Effect of Pesticides on *Colpoclypeus florus* (Hymenoptera: Eulophidae) and *Trichogramma platneri* (Hymenoptera: Trichogrammatidae), Parasitoids of Leafrollers in Washington

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ABSTRACT Pesticides were evaluated for their effect on two parasitoid species, *Colpoclypeus florus* and *Trichogramma platneri,* that are potential biological control agents of leafrollers in apple orchards. Organophosphate and carbamate insecticides were highly toxic to both parasitoids in topical applications, but foliar residues of some products were nontoxic after 7 d. At reduced rates, topically applied pyrethroids were low in toxicity to *C. florus* were highly toxic to *T. platneri,* and foliar residues were nontoxic after about 7 d. Imidacloprid and abamectin were highly toxic when applied topically to both parasitoids but were not toxic as 1-d-old residues. Insect growth regulators did not cause mortality either as topical applications or residues; however, diflubenzuron caused severe sublethal effects, completely blocking the production of *C. florus* offspring. Biorational pesticides, such as soap, oil, and *B. thuringiensis* products, caused no toxicity to *C. florus* but had a direct impact on *T. platneri* as topical applications through physical immobilization. The potential to integrate different pesticides with biological control of leafrollers and the need for a step-wise approach to evaluate the impact of pesticides against natural enemies is discussed.

KEY WORDS pesticides, bioassay, biological control, sublethal, toxicity

IMPLEMENTATION OF THE Food Quality Protection Act of 1996 (FQPA) is accelerating changes in pest management programs in many agricultural crops as broad-spectrum insecticides, especially organophosphate and carbamate insecticides are eliminated or their use is severely restricted. The impact of FQPA will be felt in apple and pear as much as, or more than, any other agricultural commodity because of their importance in the diets of infants and children (NAS 1993, Whalon et al. 1999). Organophosphate insecticides have historically constituted 75% (pounds [AI]/acre) of all insecticides and miticides used in Washington apple orchards. The primary targets are codling moth, *Cydia pomonella* (L.) (Lepidoptera: Tortricidae), and leafroller species, *Pandemis pyrusana* Kearfott (Lepidoptera: Tortricidae) and obliquebanded leafroller, *Choristoneura rosaceana* (Harris) (Lepidoptera: Tortricidae) (Beers and Brunner 1991; Beers et al. 1993; NASS 1994, 1998). Other classes of insecticides are important controls for secondary pests such as the western tentiform leafminer, *Phyllonorycter elmaella* Doganlar & Mutuura (Lepidoptera: Gracillariidae); white apple leafhopper, *Typhlocyba pomaria* McAtee (Homoptera: Cicadellidae); apple aphid, *Aphis pomi* De Geer (Homoptera: Aphididae); and woolly apple aphid, *Eriosoma lanigerum* (Hausman) (Homoptera: Aphididae) (Beers and Brunner 1991, Beers et al. 1996). Although spider mites are generally controlled biologically by the western predatory mite, *Galandromus occidentalis* (Nesbitt) (Acari: Phytoseiidae), 10–30% of apple acres receive a specific miticide to suppress spider mite populations (NASS 1994, 1998).

The implementation of mating disruption for codling moth control in Washington apple orchards has demonstrated the potential to reduced reliance on organophosphate insecticides (Brunner et al. 1996, Gut et al. 1996, Calkins 1998). Leafrollers have been the most important secondary pest in orchards using codling moth mating disruption (Knight 1996, Gut and Brunner 1998). The combination of codling moth mating disruption and use of selective controls for leafrollers (Brunner 1994, Knight et al. 1998) has opened an unprecedented window of opportunity for an increased impact of biological control in apple orchards.

Any pesticide applied during the growing season has the potential to disrupt biological control. Organophosphate, carbamate, and synthetic pyrethroid insecticides are generally considered highly toxic to biological control agents due to their broad spectrum of activity (Croft 1990). New insecticide chemistries, with novel modes of action, are potentially more selective by having greater impact on the target pest than on natural enemies, thus conserving biological control agents in agricultural environments. In some pest management systems pesticides that have been touted as selective have been shown to have negative impacts on beneficial species (Biddinger and Hull 1995, Boyd and Boethel 1998, Raguraman and Singh

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1999, Smith and Krischik 1999, Elzen et al. 2000, Hill and Foster 2000, Villanueva-Jiménez et al. 2000). A better understanding of how insecticides impact selected predators and parasitoids is necessary when developing a pest management system that strives to conserve biological control agents.

A gregarious ectoparasitoid, *Colpoclypeus florus* (Walker), was discovered in 1992 attacking *P. pyrusana* larvae in Washington apple orchards (Brunner 1996). Initial studies on the augmentative release of *C. florus* for control of *P. pyrusana* and *C. rosaceana* larvae in spring and summer have been promising (Brunner 1993). Egg parasitoids in the genus *Trichogramma* are known to attack many agricultural pests including codling moth and leafrollers (Cossentine et al. 1996, Lawson et al. 1997). *Trichogramma platneri* Nagarkatti is available commercially (Rincon-Vitova, Ventura, CA) for use as a biological control for many pests. *Trichogramma platneri* has been shown in our laboratory to attack eggs of *P. pyrusana* and *C. rosaceana* and its potential as a biological control agent of leafrollers in the field is being examined (Pfannenstiel et al. 1996).

The negative impact of many agricultural pesticides on biological control agents is well documented (Croft and Brown 1975, Croft 1990). The integration of biological and chemical control tactics requires a thorough understanding of how pesticides affect biological control agents. A step-wise assessment, moving from the laboratory to the field, with adequate consideration of both direct and sublethal effects is recommended in the screening of pesticides against biological control agents (Croft 1990). While measures of direct toxicity elucidate potential physiological selectivity, ecological selectivity should also be considered to more completely understand how a pesticide could best be integrated into a pest management program. In the following study, pesticides were evaluated for contact toxicity, as topical applications and field-aged residues on apple foliage, and for sublethal effects on two parasitoids of leafrollers, *C. florus* and *T. platneri.*

Materials and Methods

Colpoclypeus florus was obtained from a colony maintained at the Washington State University Tree Fruit Research and Extension Center (TFREC), Wenatchee, WA. This colony originated from *C. florus* collected in 1992 from an unsprayed orchard at the TFREC. *Choristoneura rosaceana* larvae, fourth or fifth instars, were used as hosts for *C. florus* in the colony. Individual female *C. florus* were placed in a small petri dish (Falcon 1006, 50 by 9 mm, Becton-Dickinson Labware, Franklin Lakes, NJ) with a *C. rosaceana* larva and a small amount of artificial leafroller diet (Shorey and Hale 1965). An average of 13.5 *C. florus* adults, 71.8% females, was reared from one leafroller larva using this method (Brunner 1996). *Trichogramma platneri* was obtained from Rincon-Vitova as larvae or pupae in eggs of *Sitotroga cerealella* Olivier (Lepidoptera: Gelechiidae) Pesticides tested were obtained as formulated products from agricultural chemical distributors. Pesticides were tested at 10, 50, or 100% of the rate recommended by Washington State University (Beers et al. 1996) or the registrant. Pesticides tested are given in Table 1.

Contact Toxicity. Two- to 4-d-old *C. florus* adult females were used in all tests. Five *C. florus* females selected at random from the colony were anesthetized with CO_2, placed on a piece of filter paper (11 cm diameter), and transferred to a Potter spray tower (Burkhardt, Rickmansworth, UK). A fine spray of 4 ml of pesticide solution was applied topically to the parasitoids at six psi. *Colpoclypeus florus* were immediately transferred to a small petri dish (Falcon 1006, 50 by 9 mm, Becton-Dickinson Labware, Franklin Lakes, NJ) using a camel's-hair brush. To provide moisture and nutrient sources for *C. florus* a 1 cm cube of artificial diet (Shorey and Hale 1965) was added to each petri dish along with a small amount of honey-water solution (50:50 vol:vol) streaked on the lid. No host larvae were present in the petri dishes. Ten petri dishes, a total of 50 *C. florus* adult females, were used for each pesticide at each rate. petri dishes were placed in a growth chamber (22 ± 1°C, 16:8 [L:D]), and mortality of *C. florus* was determined after 48 h. Lack of movement in response to probing with a camel's-hair brush was the criterion used to score mortality. Corrected percent mortality was calculated (Abbott 1925), and data were analyzed using analysis of variance (ANOVA) (Super-Anova 1993).

Insecticides expected to be highly toxic to *C. florus* were initially evaluated at 10% of the recommended rate while those expected to be low in toxicity were initially evaluated at 100% of the recommended rate (Tables 2 and 3). If mortality of *C. florus* exposed to a pesticide was low at 10% or high at 100% of the recommended rate, it was evaluated again at 50% of the recommended rate (with the exception of imidacloprid). Pesticides were considered to have low toxicity if <20% corrected mortality was observed, moderate in toxicity if >20% and <70% corrected mortality was observed and highly toxic if >70% corrected mortality was observed. Water only controls were used as a comparison for each pesticide and rate tested.

Contact toxicity effects were tested on *T. platneri* using the same methods as for *C. florus* with exceptions that 1- to 2-d-old *T. platneri* were used in all tests and a honey-water soaked cotton thread placed in the petri dish as a nutrient and moisture source. Corrected percent mortality was calculated (Abbott 1925), and data were analyzed using ANOVA (Super-Anova 1993).

Pesticide Residue Effects. Pesticides were applied to the point of drip to 15-yr-old 'Oregon Spur' apple trees at the recommended rate (Beers et al. 1996, or manufacturer's recommendation). Pesticide applications were made in July or August using a handgun sprayer at 300 psi. Each pesticide treatment was replicated three times, using individual trees as replicates. Control trees received no treatment. Leaf samples were collected at 1, 3, 7, 14 and 21 d after treatment (DAT). Ten mature leaves were collected from shoots

Table 1. Common chemical name, trade name, and manufacturing company of pesticides evaluated for effects on *C. florus* and *T. platneri*

Pesticide common chemical name	Trade name and formulation	Manufacturing company
Azinphosmethyl	Guthion 50WP	Bayer, Kansas City, MO
Chlorpyrifos	Lorsban 50WP Lorsban 4E	Dow AgroSciences, Midland, MI
Diazinon	Diazinon 50WP	Platte Chemical Company, Fremont, NE
Dimethoate	Dimethoate 2.67EC	American Cyanamid, Princeton, NJ
Methyl parathion	Penncap-M 2F	Elf-Atochem, Philadelphia, PA
Methidathion	Supracide 2E	Novartis Crop Protection, Greensboro, NC
Phosmet	Imidan 70WP	Gowan Agricultural Chemicals, Yuma, AZ
Carbaryl	Sevin 50WP	Rhône-Poulenc, Research Triangle Park, NC
Oxamyl	Vydate 2L	E.I. DuPont de Nemours, Wilmington, DE
Formetanate hydrochloride	Carzol 92SP	Novartis Crop Protection, Greensboro, NC
Amitraz	Mitac 50WP	Uniroyal Chemical, Middlebury, CT
Permethrin	Pounce 3.2EC	FMC, Middleport, NY
Esfenvalerate	Asana XL 0.66EC	E.I. DuPont de Nemours, Wilmington, DE
Endosulfan	Thiodan 50WP	FMC, Middleport, NY
Spinosad	spinosad, 80 WP spinosad, 1.6% spinosad 44.2%EC	Dow AgroSciences, Midland, MI
Imidacloprid	Provado 2F	Bayer, Kansas City, MO
Propargite	Omite 30WP	Uniroyal Chemical, Middlebury, CT
Fenbutatin-oxide	Vendex 4L	E.I. DuPont de Nemours, Wilmington, DE
Abamectin	Agri-Mek 0.15EC	Merck, Rahway, NJ
Diflubenzuron	Dimilin 25WP	Uniroyal Chemical, Middlebury, CT
Fenoxycarb	Comply 25WP	Novartis, Greensboro, NC
Tebufenozide	Confirm 2F	Rohm and Haas, Philadelphia, PA
Methoxyfenozide	Intrepid 2F	Rohm and Haas, Philadelphia, PA
Horticultural mineral oil	Orchex-796, Orchex-692, Orchex-896	Exxon, Houston, TX
Azadirachtin	Neemix 4.5%	W.R. Grace, Columbia, MD
Soap	M-Pede	Mycogen, Butte, MT
Bacillus thuringiensis kurstaki	MVP II	Mycogen, San Diego, CA
Bacillus thuringiensis kurstaki	Javelin WDG	Sandoz Crop Protection, Des Plaines, IL
Bacillus thuringiensis kurstaki	Dipel 2X WDG	Abbott, North Chicago, IL

WP, wettable powder; E, emulsion; EC, emulsifiable concentrate; F, flowable; L, liquid; SP, soluble powder; WDG, water-dispersable granule.

on each tree on each sample date. A disc (2.3 cm diameter) was taken from each leaf (10 total from each tree), and two discs were placed in a small petri dish (Falcon 1006, 50 by 9 mm, Becton-Dickinson Labware, Franklin Lakes, NJ). Five 2- to 3-d-old *C. florus* females selected at random from the colony were placed in a petri dish. Five petri dishes were used per replicate. To provide moisture and nutrient sources for *C. florus* a 1 cm cube of artificial diet (Shorey and Hale 1965) was added to each petri dish along with a small amount of honey-water solution (50:50, vol:vol) streaked on the lid. No host larvae were present in the petri dishes. The petri dishes were placed inside a plastic food storage container and kept at a constant temperature (22 ± 1°C) and photoperiod (16:8 [L:D] h). *Colpoclypeus florus* adults actively searched the surface of leaf disks (Brunner unpublished data) thus exposing them to pesticide residues. *Colpoclypeus florus* mortality was recorded after 48 h of exposure to the leaf disc residues using the method described above. No further leaf samples were collected when *C. florus* mortality in a pesticide treatment was not significantly different from the control. Corrected percent mortality was calculated (Abbott 1925), and data were analyzed using ANOVA (Super-Anova 1993). Pesticides were considered to have low toxicity if <20% corrected mortality was observed, moderate in toxicity if >20% and <70% corrected mortality was observed and highly toxic if >70% corrected mortality was observed. The effects of pesticide residues were also determined for *T. platneri* using the same methods as described for *C. florus* with the exceptions that 1- to 2-d-old *T. platneri* were used and a honey-water soaked cotton thread placed in the petri dish as a nutrient and moisture source.

Sublethal Effects. *Colpoclypeus florus* females surviving 48 h after the topical contact treatment was applied were evaluated for sublethal effects resulting from pesticide exposure. A single untreated *C. rosaceana* larva (fourth or early fifth instar) from a laboratory colony maintained at the TFREC was placed in a 1-oz plastic portion cup (#S-300, Prairie Packaging, Bedford Park, IL) containing a 1-cm cube of artificial leafroller diet. The leafroller larva was allowed to feed and construct a silken shelter for 24 h, after which a single *C. florus* female that had survived a topical contact treatment was transferred to the cup. A small amount of honey-water solution was streaked on the cup lid. Cups were placed in a growth room at 25 ± 1°C, 40–50% RH, and a photoperiod of 16:8 (L:D) h until parasitoid offspring were produced, approximately 14 d. *C. florus* is a gregarious ectoparasitoid that produces several offspring from a single female, therefore, sublethal impact from pesticide exposure was

Table 2. Percent mortality of *C. florus* females 48 h after exposure to direct sprays of different pesticides

Chemical (formulation)	Recommended rate (ppm or amount/100 gal)	Average corrected % mortality-48 h		
		10% rate	50% rate	100% rate
Azinphosmethyl (50WP)	300	98e	—	—
Chlorpyrifos (4EC)	450	100e	—	—
Chlorpyrifos (50WP)	450	100e	—	—
Diazinon (50WP)	600	100e	—	—
Dimethoate (2.67EC)	400	100e	—	—
Methyl parathion (2F) (encapsulated)	520	78d	100c	—
Methidathion (2E)	300	100e	—	—
Phosmet (50WP)	750	88d	100c	—
Carbaryl (50WP)	300	74d	100c	—
Oxamyl (2L)	225	20b	94c	—
Formetanate (92SP) hydrochloride	400	54c	100c	—
Amitraz (50WP)	450	24b	12a	18b
Permethrin (3.2EC)	50	26b	56b	100d
Esfenvalerate (0.66EC)	25	6a	28b	72c
Endosulfan (50WP)	450	8a	92c	—
Imidacloprid (2F)	48	—	—	86c
Spinosad (80WP)	48	33a	—	100b
Spinosad (1.6%)	48	66bc	—	100b
Abamectin (0.15EC)	7	100e	—	—
Propargite (30WP)	450	2a	2a	0a
Fenbutatin-oxide (4L)	300	0a	4a	0a
Diflubenzuron (25WP)	75	—	—	0a
Fenoxycarb (25WP)	37.5	—	—	0a
Tebufenozide (2F)	150	—	—	0a
Methoxyfenozide (2F)	150	—	—	0a
Oil (Orchex-796)	1% vol:vol	—	—	0a
Oil (Orchex-692)	1% vol:vol	—	—	0a
Azadirachtin (4.5%)	25	—	—	0a
Soap (M-Pede)	1 gal/100	—	—	2a
B. thuringiensis kurstaki (Javelin)	4 oz/100	—	—	0a
B. thuringiensis kurstaki (MVP)	24 fl oz/100	—	—	0a
B. thuringiensis kurstaki (Dipel 2X)	4 oz/100	—	—	0a
Water only	0	0a	0a	0a

Means in the same column followed by the same letter not significantly different ($P = 0.05$, Fisher's protected LSD) and means followed by the letter 'a' are not different from the untreated control; — indicates no bioassays were run at this rate for a particular chemical.

expected to be expressed as the number of hosts attacked, number of progeny produced, or change in sex ratios.

Sublethal effects of pesticides on *C. florus* were evaluated in three separate trials by comparing results from pesticide-treated individuals with nonpesticide treated controls in each trial. The number of leafroller hosts stung based on behavioral observations of host larvae was recorded. Determination of a host being stung was based on lethargy of the larva when probed with a camel's-hair brush, the presence of an unusually dense silken chamber constructed by the larva and the cessation of feeding activity. In addition, the number of hosts stung that produced parasitoid offspring was also determined, and for these individuals the number of male and female offspring per parasitoid and the total number of offspring were recorded.

The number of hosts stung and not stung, number of stung hosts producing offspring and not producing offspring, and numbers of females and males were analyzed using a chi-square analysis of 2 × 2 contingency tables (Data Desk 1998), comparing pesticide-exposed parasitoids to the control treatment for that trial. The average number of offspring per parasitoid was analyzed using pairwise *t*-test across the treatments in each trial (Super-Anova 1993).

Results

Contact Toxicity *(C. florus)*. All organophosphate insecticides tested (azinphosmethyl, chlorpyrifos, diazinon, dimethoate, methyl parathion, methidathion, phosmet) and abamectin were highly toxic (>70% corrected mortality) to *C. florus* at 10% of the recommended rate. Carbamate insecticides (carbaryl, oxamyl, formetanate hydrochloride) were highly toxic at 50% of the recommended rate (Table 2). The pyrethroids permethrin and esfenvalerate were low (<20% corrected mortality) to moderate (>20% and <70% corrected mortality) in toxicity at 10 and 50% of the recommended rate but were highly toxic at 100% of the recommended rate. Endosulfan was low in toxicity at 10% of the recommended rate but was highly toxic at 50% of the recommended rate. Imidacloprid was highly toxic at 100% of the recommended rate but was not tested at lower rates. Amitraz, miticides (fenbutatin-oxide, propargite), insect growth regulators (fenoxycarb, tebufenozide, methoxyfenozide, diflubenzuron), insecticidal soap, *B. thuringiensis* products, azadirachtin, and horticultural mineral oil were very low in toxicity or nontoxic at 100% of the recommended rate. Spinosad was moderately toxic at 10% and highly toxic at 100% of the recommended rate (Table 2).

Table 3. Percent mortality of *T. platneri* females 48 h after exposure to direct sprays of different pesticides

Chemical (formulation)	Recommended rate (ppm or amount/100 gal)	Avg corrected % mortality-48 h		
		10% rate	50% rate	100% rate
Azinphosmethyl (50WP)	300	67bc	—	—
Chlorpyrifos (4EC)	450	100d	—	—
Chlorpyrifos (50WP)	450	100d	—	—
Dimethoate (2.67EC)	400	100d	—	—
Diazinon (50WP)	600	60b	—	—
Methidathion (2E)	300	100d	—	—
Methyl parathion (2F)	520	0a	30b	—
Phosmet (50WP)	750	75bc	89c	—
Carbaryl (50WP)	300	79cd	98c	—
Oxamyl (2L)	225	62bc	—	100b
Formetanate (92SP) hydrochloride	400	64bc	85c	—
Amitraz (50WP)	450	31a	—	—
Permethrin (3.2EC)	50	50b	—	—
Esfenvalerate (0.66EC)	25	69bc	—	—
Endosulfan (50WP)	450	18a	2a	—
Imidacloprid (2F)	48	—	—	100b
Fenbutatin-oxide (4L)	300	33a	—	—
Propargite (30WP)	450	4a	23b	—
Abamectin (0.15EC)	7	100d	—	—
Diflubenzuron (25WP)	75	0a	—	—
Fenoxycarb (25WP)	37.5	2a	—	—
Tebufenozide (2F)	150	—	—	0a
Soap (M-Pede)	1 gal/100	—	—	98b
B. thuringiensis kurstaki (Javelin)	4 oz/100	—	—	100b
B. thuringiensis kurstaki (MVP)	24 fl oz/100	—	—	100b
B. thuringiensis kurstaki (Dipel 2X)	4 oz/100	—	—	100b
Water only	0	0a	0a	0a

Means in the same column followed by the same letter not significantly different ($P = 0.05$, Fisher's protected LSD) and means followed by the letter 'a' are not different from the untreated control; — indicates no bioassays were run at this rate for a particular chemical.

Contact Toxicity *(T. platneri)*. Organophosphate insecticides (azinphosmethyl, chlorpyrifos, diazinon, dimethoate, methidathion, phosmet) and abamectin were moderate to highly toxic to *T. platneri* at 10% of the recommended rate. The exception was methyl parathion, which was nontoxic at 10% and only moderately toxic at 50% of the recommended rate (Table 3). Carbamate insecticides (carbaryl, formetanate hydrochloride, oxamyl) were highly toxic at 50% of the recommended rate (Table 3). The pyrethroids esfenvalerate and permethrin were moderate in toxicity at 10% of the recommended rate. Endosulfan was low in toxicity at 10 and 50% of the recommended rate. Imidacloprid was highly toxic at 100% of the recommended rate but was not tested at lower rates. Amitraz, miticides (fenbutatin-oxide, propargite), and insect growth regulators (fenoxycarb, tebufenozide, diflubenzuron) were nontoxic, low, or moderate in toxicity at rates tested. Insecticidal soap and *B. thuringiensis* products were highly toxic at 100% of the recommended rate (Table 3).

Pesticide Residue Effects *(C. florus)*. Field-aged residues of the organophosphate insecticides methyl parathion, azinphosmethyl, and chlorpyrifos were highly toxic to *C. florus* at 1 through 21 DAT. Phosmet and endosulfan were highly toxic at 1 and 3 DAT, moderately toxic at 7 DAT, and low in toxicity at 14 DAT (Table 4). The carbamate insecticides carbaryl, formetanate hydrochloride, and oxamyl were highly toxic at 1 through 7 DAT. The toxicity of field-aged residues of carbaryl declined dramatically after 14 DAT and was zero at 21 DAT. Oxamyl and formetanate hydrochloride residues remained moderately toxic at 14 DAT but were low in toxicity at 21 DAT. The pyrethroid esfenvalerate was highly toxic at 1 and 3 DAT, moderately toxic at 7 DAT, and low in toxicity at 14 DAT. Spinosad residues were highly toxic through 7 DAT with a slight rate-related decline in toxicity at 14 DAT. Abamectin, imidacloprid, fenoxycarb, insecticidal soap, *B. thuringiensis* products, and horticultural mineral oil were nontoxic at 1 DAT (Table 4).

Pesticide Residue Effects *(T. platneri)*. Field-aged residues of the organophosphate insecticides, azinphosmethyl and chlorpyrifos were highly toxic to *T. platneri* at 1 through 21 DAT (Table 5). Phosmet was highly toxic at 1 and 3 DAT and remained moderately toxic at 7 through 21 DAT. The carbamate insecticide oxamyl and the pyrethroid esfenvalerate were highly toxic at 1 through 21 DAT. Field-aged residues of endosulfan were highly toxic at 1 and 3 DAT, moderately toxic at 7 and 14 DAT, and low in toxicity at 21 DAT. Abamectin residues were moderately toxic at 1 and 3 DAT and nontoxic thereafter. Insecticidal soap residues were nontoxic at 1 DAT (Table 5).

Sublethal Effects *(C. florus)*. In the first trial, the *B. thuringiensis* products MVP and Javelin showed no significant sublethal effects. However, significantly higher numbers of female progeny were produced from Dipel-treated females (Table 6). Fenoxycarb caused no significant sublethal effects. Diflubenzuron exposure had no effect on the number of hosts stung (100%); however, no parasitoid offspring were produced from host larvae that were stung. Survival of *C.*

Table 4. Percent mortality of *C. florus* exposed to field-aged residues of pesticides using a leaf-disk bioassay

Chemical (formulation)	Recommended rate (ppm or amount/100 gal)	Avg corrected % mortality-48 h				
		1 DAT	3 DAT	7 DAT	14 DAT	21 DAT
Azinphosmethyl (50WP)	300	97.3c	95.9d	97.3e	93.1e	80.8b
Chlorpyrifos (50WP)	450	100.0c	100.0d	98.7e	97.2e	75.3b
Methylparathion (2F)	520	100.0c	100.0d	100.0e	100.0e	100.0c
Phosmet (50WP)	750	100.0c	100.0d	42.7c	4.0ab	—
Carbaryl (XLR)	300	100.0c	100.0d	90.5e	18.7bc	0.0a
Oxamyl (2L)	225	93.2c	95.9d	71.6d	60.6c	8.1a
Formetanate (92SP) hydrochloride	400	95.7c	74.6c	98.7e	73.4d	2.6a
Esfenvalerate (0.67EC)	25	56.2b	39.6b	6.7ab	—	—
Endosulfan (50WP)	450	100.0c	100.0d	64.0d	1.3a	—
Imidacloprid (2F)	60	1.4a	5.7a	—	—	—
Abamectin (0.15EC)	7	0.0a	5.4a	—	—	—
Spinosad (44.2% EC)	51	100.0b	—	97.9b	77.5c	—
Spinosad (44.2% EC)	33	100.0b	—	95.7b	36.7b	—
Spinosad (44.2% EC)	12	91.5b	—	86.5b	26.5b	18.4b
Fenoxycarb (25WP)	37.5	0.7a	—	—	—	—
Soap (M-Pede)	1 qt/100	0.0a	—	—	—	—
B. thuringiensis kurstaki (Dipel 2X)	4 oz/100	0.0a	—	—	—	—
Oil (Orchex-796)	1 gal/100	0.0a	—	—	—	—
Water only	0	0.0a	0.0a	0.0a	0.0a	0.0a

Means in the same column followed by the same letter not significantly different ($P = 0.05$, Fisher's protected LSD) and means followed by the letter 'a' are not different from the untreated control; — indicates no bioassays were run at this rate for a particular chemical. DAT, days after treatment.

florus to topical sprays of esfenvalerate was low, 12 individuals. Although 83% of these *C. florus* stung hosts this value was significantly lower than the control, and while the number of female offspring was significantly lower than the control the average number of progeny per female was not different from the control.

In the second trial, the two benzoylhydrazine insect growth regulators, tebufenozide and methoxyfenozide, produced no sublethal effects (Table 6).

In the third trial, the average number of offspring was generally lower for all treatments relative to the first two trials (Table 6). Azadirachtin significantly reduced the number of hosts stung and increased the number of female offspring produced. Spinosad (80%) had similar effects. However, a different formulation of spinosad (1.6%) dramatically reduced the number of hosts stung and no offspring were produced. Of the three oil formulations, only Orchex 796 caused detrimental sublethal effects. Orchex 796 significantly decreased the number of hosts stung and reduced the number of females in the offspring. Orchex 892 had a significantly higher average number of offspring than the control.

Discussion

This study evaluated the physiological selectivity of different classes of pesticides through direct contact effects on parasitoids. A high degree of variation in effect was found among classes of insecticides and among insecticides of the same class. Some classes of insecticides, such as the organophosphates and carbamates, showed little or no physiological selectivity to the parasitoid species tested. Most of these materials also had long foliar residual activity, reducing the potential to use them in ecologically selective ways, for example, altering the timing of insecticide applications to avoid periods of adult parasitoid activity (Hull et al. 1985). Phosmet and carbaryl, as well as methyl parathion for *T. platneri,* had relatively short residual effects on the parasitoids. These materials could be used in a manner to reduce their impact on

Table 5. Effect of pesticide residue degradation on *T. platneri* mortality using a leaf-disk bioassay

Chemical (formulation)	Recommended rate (ppm or amount/100 gal)	Average corrected percent mortality-48 h				
		1 DAT	3 DAT	7 DAT	14 DAT	21 DAT
Azinphosmethyl (50WP)	300	100.0c	100.0c	100.0c	79.6c	80.7c
Chlorpyrifos (50WP)	450	100.0c	100.0c	100.0c	100.0c	100.0c
Phosmet (50WP)	750	100.0c	97.9c	39.7b	50.5b	48.5b
Oxamyl (2L)	225	100.0c	100.0c	100.0c	93.2c	90.3c
Esfenvalerate (0.66EC)	25	100.0c	100.0c	98.1c	91.5c	93.5c
Endosulfan (50WP)	450	100.0c	100.0c	34.3b	37.4b	9.1a
Abamectin (0.15EC)	7	60.7b	56.3b	0.0a	—	—
Soap (M-Pede)	1 qt/100	0.0a	—	—	—	—
Water only	0	0.0a	0.0a	0.0a	0.0a	0.0a

Means in the same column followed by the same letter not significantly different ($P = 0.05$, Fisher's protected LSD) and means followed by the letter 'a' are not different from the untreated control; — indicates no bioassays were run at this rate for a particular chemical DAT, days after treatment.

Table 6. Sublethal effects of insecticides on adult female *C. florus* surviving for 48 h after direct exposure to the insecticides

Pesticide	Pesticide rate parasitoid was exposed to (ppm or amount formulated product)	*n* (no. of surviving parasitoids exposed to hosts)	No. of hosts stung (%)	No. of hosts not stung	χ^2	*P*-value	*n* (% of parasitoids producing offspring)	χ^2	*P*-value	No. of females in progeny (%)	χ^2	*P*-value	Avg. no. of offspring/parasitoid
Trial #1													
B. thuringiensis kurstaki (MVP)	24 fl oz/100	30	30 (100)	0			30 (100)	3.16	0.076	441 (79)	1.975	0.160	18.7a
B. thuringiensis kurstaki (Javelin)	4 oz/100	30	30 (100)	0			26 (87)	0.162	0.688	417 (85)	1.584	0.208	18.8a
B. thuringiensis kurstaki (Dipel 2X)	4 oz/100	30	27 (90)	3	3.160	0.076	26 (96)	0.863	0.353	371 (91)	14.95	<0.001	15.7a
Fenoxycarb (25WP)	37.5	30	29 (97)	1	1.020	0.310	25 (86)	0.203	0.652	337 (80)	0.915	0.339	17.0a
Diflubenzuron (25WP)	75	30	30 (94)	0			0 (0)	49.09	<0.001	0 (0)			0.0
Esfenvalerate (0.66EC)	25	12	10 (83)	2	5.250	0.022	8 (80)	0.686	0.408	75 (49)	64.96	<0.001	19.3a
Control (water only)	0	30	30 (100)	0			27 (90)			361 (82)			16.3a
Trial #2													
Methoxyfenozide (2F)	150	24	16 (67)	8	0.787	0.375	15 (94)	0.039	0.843	219 (81)	0.745	0.338	19.4a
Tebufenozide (2F)	150	21	16 (76)	5	0.017	0.897	15 (94)	0.039	0.843	240 (82)	1.555	0.212	19.5a
Control (water only)	0	27	21 (78)	6			20 (95)			313 (78)			20.1a
Trial #3													
Azadirachtin (4.5%)	7	42	31 (74)	11	6.56	0.010	17 (55)	0.001	0.980	215 (91)	24.55	<0.001	13.9ab
Spinosad (80%)	48	34	22 (65)	12	10.93	<0.001	10 (45)	0.485	0.486	107 (90)	13.85	<0.001	11.9ab
Spinosad (1.6%)	48	18	3 (17)	15	38.49	<0.001	0 (0)	3.340	0.067	0 (0)			0.0
Oil (1% vol:vol) Orchex 796	1 gal/100	43	30 (70)	13	8.740	0.003	12 (40)	1.510	0.219	67 (40)	34.10	<0.001	14.0ab
Oil (1% vol:vol) Orchex 692	1 gal/100	40	32 (80)	8	3.630	0.057	13 (41)	1.437	0.231	210 (63)	3.54	0.060	12.0ab
Oil (1% vol:vol) Orchex 892	1 gal/100	47	38 (81)	9	3.44	0.064	22 (58)	0.092	0.760	240 (71)	0.017	0.890	15.3b
Control (water only)	0	47	44 (94)	3			24 (55)			117 (72)			9.3a

Means followed by the same letter not significantly different ($P = 0.05$, Fisher's protected LSD).

parasitoids, particularly if other life stages (e.g., larvae or pupae) were less susceptible or not exposed to the insecticides.

Pyrethroids showed some potential for both physiological and ecological selectivity against parasitoids in this study. Our data suggest that esfenvalerate or permethrin could be used at low rates during times when parasitoid adults were not active. There are lingering questions about the full impact of sublethal effects on parasitoids, especially since our study only measured effects for parasitoid adults directly contacted by the pyrethroids. Although foliar residues of pyrethroids were not toxic to *C. florus* after 7 d, sublethal effects from exposure to these nontoxic residues deserves further investigation.

Pyrethroid insecticides help point out an important issue in developing methods that will provide insights into a pesticide's impact on biological control in pest management programs. Basing judgments of selectivity of a pesticide or a pesticide class on only one type of natural enemy can be misleading. For example, while there may be some selectivity that would allow pyrethroids to be used in combination with leafroller biological control, the highly detrimental impact of these insecticides on predatory mites is well known (Hoyt et al. 1978, Croft et al. 1987). Beers and Brunner (1999) demonstrated how difficult it would be to use pyrethroids even as limited targeted controls in a selective approach in an apple pest management program. For these reasons, use of pyrethroids is not recommended (Beers et al. 1996, Smith et al. 2001) nor are they widely used apple pest management programs in Washington (NASS 1994, 1998, 2000).

Two insecticides used as foliar sprays for pest control in apple, abamectin and imidacloprid, could be used in an ecologically selective manner to conserve parasitoids in an integrated management program. While highly toxic when directly applied to parasitoids in this study, they had virtually no effect as residues on foliage. The translaminar and translocation properties of these insecticides make them available in host plant tissues as a control for pests but surface residues disappear quickly, making them safe for natural enemies (Iwata et al. 1985, Hoy and Cave 1985). If applied at the wrong time, however, these insecticides could have a serious impact on parasitoid adults. Although short-lived residues would theoretically allow a rapid recolonization of a parasitoid it is likely that this would not occur in a time frame to provide adequate biological control.

Based on a lack of toxicity from topical applications and foliar residues, and no apparent sublethal effects, it seems reasonable to assume that *B. thuringiensis* products, soap, and oil could be successfully integrated into a biological control program for leafrollers. The exception might be where these products are used in conjunction with small parasitoids. Mortality of *T. platneri* when exposed to sprays of soap and *B. thuringiensis* was due to physical properties of the formulations. Mortality was caused by the adhesion of wings, legs and antennae to the body thereby disabling the parasitoids. Residues of soap had no impact on *T. platneri*, and this would likely hold true for oil and *B. thuringiensis* products. However, it is the short residual activity of these biorational products against pests that results in them being repeatedly applied at short intervals. It is conceivable that this kind of use pattern, even with seemingly benign insecticides, could negatively impact the survival of small parasitoids.

The insect growth regulator (IGR) fenoxycarb and the lepidoptera-specific benzoylhydrazines should integrate easily into a pest management program aimed at conserving parasitoids for leafroller biological control. However, conclusions about the selectivity of insect growth regulators and conservation of biological control agents in a pest management system should be based on a case-by-case basis. For example, fenoxycarb has been shown to be detrimental to a key biological control agent, *Stethorus punctum* (LeConte), of spider mites in Pennsylvania apple orchards (Biddinger and Hull 1995). In our study the IGR diflubenzuron had detrimental effects on *C. florus* reproduction. These detrimental effects would have been missed if evaluation procedures had only considered direct toxicity. Without the examination of sublethal effects, selectivity of a pesticide could be greatly overstated.

Our study only evaluated direct contact and residual toxicity of insecticides on parasitoids and subsequent sublethal effects from direct contact exposure. Other methods of exposure should be considered in future studies, particularly with respect to sublethal effects. Our study also only evaluated the effects of pesticide residues by mortality of adults with no evaluation of potential sublethal effects from exposure to foliar residues. Because some of the pesticides examined had high direct but low residual toxicity (e.g., imidacloprid), sublethal effects may be underestimated relative to what would occur in the field (Smith and Krischik 1999).

Most of the pesticides tested here have some effect on the parasitoid's leafroller host (Dunley unpublished data); however, they vary widely on the length of time before leafroller mortality occurs. For example, sublethal doses of Bts extend the development time of leafrollers (Knight and Cockfield 1997), possibly making larvae vulnerable to parasitoid attack for a greater time. Leafroller larvae that receive a lethal dose of certain insect growth regulators, such as tebufenozide and fenoxycarb, die slowly, potentially increasing vulnerability to attack by parasitoids. In the future, effects of pesticide-intoxicated hosts on the development of parasitoid larvae and reproductive viability of adults should be considered in determining a pesticide's selectivity.

The International Organization of Biological Control has established guidelines for the examination of direct effects of pesticides on natural enemies, and some level of examination is required for registration of new pesticides in Europe (Hassan et al. 1991). Many pesticide manufacturers in the United States are also testing the effects of their products against selected natural enemies. However, these tests generally emphasize only direct contact effects and usually do not consider possible sublethal or residual effects (Croft 1990). In the United States, regulatory agencies do not require testing of pesticides against biological control agents nor do they recommend that this occur. Great differences exist in natural enemy fauna between cropping systems as well as within a crop grown in different regions. Therefore, testing one or several kinds of natural enemies will likely not predict the selective effects of a pesticide when introduced into an agroecosystem. Instead, evaluation of selectivity should remain within an individual pest management system, as each system is unique. While initial screening of pesticide effects on natural enemies by pesticide manufacturers may provide clues as to the selectivity of a compound, it falls to the pest management practitioner to determine the compatibility of pesticides with biological control in their particular pest management program.

Implementation of FQPA is accelerating changes in pest management programs in many agricultural crops as regulatory action alters pesticide use patterns. For many years Washington's apple pest management programs have relied upon organophosphate and carbamate insecticides for control of key pests, such as codling moth and leafrollers, and secondary pests, such as aphids, leafhoppers and leafminer (Beers et al. 1993). Although some biological control agents, such as predatory mites, are effective in Washington apple orchards, data from our study demonstrates why other biological control agents, especially certain parasitoids, are not active in orchards. New insecticides, some of which were examined in this study, have been proposed as replacements for organophosphate and carbamate insecticides. Several of these products appear to be selective and increase the possibilities for biological control of leafrollers. However, further studies will be necessary to determine the full impact of new insecticides on natural enemies and how to use them to encourage leafroller biological control.

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