Conserving Vedalia Beetle, *Rodolia cardinalis* (Mulsant) (Coleoptera: Coccinellidae), in Citrus: A Continuing Challenge as New Insecticides Gain Registration

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ABSTRACT The effects of insecticides used for California citrus pest management were evaluated using larval and adult stages of vedalia beetle, *Rodolia cardinalis* (Mulsant). This predatory beetle is essential for control of cottony cushion scale *Icerya purchasi* (Williston) (Homoptera: Margarodidae) in San Joaquin Valley citrus. When adult beetles were exposed to treated citrus leaves, adult survival was significantly reduced by the foliar neonicotinoid imidacloprid and the pyrethroid cyfluthrin. Progeny production was significantly reduced by imidacloprid, cyfluthrin, fenpropathrin, and buprofezin. Buprofezin, pyriproxifen, and foliar imidacloprid also significantly reduced successful development of larvae into the adult stage. When vedalia stages were fed insecticide-treated cottony cushion scale reared on *Pittosporum tobira* (Thunb.) Ait, toxic effects were more severe than contact toxicity alone. Adult beetle survival was most profoundly reduced by the pyrethroids and to a lesser extent the foliar neonicotinoids acetamiprid and imidacloprid. Progeny production and larval development to adulthood were reduced by all insecticides but were most severely affected by pyriproxifen and the pyrethroids. Systemically applied neonicotinoids were toxic to vedalia larvae feeding on cottony cushion scale that had ingested these insecticides. These data demonstrate that IGRs, neonicotinoid insecticides, and pyrethroid insecticides have a significant, negative impact on vedalia beetles. Depending on the rate of insecticide used, the number and timing of applications, and the level of coverage of the tree, disruption of vedalia can be minimized. However, the situation is made difficult when pests such as citrus thrips *Scirtothrips citri* (Moulton) (Thysanoptera: Thripidae), forktailed bush katydid *Scuddaria furcata* Brunner von Wattenwyl (Orthoptera: Tettigoiniidae), or glassy-winged sharpshooter *Homalodisca coagulata* Say (Homoptera: Cicadellidae) require these pesticide treatments during periods of vedalia beetle activity.

KEY WORDS cottony cushion scale, neonicotinoid, pyrethroid, IGR, organophosphate

COTTONY CUSHION SCALE, *Icerya purchasi* (Williston), was accidentally introduced into California citrus in 1868. In 1888, the vedalia beetle, *Rodolia cardinalis* (Mulsant), was collected from Australia and introduced to California (Doutt 1964). Vedalia beetles dramatically brought cottony cushion scale under control and were the first modern example of successful classical biological control of an exotic agricultural pest in the world (Caltagirone and Doutt 1989). The success of this beetle was because of its rapid generation time (4–6 wk), relative to its prey (3 mo), and prey specificity, feeding only on cottony cushion scale (Quezada and DeBach 1973). Vedalia beetle is currently the only significant natural enemy of cottony cushion scale in the San Joaquin Valley citrus-growing region of California.

A number of pesticides have been registered for citrus pest management since the vedalia beetle was first introduced. These pesticides have periodically caused outbreaks of cottony cushion scale because of their toxicity to vedalia beetle. This was noted when organophosphate and carbamate insecticides (especially formetanate) were first used in California (Ebeling 1959). However, each time the vedalia was disrupted, it adapted and currently survives single applications of organophosphate or carbamate insecticides. Thus, during the late 1980s, when California citrus growers relied primarily on organophosphates and carbamates for pest control, cottony cushion scale problems were restricted to situations where multiple applications disrupted vedalia. In Israel, outbreaks of cottony cushion scale also occurred when multiple organophosphate applications were applied for Mediterranean fruit fly, *Ceratitis capitata* (Wiedemann), during the 1960s (Mendel and Blumberg 1991).

Organophosphate and carbamate insecticides were used to control the two primary pests of California citrus, CA red scale, *Aonidiella aurantii* (Maskell) (Homptera: Diaspididae), and citrus thrips, *Scirto-*

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thrips citri Moulton, for >40 yr. Not surprisingly, resistance began to develop in a number of populations of citrus thrips in the 1980s (Morse and Brawner 1986, Immaraju et al. 1989, Morse and Schweizer 1996, Khan and Morse 1998), and in California red scale in the 1990s (Grafton-Cardwell and Vehrs 1995, Grafton-Cardwell et al. 2001). To alleviate the resistance problem, the pyrethroid cyfluthrin was given a temporary, emergency registration during 1991–1996 for citrus thrips control for the four citrus growing counties of the San Joaquin Valley. Cyfluthrin attained full California registration for citrus in 1997. In 1998, two IGRs, the chitin synthesis inhibitor buprofezin and the juvenile hormone mimic pyriproxifen, received temporary emergency registration in Kern, Tulare, and Fresno Counties of California for control of California red scale in citrus (Grafton-Cardwell, B. 1999). During 2000 and 2002, a number of insecticides attained full registration for California citrus, including pyriproxifen (2000) and buprofezin (2002) for California red scale control, the pyrethroid fenpropathrin (2001) for citrus thrips control, and the neonicotinoids imidacloprid (2001) and acetamiprid (2002) for glassy-winged sharpshooter *Homalodisca coagulata* Say control.

Severe outbreaks of cottony cushion scale caused by disruption of the vedalia beetle were observed in the San Joaquin Valley after the first uses of pyriproxifen and buprofezin in 1998 (Grafton-Cardwell, E. E. 1999, Grafton-Cardwell 2000). These IGRs, as well as others, had been implicated in cottony cushion scale outbreaks in Israel (Mendel and Blumberg 1991) and South Africa (Hattingh and Tate 1995). It was suspected that pyrethroids and neonicotinoids were also disrupting vedalia beetle populations in California.

San Joaquin Valley citrus pest management is currently in a rapid transition from an organophosphate and carbamate insecticide-based program to a program of reduced risk (IGRs, acetamiprid, and spinosad) and organophosphate-replacement (pyrethroid and neonicotinoid) insecticides. Because cottony cushion scale is difficult to control with insecticides, conservation of vedalia populations is essential for citrus pest management. The purpose of this project was to determine the relative toxicity of several new groups of insecticides to various stages of the vedalia beetle.

Materials and Methods

Contact Toxicity Alone. Citrus leaves were collected from four separate field experiments to determine the effects of contact toxicity (insecticide residues on leaves) on vedalia larvae and adults. In experiment 1, a 16.2-ha commercial navel orange orchard in Orange Cove, CA, was divided into six 2.7-ha plots (≈22 rows by 42 trees). Three of the plots were treated on 14 June 1999 with 0.12 kg (AI)/ha pyriproxifen (Esteem 0.86 emulsifiable concentrate [EC]; Valent Agricultural Products, Walnut Creek, CA) using an airblast sprayer with 14,030 liters of water per ha. The other three plots were not treated (control). Treated foliage was collected from the center trees of each plot. There was concern that pyriproxifen drift into the nontreated regions was sufficient to harm vedalia beetles, and therefore, additional control leaves were collected from nontreated trees at the Lindcove Research and Extension Center (Exeter, CA). Terminals of branches with at least five leaves were collected at intervals of 11, 72, 116, 156, and 177 d after treatment (DAT).

In experiment 2, a 13.2-ha commercial Valencia orange orchard in Yettem, CA, was divided into six 2.2-ha plots (≈21 rows by 33 trees). One-half of the plots were treated on 23 June 1999 with 1.18 kg (AI)/ha buprofezin (Applaud 70 wettable powder [WP]; Nichino America, Wilmington, DE) in 14,030 liters of water/ha using an airblast sprayer, and the other three plots were not treated (control). Foliage was collected from the center trees in each plot. There was concern that buprofezin drift into the nontreated regions was sufficient to harm vedalia beetles, and therefore, additional control leaves were collected from nontreated trees at the Lindcove Research and Extension Center. Leaves were collected at intervals of 16, 51, and 70 DAT.

In experiment 3, "Washington" navel orange trees at the Lindcove Research and Extension Center were treated with insecticides as part of a California red scale insecticide trial. Treatments included foliar 0.14 kg (AI)/ha imidacloprid (Provado 1.6 flowable [F]; Bayer Crop Protection, Kansas City, MO) applied on 18 June, 0.56 kg (AI)/ha imidacloprid (Admire 2 F, Bayer Crop Protection) applied through the irrigation on 28 April, and 2.10 kg (AI)/ha methidathion (Supracide 25 WP; Gowan Co., Yuma, AZ) applied on 2 June 1999. The foliar treatments were applied with a Bean hand-sprayer at 500 psi, with thorough coverage, using 7,015 liters water/ha. Leaves were collected from treated and nontreated trees 26, 35, 42, 51, 77, and 86 DAT.

In experiment 4, citrus trees at the Lindcove Research and Extension Center were treated with insecticides as part of a citrus thrips experiment. Citrus thrips treatments included 0.112 kg (AI)/ha cyfluthrin (Baythroid 2 EC; Bayer Crop Protection), 0.105 kg (AI)/ha spinosad (Success 2 soluble concentrate [SC]; Dow AgroSciences, Indianapolis, IN), 0.013 kg (AI)/ha abamectin (Agri-Mek 0.15 EC; Syngenta, Greensboro, NC) + 0.5% 415 oil, and 22.42 kg (AI)/ha sabadilla (Veratran D; Dunhill Chemical Co., Rosemead, CA) + 11.21 kg (AI)/ha sugar. These treatments were applied on 24 May 1999 to 30-yr-old "Atwood" navel oranges with a Bean hand-sprayer at 500 psi, outside coverage, using 1,871 liters water/ha. Leaves were collected from treated and nontreated trees 4, 14, 23, and 45 DAT.

In all four experiments, 10 or 15 adult vedalia beetles were placed in each 1.2-liter, 16 by 16 by 6-cm plastic container replicate with a treated or control terminal branch of 5–10 citrus leaves and 5 g nontreated cottony cushion scale adult females provided as food. It was difficult to determine if the insecticide treatments had affected the cottony cushion scale eggs inside the egg sac; therefore, untreated food was provided to ensure that the adults were well fed. There were three replicates for each treatment. Beetles were removed after 72 h in experiments 1–3 and after 48 h in experiment 4 and were sexed, and mortality was assessed. Seven days later, the containers were examined for emerged larvae, and the number of progeny produced per female beetle was calculated. Experiments were conducted at room temperature (21–24°C) with 12L: 12D.

For experiments 1, 2, and 3, the responses of vedalia larvae were also examined. For each replicate, 10–15 second instar larvae were placed in each of three containers per treatment with a treated or control citrus terminal branch of 5–10 citrus leaves. Larvae were provided 5 g of nontreated cottony cushion scale adult females to ensure they were well-fed and to minimize cannibalism. Every 2–3 d, the larvae were provided an additional 5 g of cottony cushion scale females until the larvae pupated. Every 2–3 d, the mortality and stage of development were recorded. After 20 d, the percentage survival of the larvae to adulthood was calculated. All experiments were conducted at room temperature (21–24°C) with 12L:12D.

Feeding and Contact Toxicity Combined. Containers of *Pittosporum tobira* (Thunb.) Ait, 3.75 liters in size, were fumigated with nicotine. Two to 3 wk later, 50 cottony cushion scale crawlers were placed on each plant, and the populations were allowed to develop for 77–78 d until third instar females were abundant. Insecticides were mixed as field rates in 14,030 liters water/ha if the insecticide was applied as a foliar for a scale pest (pyriproxifen, buprofezin, acetamiprid, imidacloprid, methidathion) or 1,871 liters water/ha if the insecticide was targeting citrus thrips (cyfluthrin, fenpropathrin, spinosad, and abamectin).

In experiment 5, initiated August 9–11, 2000, insecticide solutions were prepared in 3.75 liters of water, and the plants were sprayed to runoff using a pump hand sprayer. Treatments included 0.32 ml pyriproxifen (Esteem 0.86 EC), 0.07 g acetamiprid (Assail 70 WP; Aventis CropScience, Research Triangle Park, NC), 4.54 g methidathion (Supracide 25 WP), and 0.65 g buprofezin (Applaud 70 WP). Two insecticides were applied to the soil, 0.15 ml imidacloprid (Admire 2 F; Bayer Crop Protection) in 118 ml water and 0.52 ml thiomethoxam (Platinum 2 SC; Aventis CropScience) per pot. Fifteen plants were treated with each insecticide, allowed to air dry, and placed in a greenhouse inside cloth cages. An additional 15 plants acted as nontreated controls.

In experiment 6, initiated 12 September 2001, insecticides solutions were prepared in 3.75 liters of water, and the plants were sprayed to runoff using a pump hand sprayer. Treatments included 0.32 ml pyriproxifen (Esteem 0.86), 0.11 g acetamiprid (Assail 70 WP) both as a foliar and as a drench, 0.2 ml imidacloprid (Provado 1.6 F), 0.89 ml spinosad (Success 2 SC), 0.94 ml cyfluthrin (Baythroid 2 SC; Bayer Crop Protection), 3.15 ml fenpropathrin (Danitol 2.4 EC; Valent Agricultural Products), and 1.48 ml abamectin + 18.9 ml 415 NR oil (Agri-Mek 0.15 EC). Fifteen plants were treated with each insecticide, allowed to air dry, and placed in a greenhouse inside cloth cages. An additional 15 plants acted as nontreated controls.

At various intervals after treatment, six cottony cushion scale-infested *P. tobira* branches were removed from each treatment, and two were placed in each of three containers (1.2 liters, 16 by 16 by 6 cm) per treatment. A nontreated branch of cottony cushion scale-infested *P. tobira* was added to each container to ensure that every treatment had sufficient food. In all cases, the *P. tobira* branches were infested with a minimum of five adult female cottony cushion scale as well as a mixture of other stages. For the tests of toxicity to adults, 15 adults were placed in each container on the treated branches, and adult mortality was assessed after 48 h. One week after eggs were deposited, the number of larvae produced was assessed. The beetles were sexed at the end of the experiment. The percentage survival of adult beetles and the number of progeny per live adult female were calculated.

Larval bioassays were conducted in a similar manner to the adults. Two branches each of cottony-cushion scale infested *P. tobira* foliage were placed in each of three containers per treatment. Fifteen second-instar larvae were placed in each container on the treated foliage, and an additional branch of nontreated, cottony cushion scale-infested *P. tobira* was added to each container every 2–3 d until pupation to ensure that there was sufficient live food for the predators to develop fully. The survival and development of the larvae was recorded every 2–3 d. The percentage survival and development of larvae into adults was recorded after 20 d.

For all experiments, the percentage survival of adults and larvae was arcsine-transformed (squareroot x) before analysis of variance (ANOVA) was conducted, and treatment means were separated using the least significant difference (LSD) test (Statistical Graphics 2000). The data for the number of progeny produced per female were log-transformed ($x + 1$) before ANOVA and LSD were conducted.

Results

Contact Toxicity Alone. Table 1 shows the contact effect of pyriproxifen (IGR)-treated leaves on vedalia adults and larvae. Pyriproxifen was nontoxic to the adults but significantly reduced the number of progeny produced by the females for at least 72 d and prevented a significant number of larvae from maturing to adulthood for 116 d. Leaves collected from the center of the nontreated plots of the pyriproxifen experiment, separated by 11 rows (67 m) from treated areas, did not cause significantly different mortality of vedalia adults than control leaves collected from Lindcove Research and Extension Center.

Table 2 shows the contact effect of buprofezin (IGR)-treated leaves on vedalia adults and larvae. There was no significant effect of buprofezin on adult survival or progeny production. There was a slight significant effect of contact toxicity of buprofezin on

Table 1. Survival of adults and progeny produced during a 72-h period of exposure and the percentage of larvae developing to the adult stage over a 20-d period of exposure to citrus leaves treated with pyriproxifen on 14 June 1999

Insecticide	Days after treatment											
	11	72	156	177	11	72	156	177	11	72	116	177
	Mean percentage adult survival ± SE				Mean progeny per female ± SE				Mean percentage larval development to adulthood ± SE			
Control LREC[a]	100.00a	97.78 ± 2.22a	93.33 ± 3.84a	100.00a	2.75 ± 1.09a	2.99 ± 0.36a	6.67 ± 2.12a	11.59 ± 2.72a	73.33 ± 6.67a	84.44 ± 2.22a	82.22 ± 4.44a	84.44 ± 2.22a
Control neighboring plots	96.70 ± 3.33a	97.80 ± 2.22a	95.56 ± 4.44a	100.00a	2.20 ± 0.70a	5.69 ± 0.77a	2.33 ± 1.86a	15.21 ± 1.32a	86.67 ± 3.33a	91.11 ± 4.44a	80.00 ± 3.85a	84.44 ± 2.22a
Pyriproxifen	100.00a	88.89 ± 4.44a	91.11 ± 2.22a	97.78 ± 2.22a	0.07 ± 0.07b	0.93 ± 0.47b	3.78 ± 0.25a	13.37 ± 0.73a	0.00b	26.67 ± 11.55b	60.00 ± 3.85b	80.00 ± 6.67a
F	1.00	2.96	0.78	1.00	6.52	6.52	2.10	1.00	165.67	14.86	8.14	0.31
df	2, 8	2, 8	2, 8	2, 8	2, 8	2, 8	2, 8	2, 8	2, 8	2, 8	2, 8	2, 8
P	0.422	0.128	0.500	0.422	0.031	0.031	0.203	0.422	<0.001	.005	0.020	0.745

Means in each column followed by the same letter are not significantly different according to the LSD test ($P > 0.05$). Percentage survival was arcsine–transformed (squareroot x), and mean progeny production was log-transformed ($x + 1$). Untransformed means are shown.

[a] LREC, = Lindcove Research and Extension Center.

larval development to adulthood at 16 d after treatment. Leaves collected from the center of the nontreated plots of the buprofezin experiment, separated by 11 rows from treated areas, did not cause significantly different mortality of vedalia adults than control leaves collected from the Lindcove Research and Extension Center.

Table 3 shows the contact effects of leaves treated with foliar- or soil-applied imidacloprid and the organophosphate methidathion on vedalia beetle adult survival and progeny production. The soil-applied imidacloprid and the organophosphate methidathion did not significantly affect adult survival or progeny production. The foliar imidacloprid application significantly reduced adult survival and progeny production 26 d after treatment.

Table 4 shows the contact effects of various insecticides, commonly used for citrus thrips control, on adult vedalia beetle survival and progeny production. Treatments of spinosad, abamectin, and the botanical insecticide sabadilla had no significant effect on adult survival or their ability to produce progeny. The pyrethroid cyfluthrin significantly reduced adult survival for 45 d, and consequently, progeny production for 23 d.

Contact and Feeding Toxicity Combined. Tables 5 and 6 show the survival of adult beetles when exposed through feeding on treated cottony cushion scale as well as by contact toxicity to various insecticides used for California red scale control (methidathion, pyriproxifen, buprofezin), glassy-winged sharpshooter control (thiomethoxam, acetamiprid, imidacloprid), and citrus thrips control (cyfluthrin, fenpropathrin, spinosad, abamectin + oil). The organophosphate insecticide methidathion, the IGRs pyriproxifen and buprofezin, the spinosad, and the abamectin + oil treatments did not significantly affect adult survival during the periods tested. The neonicotinoids significantly reduced adult beetle survival for 22–71 d. Within that class of insecticides, the foliar-applied formulations were more toxic to adults and had a longer residual effect than the systemically applied formulations. The pyrethroid insecticides were the most toxic class of insecticides for adult beetles, significantly reducing survival for 126 d after treatments were applied.

Tables 7 and 8 show the effects of the insecticides on progeny production during the 72-h period when adults were feeding on treated cottony cushion scale. All insecticides tested, except abamectin + oil, reduced progeny production to some extent. Progeny production was reduced by the pyrethroids for >182 d and the IGRs for 126–155 d. The neonicotinoids reduced progeny for 41–127 d, and the foliar formulations caused a more severe effect than the systemic formulations. The most severe progeny reduction occurred from the foliar acetamiprid, pyriproxifen, cyfluthrin, and fenpropathrin treatments.

Tables 9 and 10 show the effects of the insecticides on the development of larvae into adults during a 20-d period of feeding on insecticide-treated and nontreated cottony cushion scale. The organophosphate

Table 2. Survival of adults and progeny produced during a 72-h period of exposure and the percentage of larvae developing to the adult stage over a 20-d period of exposure to citrus leaves treated with buprofezin on 23 June 1999

Insecticide	Days after treatment					
	16	70	16	70	16	51
	Mean percentage adult survival ± SE		Mean progeny per female ± SE		Mean percentage larval development to adulthood ± SE	
Control LREC[a]	100.00a	93.33 ± 0.00a	0.83 ± 0.97a	7.76 ± 2.46a	83.33 ± 3.33a	91.11 ± 2.22a
Control neighboring plots	96.67 ± 3.33a	93.33 ± 3.84a	2.21 ± 1.97a	10.75 ± 4.22a	90.0 ± 0.00a	95.56 ± 2.22a
Buprofezin	86.67 ± 6.67a	95.56 ± 4.44a	2.12 ± 0.97a	12.29 ± 2.42a	70.0 ± 5.77b	95.56 ± 2.22a
F	2.09	0.52	0.37	0.51	7.85	0.94
df	2, 8	2, 8	2, 8	2, 8	2, 8	2, 8
P	0.205	0.621	0.706	0.624	0.021	0.442

Means in each column followed by the same letter are not significantly different according to the LSD test ($P > 0.05$). Percentage survival was arcsine-transformed (squareroot x) and mean progeny production was log-transformed ($x + 1$). Untransformed means are shown.
[a] LREC, Lindcove Research and Extension Center.

insecticide methidathion was the only insecticide that did not significantly affect larval development. The toxic effects of spinosad and abamectin were short lived (6 d). The effects of the neonicotinoids varied from 27 to 141 d and varied between experiments in the case of foliar acetamiprid. The pyrethroids were highly toxic to larvae, causing >50% mortality for >167 d. Buprofezin was less toxic to vedalia larvae than pyriproxifen, which significantly reduced development for >169 d.

Figure 1, A and B, shows the number of larvae alive during 20 d of exposure to 6 d-old residues of the tested insecticides. The larvae began to pupate in the control treatment after ≈8 d and began to emerge as adults after 13 d. The pyrethroids, cyfluthrin and fenpropathrin, and the imidacloprid drench were immediately toxic to the larvae and prevented most from surviving past the first day of exposure. The neonicotinoids, thiomethoxam drench, acetamiprid, and imidacloprid, and the chitin synthesis inhibitor buprofezin caused total mortality over an 8 d period, exerting their effect during the larval stage. The juvenile hormone mimic, pyriproxifen, did not affect vedalia until it reached the pupal stage and then completely prevented adult emergence. The abamectin+oil, spinosad, and acetamiprid drench caused a slight mortality of larvae. The organophosphate methidathion was not toxic to the vedalia stages tested.

Discussion

Vedalia adults and larvae did not avoid treated foliage or cottony cushion scale. The level of toxicity and the residual length of effect of the insecticides increased when vedalia stages not only contacted treated foliage but also fed on treated cottony cushion scale. Adult beetle survival was less affected by insecticides than larval development. The pyrethroid insecticides and the IGR pyriproxifen were the most toxic insecticides to vedalia stages tested. Next in order of toxicity were the neonicotinoids and buprofezin. The selective thrips insecticides sabadilla, abamectin, and spinosad, and the organophosphate methidathion were relatively nontoxic to vedalia stages. There was no significant toxicity to the beetle stages when exposure to the systemic neonicotinoid imidacloprid was contact through the treated plant alone (Table 3), yet toxicity occurred when vedalia stages fed on treated cottony cushion scale. These data suggest that vedalia ingested the insecticide by feeding on the cottony cushion scale. With the exception of the pyrethroids, little mortality of cottony cushion scale was observed during the 4–5 mo after the scale were treated with the pesticides.

San Joaquin Valley citrus growers experienced the results of pyriproxifen-decimated vedalia beetle populations as an area-wide phenomenon when they be-

Table 3. Survival of adults and progeny produced during a 72-h period of exposure to citrus leaves treated on 18 June (foliar imidacloprid), 2 June 1999 (methidathion), or 28 April 1999 (systemic imidacloprid)

Insecticide	Days after treatment			
	26, 42, and 77	35, 51, and 86	26, 42, and 77	35, 51, and 86
	Mean percentage adult survival ± SE		Mean progeny per female ± SE	
Imidacloprid—foliar	50.00 ± 11.55b	83.33 ± 12.02a	0.33 ± 0.33b	6.73 ± 1.60a
Imidacloprid—soil	90.00 ± 5.77a	100.00a	1.11 ± 0.67ab	10.22 ± 4.78a
Methidathion	100.00a	89.63 ± 5.78a	4.10 ± 1.42a	10.53 ± 3.22a
Control	96.67 ± 3.33a	100.00a	2.57 ± 1.09ab	6.36 ± 5.54a
F	10.92	2.13	3.28	0.59
df	3, 8	3, 8	3, 8	3, 8
P	0.003	0.174	0.080	0.641

Means in each column followed by the same letter are not significantly different according to the LSD test ($P > 0.05$). Percentage survival was arcsine-transformed (squareroot x) and mean progeny production was log-transformed ($x + 1$). Untransformed means are shown.

Table 4. Survival of adults and progeny produced during a 48-h period of exposure to citrus leaves treated on 24 May 1999

Insecticide	Days after treatment							
	4	14	23	45	4	14	23	45
	Mean percentage adult survival ± SE				Mean progeny per female ± SE			
Cyfluthrin	0.00b	0.00b	0.00c	73.33 ± 8.82b	0.33 ± 0.33b	0.09 ± 0.05b	0.05 ± 0.05c	1.47 ± 1.47a
Spinosad	96.67 ± 3.33a	100.00a	83.3 ± 6.67b	—	2.23 ± 0.50a	3.31 ± 1.15a	1.59 ± 0.99bc	—
Abamectin	100.00a	—	100.00a	—	3.14 ± 0.83a	—	6.28 ± 2.12a	—
Sabadilla	100.00a	—	88.43 ± 6.43ab	—	2.18 ± 0.90a	—	5.18 ± 2.18abc	—
Control	100.00a	86.67 ± 8.82a	93.33 ± 6.67ab	100.00a	5.27 ± 2.28a	1.83 ± 0.85ab	3.47 ± 0.81ab	3.77 ± 2.06a
F	208.19	74.19	37.13	24.04	3.75	5.84	5.32	1.31
df	4, 14	2, 8	4, 14	1, 5	4, 14	2, 8	4, 14	1, 5
P	<0.001	<0.001	<0.001	0.008	0.041	0.039	0.015	0.316

Means in each column followed by the same letter are not significantly different according to the LSD test ($P > 0.05$). Percentage survival was arcsine-transformed (squareroot x) and mean progeny production was log-transformed ($x + 1$). Untransformed means are shown.

gan using this insecticide in 1998. Because of California red scale resistance to organophosphates, pyriproxifen usage was heavy in the first year. A total of 20,139 ha of an estimated 68,197 total ha of San Joaquin Valley citrus were treated with pyriproxifen (University of California Statewide IPM Program 1998). Only 1,769 ha were treated with buprofezin because of its longer preharvest interval, greater cost, and somewhat less efficacy than pyriproxifen. The vedalia beetle was not seen for >9 mo after pyriproxifen was first used in 1998 (Grafton-Cardwell, E. E. 1999). During 1999, cottony cushion scale outbreaks occurred in a number of citrus orchards because of the lack of vedalia beetles. Because growers had little experience with this pest, many growers allowed densities of this pest to attain very high levels. The result was twig dieback, heavy honeydew production resulting in sooty mold that was difficult to wash off of the fruit, and in some cases, yield was severely reduced.

The situation was further complicated by the fact that the vedalia is highly sensitive to pyriproxifen and was eliminated for many miles around orchards that were treated. Those growers who sprayed pyriproxifen or buprofezin did not have cottony cushion scale outbreaks, because these insecticides exert some control of cottony cushion scale (Mendel et al. 1991, E.E.G.-C., unpublished data). However, their neighbors, who were releasing natural enemies and avoiding red scale insecticide treatments, experienced cottony cushion scale outbreaks because vedalia beetles were eliminated. These growers were forced to treat for cottony cushion scale with methidathion or malathion, disrupting natural enemies for other pests. This same pattern of vedalia disruption by IGRs followed by cottony cushion scale outbreaks was observed in South Africa (Hattingh and Tate 1995).

Hattingh and Tate (1995) suggested that spray drift was significant, and beetles were very sensitive to minute quantities of IGRs. However, our tests of contact toxicity of buprofezin and pyriproxifen indicate that leaves collected from trees only 11 rows or 67 m from treated areas had no effect on progeny production or larval development. This suggests that the cause of areawide disruption of vedalia by a patchwork application of IGRs is caused by the initial impact of spray drift and/or the high dispersal activity of vedalia beetle.

Pyriproxifen, methidathion, and buprofezin are applied by growers during the first (early May) or second (mid June–July) generations of California red

Table 5. Survival of adults after 72 h when exposed to insecticide-treated, cottony cushion scale–infested *P. tobira* foliage treated on 9 August, 2000

Insecticide	Mean percentage survival of adult beetles ± SE					
	22 DAT	43 DAT	71 DAT	99 DAT	127 DAT	155 DAT
Control	100.00a	100.00a	100.00a	100.00a	100.00a	100.00a
			Organophosphate			
Methidathion	100.00a	100.00a	100.00a	100.00a	100.00a	100.00a
			Neonicotinoids			
Thiomethoxam systemic	68.90 ± 14.6b	93.33 ± 3.85c	91.11 ± 2.22bc	97.78 ± 2.22a	100.00a	100.00a
Acetamiprid foliar	40.00 ± 6.67c	66.66 ± 6.67d	80.00 ± 0.0c	95.55 ± 2.22a	100.00a	100.00a
Imidacloprid systemic	84.40 ± 2.2b	100.00a	97.78 ± 2.22a	100.00a	95.56 ± 4.44ab	100.00a
			IGRs			
Pyriproxifen	95.60 ± 4.44a	97.78 ± 2.22ab	95.56 ± 4.44ab	95.55 ± 2.22a	93.33 ± 0.0b	97.78 ± 2.22a
Buprofezin	100.00a	95.55 ± 2.22ab	97.78 ± 2.22a	97.78 ± 2.22a	93.33 ± 3.85b	97.78 ± 2.22a
F	18.46	10.46	6.33	1.42	3.26	0.83
df	6, 20	6, 20	6, 20	6, 20	6, 20	6, 20
P	<0.001	<0.001	0.002	0.276	0.032	0.564

Means in each column followed by the same letter are not significantly different according to the LSD test ($P > .05$). Percentage survival was arcsine-transformed (squareroot x). Untransformed means are shown.

Table 6. Survival of adults after 72 h when exposed to insecticide-treated, cottony cushion scale–infested *P. tobire* foliage treated on 12 September 2001

Insecticide	Mean percentage survival of adult beetles ± SEM						
	20 DAT	41 DAT	70 DAT	98 DAT	126 DAT	154 DAT	182 DAT
Control	100.00a	100.00a	100.00a	100.00a	100.00a	100.00a	100.00a
Neonicotinoids							
Imidaeloprid foliar	8.90 ± 4.40c	73.3 ± 3.70b	97.8 ± 2.20a	—	—	—	—
Acetamiprid foliar	0.00d	80.0 ± 4.00b	93.3 ± 6.67a	—	—		—
Acetamiprid systemic	88.90 ± 2.2b	100a	95.5 ± 2.20a	—	—		—
IGR							
Pyriproxifen	100.00	97.70 ± 2.30a	97.8 ± 2.20a	100.00a	97.8 ± 2.20a	100.00a	100.00a
Pyrethroids							
Cyfluthrin	0.00d	13.30 ± 3.80c	44.4 ± 2.20b	68.90 ± 5.87b	64.4 ± 4.40c	93.30 ± 3.84a	91.10 ± 2.2b
Fenpropathrin	4.50 ± 2.20cd	4.70 ± 2.30c	62.2 ± 4.40b	77.80 ± 2.22b	84.4 ± 5.90b	93.30 ± 3.84a	100.00a
Other Chemistries							
Spinosad	97.8 ± 2.20a	97.70 ± 2.30a	100.00a	—	—	—	—
Abamectin + oil	97.8 ± 2.20a	97.70 ± 2.30a	100.00a	—	—	—	—
F	120.57	67.13	17.55	79.45	20.67	2.44	63.3
df	8, 26	8, 26	8, 26	3, 11	3, 11	3, 11	3, 11
P	<0.001	<0.001	<0.001	<0.001	<0.001	0.140	<0.001

Means in each column followed by the same letter are not significantly different according to the LSD ($P > 0.05$). Percentage survival was arcsine-transformed (squareroot x). Untransformed means are shown.

scale crawler activity (Grafton-Cardwell et al. 2002). After the disastrous 1999 season, growers learned to apply these insecticides after vedalia completed predation of cottony cushion scale in March–May. These insecticides are applied with thorough coverage (7,015–14,030 liters water/ha) and slow speed (2.4 kph) to achieve maximum penetration of the citrus canopy. Thus, the high rates used and the thorough coverage of the tree heighten the risk for the vedalia beetle.

In commercial citrus, the effects of pyrethroids, applied for citrus thrips control, on vedalia beetle have not been as dramatic as pyriproxifen, although our tests demonstrate a highly toxic and long residual effect, probably because of the coverage and timing of applications of these insecticides. Citrus thrips treatments are applied using outside coverage with low volumes of water (935–1,871 liters/ha). Thus, there is very little penetration to the interior of the tree where the adult female cottony cushion scale reside. Contact toxicity alone was far less toxic to the beetles than feeding on treated cottony cushion scale. Vedalia beetles are actively consuming cottony cushion primarily in the early spring (March–early May). Citrus thrips sprays are applied just after petal fall, which generally occurs in the San Joaquin Valley between 21 April and 15 May. Thus, in many situations, the pyrethroid insecticides are applied after vedalia beetles have cleared the orchard of cottony cushion scale or the grower used a selective insecticide such as spinosad, sabadilla, or abamectin for citrus thrips control.

There is an increasing trend in citrus thrips treatments to combine an organophosphate or pyrethroid

Table 7. Progeny resulting from adults exposed for 72 h to insecticide-treated, cottony cushion scale–infested *P. tobira* foliage treated on 9 August 2000

Insecticide	Mean number of progeny per female ± SE					
	22 DAT	43 DAT	71 DAT	99 DAT	127 DAT	155 DAT
Control	14.25 ± 2.59a	19.96 ± 1.12a	8.69 ± 2.91a	18.51 ± 5.67a	14.59 ± 1.41a	10.37 ± 2.57ab
Organophosphate						
Methidathion	5.34 ± 1.87b	7.85 ± 0.62b	7.92 ± 1.15a	5.44 ± 2.41bc	4.76 ± 1.05b	8.97 ± 0.26abc
Neonicotinoids						
Thiomethoxam systemic	6.57 ± 0.57b	6.91 ± 0.41b	7.08 ± 1.57a	9.60 ± 2.63ab	3.05 ± 1.04bc	12.01 ± 3.01a
Acetamiprid foliar	0.11 ± 0.06d	1.86 ± 1.00c	3.59 ± 1.24b	5.72 ± 1.58b	5.69 ± 1.42b	8.19 ± 1.36abc
Imidacloprid systemic	6.01 ± 1.50b	7.79 ± 0.68b	6.41 ± 0.28ab	8.2 ± 0.92ab	1.96 ± 0.56c	5.94 ± 1.15bc
IGRs						
Pyriproxifen	0.47 ± 0.17d	1.10 ± 0.86c	1.24 ± 0.38c	1.60 ± 0.61c	1.60 ± 0.62c	6.46 ± 1.03abc
Buprofezin	1.87 ± 0.32c	5.02 ± 0.39b	8.46 ± 1.01a	7.46 ± 1.34ab	1.64 ± 0.48c	5.42 ± 0.93c
F	26.90	15.52	7.05	4.08	10.37	2.02
df	6, 20	6, 20	6, 20	6, 20	6, 20	6, 20
P	<0.001	<0.001	0.001	0.014	<0.001	0.131

Means in each column followed by the same letter are not significantly different according to the LSD test ($P > .05$). Mean progeny production was log-transformed ($x + 1$). Untransformed means are shown.

Table 8. Progeny resulting from adults exposed for 72 h to insecticide-treated, cottony cushion scale–infested *P. lobira* foliage treated on 12 September 2001

Insecticide	Mean number of progeny per female ± SE						
	20 DAT	41 DAT	70 DAT	98 DAT	126 DAT	154 DAT	182 DAT
Control	5.57 ± 1.42a	5.03 ± 1.08a	7.98 ± 0.67b	4.21 ± 1.27a	4.93 ± 1.8a	5.31 ± 0.65a	6.67 ± 1.78a
			Neonicotinoids				
Imidacloprid foliar	1.10 ± 0.55b	0.79 ± 0.21cd	11.97 ± 2.08a	—	—	—	—
Acetamiprid foliar	0.04 ± 0.04c	1.71 ± 0.57bc	6.43 ± 0.59b	—	—	—	—
Acetamiprid systemic	6.32 ± 1.04a	1.97 ± 0.32bc	6.93 ± 0.41b	—	—	—	—
			IGR				
Pyriproxifen	0.54 ± 0.23bc	0.03 ± 0.03e	0.84 ± 0.25c	1.04 ± 0.44b	1.19 ± 0.28b	3.50 ± 2.56ab	6.27 ± 2.44a
			Pyrethroids				
Cyfluthrin	0.00c	0.22 ± 0.11de	0.00d	0.11 ± 0.07b	0.00c	0.08 ± 0.08bc	1.22 ± 0.51b
Fenpropathrin	0.00c	0.00e	0.00d	0.26 ± 0.26b	0.00c	0.00c	0.93 ± 0.58b
			Other chemistries				
Spinosad	0.44 ± 0.01bc	2.01 ± 0.62b	7.91 ± 0.40b	—	—	—	—
Abamectin + NR 415 oil	4.96 ± 1.44a	3.15 ± 1.04ab	7.80 ± 0.85b	—	—	—	—
F	21.18	13.31	135.11	13.24	26.91	7.06	5.82
df	8, 26	8, 26	8, 26	3, 11	3, 11	3, 11	3, 11
P	<0.001	<0.001	<0.001	0.002	<0.001	0.012	0.021

Means in each column followed by the same letter are not significantly different according to the LSD test ($P > .05$). Mean progeny production was log-transformed ($x + 1$). Untransformed means are shown.

insecticide with the spinosad treatment because spinosad alone does not sufficiently control the secondary pest forktailed bush katydid, *Scuddaria bifurcata* Brunner von Wattenwyl. During the organophosphate and carbamate era, katydids were not a problem because they are extremely sensitive to low rates of these insecticides. The newer, more selective insecticides do not control the larger instars or have sufficiently long residual effect to control prolonged hatches. If this trend increases and if pyrethroids are used, the risk of toxicity to vedalia beetle is heightened.

The exotic pest glassy-winged sharpshooter became a serious problem in the San Joaquin Valley in 2000. It is a vector of the bacteria, *Xylella fastidiosa,* that causes Pierce's disease in grapes. Because the glassy-winged sharpshooter uses citrus as a key oviposition host, citrus growers are under great pressure from the grape industry to apply treatments to reduce sharpshooter numbers early in the citrus season (March–April). The neonicotinoids are registered (imidacloprid, acetamiprid) or nearing registration (thiomethoxam) and provide fairly effective control of the glassy-winged sharpshooter (Grafton-Cardwell and Reagan 2001). Pyrethroids are also very effective against the glassy-winged sharpshooter. Uses of neonicotinoids, especially the very long-lasting systemic imidacloprid, and pyrethroids are likely to increase in citrus as the glassy-winged sharpshooter increases its numbers and moves through the citrus belt of the San Joaquin Valley. Our data suggest that these treatments

Table 9. Percentage development to adulthood of second-instar larvae exposed for 20 d to insecticide-treated, cottony cushion scale–infested *P. tobira* foliage treated on 9 August 2000

Insecticide	Mean percentage larvae reaching adulthood after 20 days ± SE						
	8 DAT	29 DAT	57 DAT	85 DAT	113 DAT	141 DAT	169 DAT
Control	17.78 ± 5.88b	53.33 ± 10.18a	80.00 ± 6.67a	91.11 ± 2.22a	86.67 ± 3.85a	86.67 ± 3.85a	82.22 ± 5.88a
			Organophosphate				
Methidathion	28.89 ± 2.22a	71.11 ± 11.11a	82.22 ± 8.01a	82.22 ± 5.88a	75.56 ± 5.88ab	73.33 ± 3.85ab	—
			Neonicotinoids				
Thiomethoxam systemic	0.00c	4.44 ± 2.22cd	13.33 ± 6.67c	28.89 ± 12.37c	24.44 ± 4.44d	42.22 ± 8.89d	—
Acetamiprid foliar	0.00c	15.55 ± 5.87bc	55.56 ± 9.69b	62.22 ± 4.44b	35.56 ± 11.76cd	51.11 ± 2.22cd	84.44 ± 8.01a
Imidacloprid systemic	0.00c	24.44 ± 4.44b	66.67 ± 6.67ab	57.78 ± 5.88b	51.11 ± 11.76bc	62.22 ± 5.88bc	82.22 ± 4.44a
			IGRs				
Pyriproxifen	0.00c	0.00d	0.00d	0.00d	0.00e	0.00e	2.22 ± 2.22b
Buprofezin	0.00c	0.00d	22.22 ± 5.88c	44.44 ± 2.22bc	15.56 ± 8.89d	51.11 ± 2.22cd	66.67 ± 3.85a
F	55.15	23.26	26.90	37.61	20.66	34.76	23.26
df	6, 20	6, 20	6, 20	6, 20	6, 20	6, 20	6, 20
P	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Means in each column followed by the same letter are not significantly different according to the LSD test ($P > .05$). Percentage survival was arcsine-transformed (squareroot x). Untransformed means are shown.

Table 10. Percentage development to adulthood of second instar larvae exposed for 20 d to insecticide-treated, cottony cushion scale–infested *P. lobira* foliage treated on 12 September 2001

Insecticide	Mean percentage larvae surviving to adulthood after 20 days ± SE							
	6 DAT	27 DAT	55 DAT	83 DAT	112 DAT	139 DAT	167 DAT	195 DAT
Control	88.89 ± 2.22a	80.00 ± 7.70a	91.11 ± 4.44a	95.56 ± 2.22a	95.56 ± 4.44a	97.78 ± 2.22a	95.56 ± 2.22a	95.56 ± 2.22a
				Neonicotinoids				
Imidacloprid foliar	0.00e	35.56 ± 9.69b	80.00 ± 10.18a	93.33 ± 3.85a	91.11 ± 4.44a	—	—	—
Acetamiprid foliar	0.00e	4.44 ± 2.22c	86.67 ± 6.67a	93.33 ± 3.85a	95.56 ± 2.22a	—	—	—
Acetamiprid systemic	62.22 ± 4.44b	84.44 ± 5.88a	—	—	—	—	—	—
				IGR				
Pyriproxifen	0.00e	0.00e	0.00c	2.22 ± 2.22c	4.44 ± 2.22c	17.78 ± 8.01c	46.67 ± 10.18b	37.78 ± 8.89c
				Pyrethroids				
Cyfluthrin	0.00e	0.00c	11.11 ± 2.22b	13.3 ± 3.85b	15.56 ± 5.89bc	40.00 ± 3.85b	33.33 ± 6.67b	53.33 ± 0.0c
Fenpropathrin	0.00e	0.00c	11.11 ± 2.22b	17.78 ± 2.22b	31.11 ± 4.44b	48.89 ± 5.88b	48.89 ± 5.88b	80.00 ± 3.85b
				Other chemistries				
Spinosad	15.6 ± 2.22c	80.00 ± 0.00a	—	—	—	—	—	—
Abamectin + NR 415 oil	8.89 ± 2.22d	84.44 ± 5.88a	—	—	—	—	—	—
F	331.10	65.86	33.70	49.24	24.87	35.21	17.94	22.28
df	8, 26	8, 26	5, 17	5, 17	5, 17	3, 11	3, 11	3, 11
P	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.001	<0.001

Means in each column followed by the same letter are not significantly different according to the LSD test ($P > 0.05$). Percentage survival was arcsine-transformed (squareroot x). Untransformed means are shown.

are likely to reduce vedalia beetle survival and cause cottony cushion scale outbreaks.

Despite the cottony cushion scale problems observed during 1998–2001, there have been significant benefits of IGRs that warrant their continued use in citrus. The use of IGRs for California red scale control and spinosad for citrus thrips control has reduced organophosphate and carbamate use in citrus by 0.3 million kg each year (Grafton-Cardwell 2003). This has provided a more favorable environment for parasites and predators other than beetles, improving other aspects of the integrated pest management (IPM) program as well as worker safety. The IGRs have been found to be relatively nontoxic to hymenopterous parasitoids (Ishaaya 1990, Mendel et al. 1994). Currently, vedalia beetles are returning 3–4 mo after pyriproxifen sprays have been applied in the San Joaquin Valley, and the number of cottony cushion scale outbreaks has lessened considerably since the first year. Thus, vedalia seems to be adapting, perhaps by developing resistance, to the presence of these insecticides and/or the growers are learning to use the insecticides more carefully.

The data indicate that by replacing organophosphate and carbamate insecticides with IGRs, pyrethroids, and neonicotinoids, CA citrus growers have greatly increased toxicity to vedalia beetles. Pyrethroids and neonicotinoids are known to be broad spectrum in their activity and so toxicity to natural enemies is expected. IGRs, however, are considered by regulatory agencies to be selective chemicals that should be more compatible with IPM programs. Our data contribute to the growing concern that IGRs are causing pest outbreaks of scales, mealybugs, and mites because of disruption of coccinellid beetles (Loia and Viggiani 1991, Loia and Viggiani 1992, Biddinger and Hull 1995, Hattingh and Tate 1995, Magagula and Samways 2000).

The United States Environmental Protection Agency (1999) has defined reduced-risk insecticides as insecticides that have one or more of the following advantages over existing products: lower impact on human health; lower toxicity to birds, fish, and plants; lower potential for groundwater contamination; lower use rates; pest resistance potential; and a greater compatibility with IPM. Of the new products registered for California citrus with reduced-risk status (spinosad, pyriproxifen, buprofezin, and acetamiprid), all except spinosad are toxic to the vedalia beetle and can cause cottony cushion scale outbreaks. These data suggest that reduced-risk status does not necessarily mean that an insecticide has a greater compatibility with citrus IPM.

The problems of natural enemy disruption by new pesticides coupled with the ever-present potential for the development of resistance point once again to the need to rely on natural enemies for long-term control of citrus pests. Vedalia beetles provide the most effective control of cottony cushion scale, and insecticides must be used carefully to conserve and protect this natural enemy.

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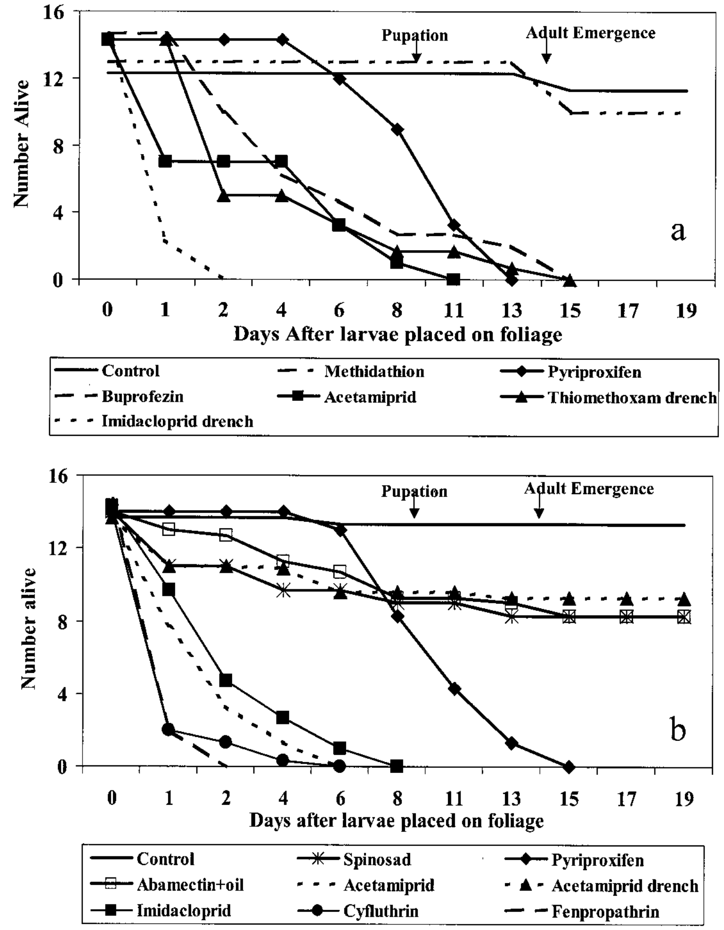

Fig. 1. The number of live individuals over a 20-d period of exposure to various insecticides. Second-instar larvae were placed on cottony cushion scale–infested *P. tobira* leaves 6 d after the plants and scale were treated with insecticides. The points in time at which pupation and adult emergence began in the control treatment are noted. A and B are the results of two different experiments.

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