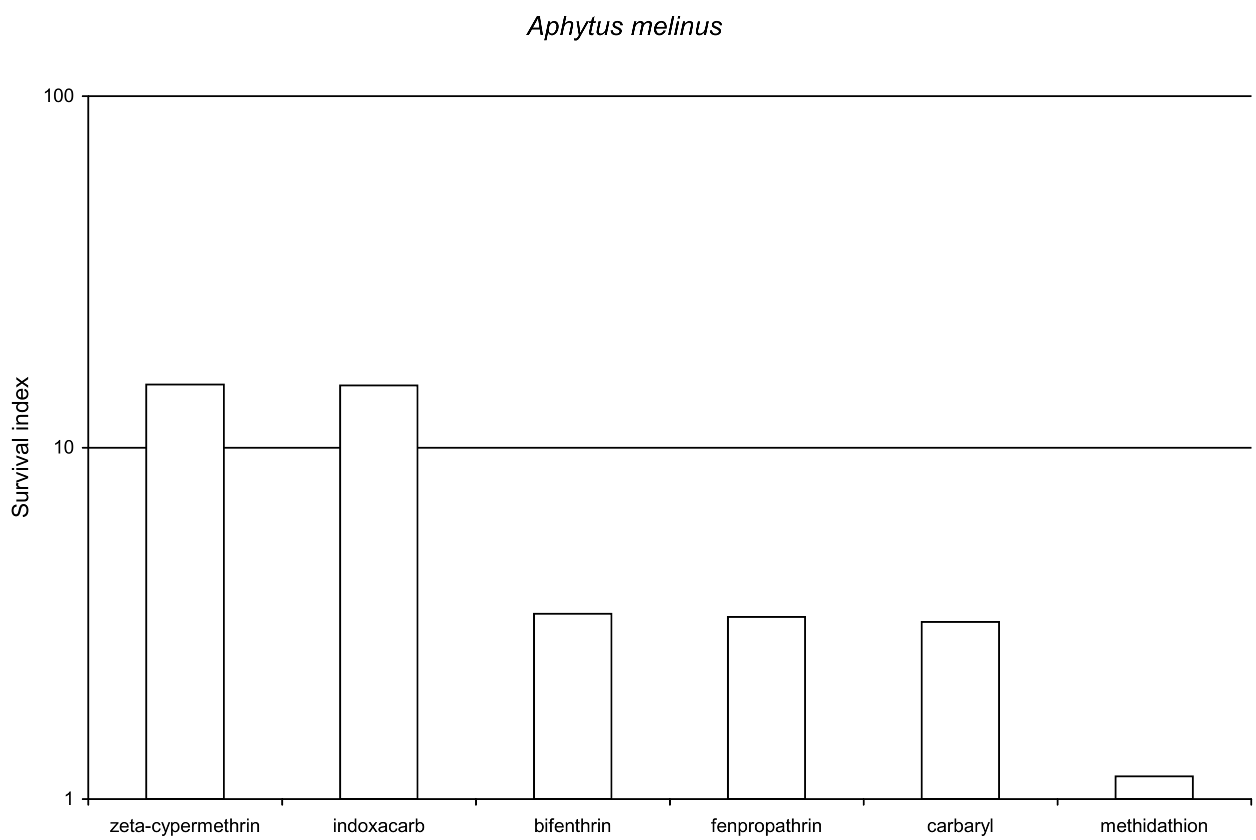

Figure 3. Mean survival indices calculated for *Aphytis melinus* treated as adults (< 3 d old) with 24 h exposures to leaf residues of six insecticides applied at three concentrations.

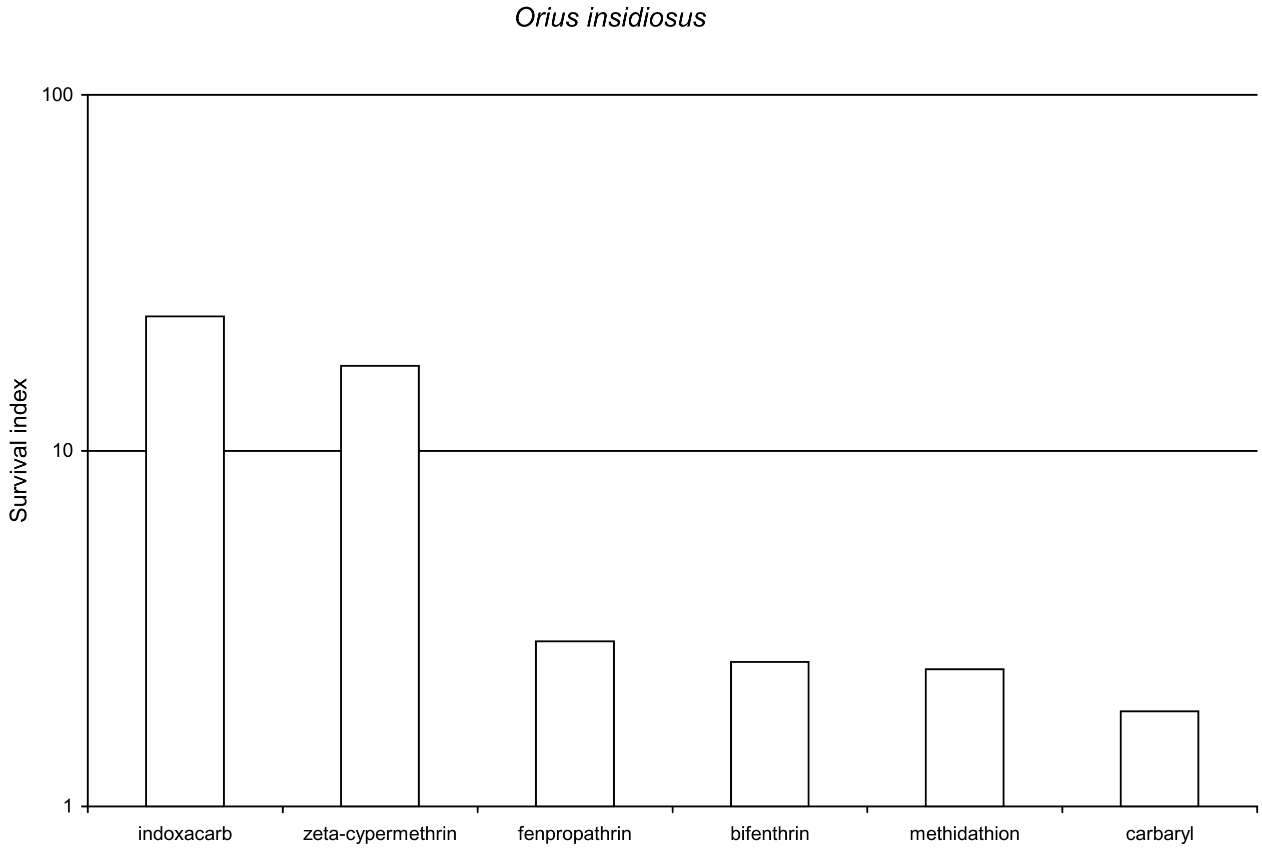

Figure 4. Mean survival indices calculated for *Orius insidiosus* treated as second instar nymphs with 24 h exposures to leaf residues ofsix insecticides applied at three concentrations.

were not reported in the former paper. The major shortcoming of our particular index calculation is relatively poor resolution among either highly toxic, or predominantly benign, materials, although resolution between these two groups is excellent. Because all highly toxic materials yield very low survival values (and hence low indices) a single species exhibiting good survival can substantially augment the index for a particular compound. Nevertheless, we contend that any numerical ranking system of this sort is still preferable to categorizing compounds as 'highly toxic', 'moderately toxic' etc. by virtue of arbitrary criteria, as has often been the convention for these sorts of data.

The lack of significant differences among coccinellid species in terms of their overall sensitivity to materials, as determined by ANOVA of their survival indices for twelve compounds, might suggest that the testing of a single species could be adequate for predicting general insecticide susceptibility within the family Coccinellidae, and that any of these could be useful as an indicator species. While previous work (Michaud, 2002b; 2002c) indicated that *C. sanguinea* has a generally higher susceptibility to many pesticides than does *H. axyridis*, this pattern was not evident in the present study. However, the former studies included both leaf residue assays and topical sprays and did not attempt direct statistical comparisons of sensitivity. Bartlett (1963) tested larvae and adults of six coccinellid species that spanned a broader range of subfamilies (our study had only one chilochorine species, *C. coeruleus*, and three coccinelline species). Although Bartlett (1963) tested a wide range of older materials, he found far more diverse responses among coccinellid species. In contrast, the sensitivities of hymenopterous parasitoids were generally higher and far more uniform across species in the same study. However, our data did reveal significant differences among materials across coccinellid species (Fig. 1). The order of toxicity was generally highest for carbamates (with the exception of methomyl), followed by pyrethroids and organophosphates. A similar pattern was observed for *C. rufilabris* (Fig. 2). Indoxacarb and methidathion had lower contact toxicity for the coccinellids than all other materials except phosmet. Similarly, Edwards & Hodgson (1973) found carbamates to be highly toxic to the coccinellid *Stethorus nigripes*, an important mite predator in citrus. Cho *et al*. (1997) found esfenvalerate to be the most toxic of materials they tested against *H. axyridis* and its toxicity index to the coccinellid species in this study was not significantly lower than that of the carbamates and pyrethroids (Fig. 1).

It is notable that effects on the developmental rate of predatory larvae in the topical spray assays resulted almost exclusively from exposure to pyrethroid materials (Fig. 6), with the singular exception of *H. axyridis* larvae surviving methidathion exposure. The effect was typically increased developmental time, an obviously negative effect on fitness, but there were also two instances of reduced developmental time. Michaud (2002b) observed accelerated development of *H. axyridis* larvae following exposure to leaf residues of fenpropathrin. Although accelerated larval development in response to diet or temperature is generally favorable for insects, it may well have negative effects on the adult when it results from exposure to toxic materials, effects that were neither observed nor measured in these trials.

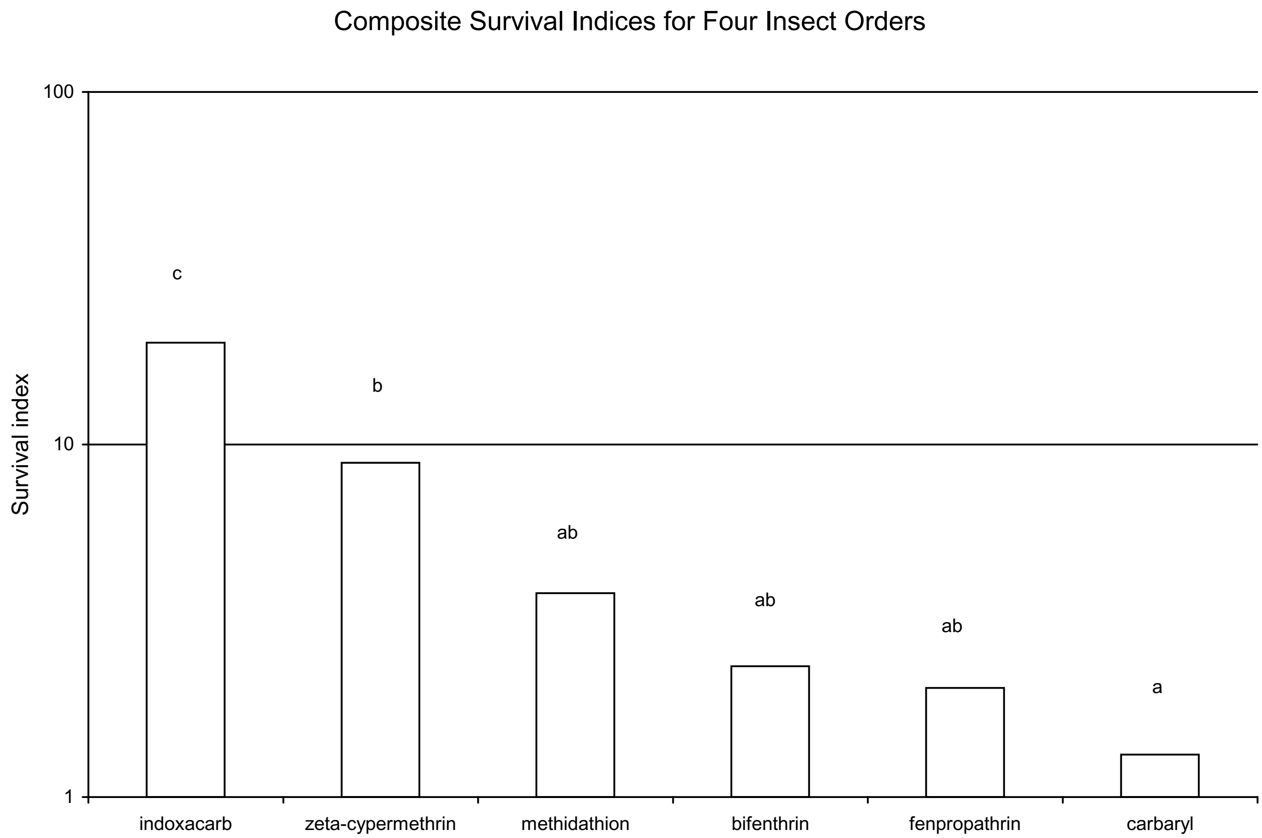

Figure 5. Composite mean survival indices derived from four insect orders exposed to six materials, each applied at three concentrations. Columns bearing the same letter were not significantly different in a one-way ANOVA followed by LSD ($\alpha \leq 0.05$).

Bellows & Morse (1993) found that toxicity to *A. melinus* and *Rhizobius lophanthae* (Coleoptera: Coccinellidae) was highest for pyrethroids, followed by carbamates and organophosphates, and that fenpropathrin was the most toxic of the pyrethroids. The responses of *A. melinus* and *O. insidiosus* to these chemical groups were quite similar in our trials (Figs. 3 & 4) and indicate high sensitivity to carbaryl and methidathion, as well as the pyrethroids fenpropathrin and bifenthrin. Carbaryl and methidathion were both found to elevate populations of citrus red mite, *Panonychus citri*, in both years of a two year field study in California citrus (Walker & Aitken, 1996). Morse & Bellows (1986) compared the toxicity of various insecticides over a range of concentrations to *A. melinus* and *Cryptolaemus montrouzieri* and generated concentration-mortality regressions to compare sensitivity. They found that *A. melinus* was generally more sensitive than the coccinellid to materials demonstrating toxicity, including methidathion and carbaryl, and our findings seem consistent with their results. Al-Deeb *et al.* (2001) showed generally high sensitivity of *O. insidiosus* to a large number of insecticides used on corn, sorghum and alfalfa, both in the presence and absence of prey.

Comparison of our composite survival indices revealed significant differences among materials in their overall toxicity to beneficial insects (Fig. 5). Notably, fenpropathrin and carbaryl, both materials currently registered for use in Florida citrus and relied upon to control various foliar-feeding citrus pests (2003 Florida Citrus Pest Management Guide), were the least selective for biological control agents. Carbaryl usage in citrus has been previously linked to increases in populations of *P. citri* (Ho, 1984). Part of the reason carbaryl emerged as so toxic in these assays may derive from the high field rate employed (Table 1), a rate required to prolong residual activity on citrus foliage (Wong *et al.*, 1975). Fenpropathrin was previously shown to have high toxicity to *C. sanguinea* and *H. axyridis* in both topical spray and leaf residue assays (Michaud, 2002b). Integrated management of citrus pests might be improved if alternatives could be substituted for these materials. Among the pyrethroids, zeta-cypermethrin (Super-Fury®) scored significantly less toxic than either fenpropathrin (Danitol®) or bifenthrin (Pounce®), largely as a result of its low toxicity as a leaf residue to *A. melinus* and *O. insidiosus*. However, indoxacarb emerged as significantly safer than all other materials to these biological control agents as a group (Fig. 5).

Avaunt® (indoxacarb) has been classified as a "reduced risk" insecticide to be considered as a replacement for various organophosphate materials (United States Environmental Protection Agency, 2000). However, the same document states that indoxacarb has a high contact toxicity for bees, a finding that would not have been predicted from the results of this study that indicate low contact toxicity to all insects tested, whether contact was by direct spray or by exposure to dried residues. It seems likely bees might be susceptible to ingesting indoxacarb residues on pollen or disolved in nectar. Wing *et al.* (2000) reported that the toxicity of indoxacarb to insects is dependent on bioactivation of the parent oxadiazines to the S-enantiomers of *N*-decarbomethoxylated metabolites. This process may occur to varying degrees in different insects, leading to variation in susceptibility.

The primary, but not exclusive, route of entry of indoxacarb is via ingestion (Andaloro *et al.*, 2000), a factor that may contribute to its safety for beneficial insects that do not consume treated foliage. Similarly, Spinosad® requires bioactivation following ingestion and becomes toxic to some beneficial insects, particularly Hymenoptera and Neuroptera, when consumed in a bait formulation (Michaud 2003). Tillman *et al.* (2002) concluded that major route of indoxacarb intoxication of *Lygus lineolaris* was oral ingestion, rather than cuticular exposure. The same authors found that indoxacarb caused negligible mortality to the hemipteran predator *Geocoris punctipes* and that it had minimal impact on field populations of beneficial insects in cotton. Ruberson *et al.* (1999) tested indoxacarb for toxicity against *C. rufilabris*, *O. insidiosus, G. punctipes*, *Trichogramma pretiosum* and *Cotesia marginiventris* and reported no adverse effects on any of these species. Pasqualini *et al.* (1999) likewise concluded that indoxacarb was safe for *Anthocoris nemoralis*. Nowak *et al.* (2001) measured toxicity of indoxacarb to four parasitoids of the Nantucket pine tip moth that was no different from controls, and lower than that of spinosad, permethrin, or lamda-cyalothrin. Safety of indoxacarb has also been reported for the Phytoseiid mites *Amblyseius andersoni* (Mattedi *et al.*, 1998) and *Kampimodromus aberrans* (Mori *et al.*, 1999). Susceptible insects include species of Lepidoptera, some Homoptera, and certain Coleoptera. Our results indicate that indoxacarb is significantly safer than pyrethroids or carbamates for the major groups of beneficial insects in citrus. Further research is warranted to determine its potential efficacy against foliage-feeding pests such as the citrus leafminer, *P. citrella*, Asian citrus psyllid, *D. citri*, and the citrus root weevil, *D. abbreviatus*. IPM-compatible alternatives should be sought for the currently registered materials fenpropathrin and carbaryl that appear to have high contact toxicity for most beneficial insects.

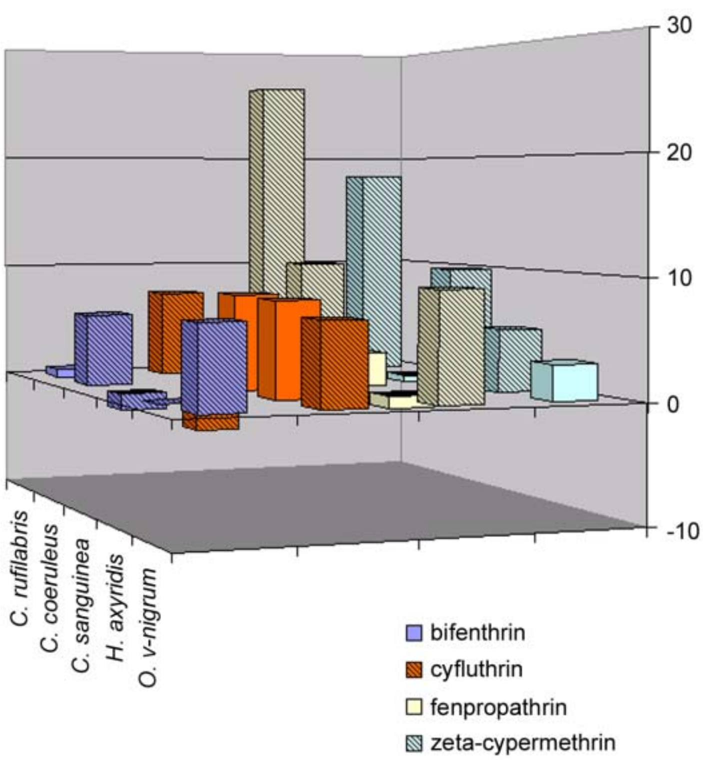

Figure 6. Mean percentage increases or decreases in developmental time for predatory larvae treated with topical sprays of four pyrethroid insecticides applied at various concentrations. Unshaded bars indicate values not significantly different from controls in one-way ANOVA ($P > 0.05$). The respective material concentrations for *C. rufilabris*, *C. coeruleus*, *C. sanguinea*, *H. axyridis* and *O. v-nigrum* were as follows: bifenthrin – FR/10, FR/1000, FR/1000, FR/1000 and FR/100; cyfluthrin – FR/10, FR/1000, FR/100, FR/100 and FR/100; fenpropathrin – FR/10, FR/100, FR/100, FR/1000 and FR/100; zeta-cypermethrin – FR/10, FR/1000, FR/1000, FR/1000 and FR/100. FR = field rate (see Table 1 for ppm).

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