Sublethal Effects of Pesticides on the Parasitoid *Aphytis melinus* (Hymenoptera: Aphelinidae)

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ABSTRACT Sublethal effects of insecticides on the parasitoid *Aphytis melinus* DeBach were investigated. Longevity, daily rate of progeny production per female, and size and sex ratio of offspring were measured for parasitoids exposed to rates near the LC_{50}'s of carbaryl, chlorpyrifos, dimethoate, malathion, and methidathion. Survivors of the exposure to carbaryl exhibited no significant sublethal effects. Exposure to each of the organophosphorous materials reduced longevity by 73–85% and temporarily depressed progeny production. Chlorpyrifos also shifted the sex ratio of offspring toward more males. The strength and variability of sublethal effects found in this and other studies indicate that sublethal effects must be considered to evaluate accurately the selectivity of pesticides in favor of parasitoids.

KEY WORDS Insecta, *Aphytis melinus*, biological control, integrated pest management

THE IMPORTANCE of integrating chemical and biological control has become increasingly apparent since the advent of synthetic organic pesticides. Use of pesticides incompatible with parasitoid and predator activity has produced target pest resurgences and secondary pest outbreaks throughout the world's agroecosystems (Luck et al. 1977, Metcalf 1986). These ecological disruptions have resulted in increased crop damage, increased need for additional pesticide applications, accelerated evolution of pesticide resistance, and increased general contamination of the environment (Metcalf 1986). An important means of avoiding these problems is the use of pesticides whose action spares natural enemies through either physiological or ecological selectivity. Identification of selective compounds depends upon an understanding of pesticidal effects on both pest and natural enemy populations in the field. Therefore, host–parasitoid–pesticide interactions have been investigated since the acceptance of the integrated pest management (IPM) approach (e.g., DeBach & Bartlett 1951, Stern et al. 1959, Bartlett 1964, 1966, Hull & Beers 1985, Hassan et al. 1987).

The complexity of host–parasitoid–pesticide interactions is introduced by parasitoid behavior (Bartlett 1966, Croft 1977), pesticide residue chemistry, insect developmental physiology (Schoonees & Giliomee 1982, Flanders et al. 1984, Bellows et al. 1985, Bull & Coleman 1985), the variable genetic composition of parasitoid populations (Schoonees & Giliomee 1982, Rosenheim & Hoy 1986), and the impact of pesticides upon the host population (Waage et al. 1985). A pesticide's toxic effects on the parasitoid are also complex. Pesticides may cause both acute mortality and various sublethal effects that may alter the parasitoid's ability to reproduce at the expense of the host population (Irving & Wyatt 1973, Croft & Brown 1975, O'Brien et al. 1985, Hassan et al. 1987).

The facultatively gregarious ectoparasite *Aphytis melinus* DeBach is the major biological control agent of California red scale, *Aonidiella aurantii* (Maskell) (Homoptera: Diaspididae), a key pest of citrus in California and other areas of the world (Rosen & DeBach 1979). Because biological control of *A. aurantii* and other key pests of citrus, including citrus thrips, *Scirtothrips citri* (Moulton), citrus red mite, *Panonychus citri* (McGregor), and several lepidopteran species, is often incomplete in California, application of pesticides is currently a major element of citrus IPM (University of California 1984, Luck et al. 1986). Pesticide impact on *A. melinus* in the field appears to be severe (Phillips et al. 1983, Griffiths et al. 1985). Attempts have been made to lessen this impact by identifying pesticides with low acute toxicity to *A. melinus* (Bartlett 1966, Abdelrahman 1973, Davies & McLaren 1977, Morse & Bellows 1986), short residual activity (Campbell 1975, Bellows et al. 1985), or pesticides to which *A. melinus* has evolved increased tolerance (Rosenheim & Hoy 1986). The results of these laboratory studies have not always agreed with observations in the field. Chlorpyrifos, consistently the most acutely toxic scalicide in the laboratory (Morse & Bellows 1986, Rosenheim & Hoy 1986), appears to be one of the least disruptive to *A. melinus* in the field (J. Gorden, Pest Management Associates, Exeter, Calif.; H. J. Griffiths, Entomological Services Inc., Corona, Calif., personal communications), apparently at least in part due to a shorter residual toxicity (Luck et al. 1986; H. J. Griffiths, personal communication). An additional factor possibly contributing to these apparently conflicting results is the variable sublethal effects of different insecticides. This possibility was

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suggested by observations, made during artificial selection for increased pesticide tolerance in *A. melinus*, that parasitoids surviving exposures to insecticides were not reproducing at normal rates (unpublished data).

Our study was conducted to determine if variable sublethal effects explain the discrepancies between laboratory and field studies of pesticide selectivity towards *A. melinus*, and to use *A. melinus* in citrus as a model system to evaluate the contribution of sublethal effects to the overall impact of pesticides on parasitoids.

Materials and Methods

Colony Collection and Maintenance. The *A. melinus* colony was collected October 1984 in a commercial navel orange grove in Tulare County, Calif. The population's field history of pesticide exposure has been described previously (colony no. 1, Rosenheim & Hoy [1986]). The colony has a high tolerance to insecticides relative to other field populations tested (Rosenheim & Hoy 1986). The colony was maintained in the laboratory at 27 ± 2°C, 70 ± 15% RH, and a photoperiod of 16:8 (L:D) on a uniparental strain of oleander scale, *Aspidiotus nerii* Bouché, that was grown under constant darkness at 24 ± 1°C on russet potatoes, *Solanum tuberosum* L. Honey was provided in the colony cage.

Experimental Design. Our general approach was to expose young female *A. melinus* to pesticide residues that would cause about 50% mortality within 24 h, remove the survivors, provide them with excess numbers of hosts, and then assess their longevity, progeny production, and the size and sex ratio of their progeny. Exposure to an LC_{50} was chosen as a means of comparing sublethal effects of pesticides with widely varying acute toxicities. In the field, parasitoids are exposed to a range of pesticide concentrations that is high at the time of application and decreases as the residue degrades, so that some parasitoids are exposed to rates equivalent to the LC_{50}.

Our experimental protocol was as follows. On day 1, adult parasitoids (0–24 h old) were collected for testing by placing parasitized *A. nerii* in an emergence cage. The emergence cage was lightproof except for 12 removable glass test tubes, each provided with streaks of honey, in which the parasitoids congregated due to their positive phototropism. On day 2, the host material was removed and the parasitoids were left in the cage to ensure mating. On day 3, disposable plastic cups (30 ml) and polyester gauze were treated by dipping them for 5 s into commercial grade insecticide solutions formulated in distilled water with a spreader (0.025% Triton AG-98; Rohm & Haas Co., Philadelphia, Pa.). The cups were drained onto paper toweling, the gauze was pressed to remove excess solution, and both were air-dried in a hood. The cups capped with the gauze were then used as exposure vials. Honey was provided on an untreated strip of electrician's tape (5 × 18 mm) affixed to the gauze cap.

Three materials widely used for California red scale control—carbaryl (Sevin 80S [sprayable]; Union Carbide Chemical Co., Research Triangle Park, N.C.), malathion (Malathion 25S; American Cyanamid Co., Wayne, N.J.), and methidathion (Supracide 2EC [emulsifiable concentrate]; CIBA-Geigy Co., Basel, Switzerland)—one material used for citrus thrips control (dimethoate [Cygon 400]; American Cyanamid Co., Wayne, N.J.), and one material used for control of both California red scale and several lepidopteran pests (chlorpyrifos [Lorsban 4EC]; Dow Chemical Co., Midland, Mich.) were tested, along with a water plus spreader control. Time requirements precluded completely simultaneous treatments, but all treatments began within a 6-d period and were evaluated together during the following 4–6 wk.

Approximately 10 female *A. melinus*, distinguished from males under a stereomicroscope without using anaesthesia, were added to each of 10 vials after carbon dioxide anaesthesia (10 s). The vials were held for 24 h at 27 ± 0.5°C and 74% RH under constant light. On day 4, results of the tests were recorded. Individuals were considered dead if they were unable to maintain a normal posture or walk normally at a rate of at least 1 mm/s. Survivors from two exposure vials or a single control vial (about 10 females total) were added to a single glass jar (3.8 liter) covered with gauze and provided with honey and a single potato bearing excess mature oleander scales (ca. 70 d old). These colony jars (n = 5 for each treatment) were held for parasitoid oviposition at 27 ± 2°C, 70 ± 15% RH, and a photoperiod of 16:8 for the remainder of the experiment.

On each successive day, mortality was assessed. Jars were filled with carbon dioxide for 60 s to anaesthetize the parasitoids, which were collected by removing the potato and inverting the jar over a glass funnel positioned over a small collecting vial. Parasitoids were scored as dead or alive using the same criterion described earlier. Dead parasitoids were removed every day, a fresh potato with scales was provided (on oviposition days 1–6 and every third day thereafter), and fresh honey was added every fifth day. Parasitoids found dead were assigned a time of death 12 h before. Those parasitoids that were still alive were returned to the colony jars following 10 s of additional carbon dioxide anaesthesia. This procedure was continued until all parasitoids had died. Parasitoids lost between successive scorings (13/287 = 4.5% of all females) were assumed to have died (dead wasps became dry and were difficult to collect). To avoid biasing the data, live parasitoids that escaped or were crushed during handling (4/287 = 1.4% of total) were assigned longevities equal to the average of the other parasitoids then alive.

Potatoes removed from the colony jars were held individually for parasitoid development and emer-

gence in glass jars (950 ml) covered with gauze and not provided with honey. (By withholding honey, the emerging parasitoids quickly starved, enabling us to assess more accurately the duration of the emergence period.) A preliminary experiment was conducted to determine the development rate of *A. melinus* under our experimental conditions. Twenty female parasitoids were held for 24 h on day 0 with excess *A. nerii* for oviposition (three replicates). The parasitoids were then removed. The progeny were reared at 28 ± 0.5°C, 65 ± 10% RH, and a photoperiod of 16:8, and monitored daily for adult emergence. No emergence occurred before day 12; 1.00 ± 1.00 ($\bar{x}$ ± SD) parasitoids emerged on day 12, 36.33 ± 12.66 on day 13, 16.33 ± 2.08 on day 14, 0.33 ± 0.58 on day 15, 0.33 ± 0.58 on day 16, and none thereafter until the second generation began emerging on day 24. Thus, potatoes removed from the colony jars were held for 21 d (or 19 d for potatoes left in colony jars for 3 d) under the same conditions used with the colony jars. This holding period encompassed the entire emergence of the first generation and excluded the second generation. Although sublethal effects of pesticide exposure on the developmental rate of progeny were not specifically investigated, 25 holding jars for each treatment were inspected daily to determine the earliest day of emergence; in no case did emergence occur before day 12. In addition, none of the emerged parasitoids was still alive at the end of the 19- or 21-d holding periods in any of the jars (parasitoids die in one to several days when held without honey), indicating that the emergence was complete in all cases.

All emerged progeny were collected from the holding jars, counted, and their sex was determined. Progeny from oviposition days 1 and 2 were cleared in glacial acetic acid and chloral phenol for 24 h and mounted on slides using the procedure of Rosen & DeBach (1979). Hind tibia length, an index of parasitoid size, was measured to the nearest 0.003 mm at 400× magnification with an ocular micrometer.

Statistical Analysis. Data on longevity, overall progeny production per female, average rate of progeny production, and the sex ratio and size of offspring were analyzed with one-way analyses of variance (ANOVA). Sex ratio data were analyzed as the arcsine transformed proportion of female progeny. Families of pairwise contrasts, computed for each one-way ANOVA, were done using the Bonferroni inequality to maintain overall $\alpha \leq 0.05$ (Dixon 1985). The assumption of equal variance of ANOVA was explicitly tested in all cases, and separate variance tests (Welch model) were employed when variances differed with $P < 0.10$ (Dixon 1985). Trends in arcsine transformed proportion of female progeny produced (the dependent variable) over time (the independent variable) were examined with simple linear regression (regression model I, Sokal & Rohlf [1981]). Changes in progeny production rate per female were analyzed using repeated-measures ANOVA. An orthogonal polynomial decomposition of the within subjects terms (the main effect for time and the interaction of time with insecticide) into linear, quadratic, and cubic trend components was performed to provide a detailed analysis of the progeny production curves (Sokal & Rohlf 1981; Dixon 1985, 367–379). Analyses were performed using the BMDP computer statistical package, programs P7D and P2V (Dixon 1985).

Results

Acute mortality and sublethal effects of insecticides on the longevity, progeny production, and size and sex ratio of offspring of *A. melinus* are summarized in Table 1. The total number of progeny produced per female surviving the exposure varied significantly between treatments ($F = 19.07$; df = 5, 11; $P < 0.0001$). Exposure to carbaryl, the only carbamate tested, did not reduce progeny production, whereas the remaining four chemicals, all organophosphates (OPs), caused reductions of about 82–90%. Most of these reductions are attributable to the impact of the OPs on longevity, which also varied significantly between treatments ($F = 71.71$; df = 5, 11; $P < 0.0001$). Carbaryl produced an insignificant increase in mean longevity relative to the control, whereas the OPs caused reductions of about 73–85%. Survivorship curves (Fig. 1) revealed substantial delayed mortality of the OP-exposed parasitoids during days 1–3 after exposure. Parasitoids surviving this early period of high mortality displayed longevities similar to those of the controls. This unimodal distribution of mortalities is not analogous to "latent toxicity" sensu Moriarty (1969), which implies a polymodal distribution.

Progeny production figures were standardized to include the effects of variable longevity by calculating the average progeny production per female per day lived (i.e., progeny per female-day) (Table 1). Overall average numbers of progeny per female-day were not significantly lower in the OP treatments than in the carbaryl or control treatments ($F = 1.31$; df = 5, 24; $P = 0.29$). These overall average figures are, however, somewhat misleading, because they are confounded by the considerable variation in daily progeny production associated with parasitoid age (Fig. 2). To include the effects of this variation, the data were analyzed in two ways: first, simple one-way analyses of variance on each day's progeny production values were made separately. These analyses revealed significant treatment effects on days 1 and 2 after exposure ($F = 7.86$; df = 5, 24; $P = 0.0002$ and $F = 3.80$; df = 5, 24; $P = 0.0112$, respectively), with the parasitoids in the OP treatments producing fewer progeny than the parasitoids in the carbaryl or control treatments (Fig. 2). Differences in daily progeny production between treatments decreased rapidly, becoming statistically insignificant after day 2. (One exception—significantly greater prog-

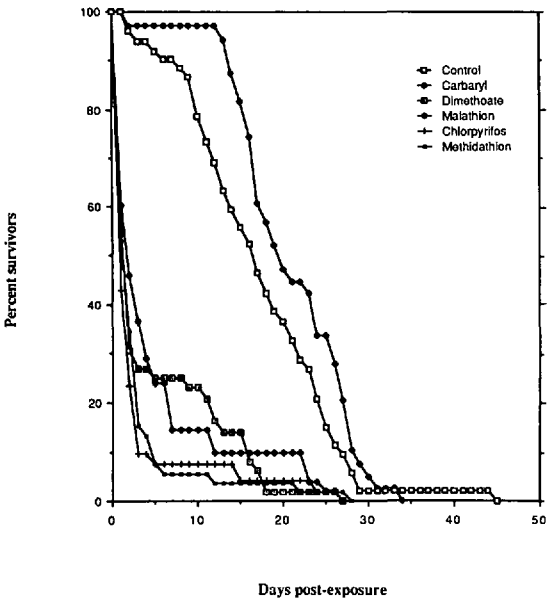

Fig. 1. Sublethal effects of five insecticides on longevity of *A. melinus*. Mean percent survivorship is plotted versus time since the end of the exposure.

eny production by methidathion-treated parasitoids on day 9 ($F = 6.00$; df = 5, 20; $P = 0.0015$)—was apparently a chance result).

A second analysis was made to consider the overall shapes of the daily progeny production curves (Fig. 2). Because our experimental design entailed the repeated measurement of progeny production, an ANOVA with a repeated-measures design was appropriate. One complication, however, was that this analysis required complete cases (i.e., all replicates must contain the same number of samples); the number of complete cases per treatment in our experiment decreased from five to zero over time because of natural parasitoid mortality. Therefore, we performed the repeated-measures ANOVA on the progeny production data for days 1–12 only, grouped into four 3-d periods (Table 2). This procedure excluded one incomplete case for the malathion treatment and two incomplete cases for the chlorpyrifos and methidathion treatments; these exclusions did not greatly alter the mean values for these treatments (average progeny per female-day for days 1-12 changed from 1.20 to 1.32 for malathion, from 1.46 to 1.31 for chlorpyrifos, and from 1.47 to 1.64 for methidathion as the incomplete cases were removed) and decreased the sample size, resulting in a more conservative test.

The results of the analysis (Table 2) confirmed the key patterns apparent in Fig. 2. The main effect for insecticide was significant ($F = 4.81$; df = 5, 19; $P = 0.0052$), reflecting the generally depressed progeny production by parasitoids exposed to OPs. The main effect for time was also significant ($F = 15.45$; df = 3, 57; $P < 0.0001$), indicative of the decreasing progeny production associated with

Table 1. Sublethal effects of insecticides on progeny production, longevity, and size and sex ratio of offspring of *A. melinus*

Treatment	Pesticide concn in mg (AI)/liter	% mortality after 24 h ($\bar{x} \pm$ SD)	Total no. survivors	Total no. progeny per surviving female ($\bar{x} \pm$ SD)	Avg longevity in days ($\bar{x} \pm$ SD)	Avg no. progeny per female-day ($\bar{x} \pm$ SD)	Sex ratio of progeny ♀/♂		Avg tibia length in mm of progeny produced within 2 d after exposure ($\bar{x} \pm$ SD)	
							$\bar{x} \pm$ SD (n)		♀♀ (n)	♂♂ (n)
Dimethoate	1.200	50.7 ± 18.6	49	3.9 ± 2.4a	4.5 ± 1.8a	0.91 ± 0.42a	2.66 ± 0.64	(202)a	0.252 ± 0.008 (38)a	0.201 ± 0.027 (11)a
Malathion	0.576	56.7 ± 12.8	45	5.4 ± 4.2a	4.6 ± 2.3a	1.09 ± 0.35a	3.77 ± 2.74	(228)ab	0.250 ± 0.013 (63)a	0.188 ± 0.013 (36)a
Methidathion	0.600	47.5 ± 21.2	53	3.0 ± 1.9a	2.7 ± 1.3a	1.16 ± 0.39a	2.94 ± 0.90	(163)ab	0.238 ± 0.015 (52)a	0.191 ± 0.009 (27)a
Chlorpyrifos	0.126	48.6 ± 19.3	50	3.0 ± 1.7a	2.5 ± 1.3a	1.44 ± 1.20a	1.39 ± 0.29	(150)b	0.247 ± 0.010 (54)a	0.191 ± 0.010 (32)a
Carbaryl	4.800	62.8 ± 24.0	39	30.3 ± 10.9b	20.6 ± 3.1b	1.53 ± 0.60a	3.12 ± 1.07	(1,142)a	0.242 ± 0.010 (222)a	0.189 ± 0.005 (78)a
Control	—	0.0 ± 0.0	52	29.2 ± 6.1b	16.8 ± 2.2b	1.77 ± 0.32a	2.71 ± 0.59	(1,508)a	0.238 ± 0.011 (348)a	0.183 ± 0.009 (147)a

Figures in the same columns followed by different letters differ significantly (Bonferroni probability, $P < 0.05$; Dixon [1985]).

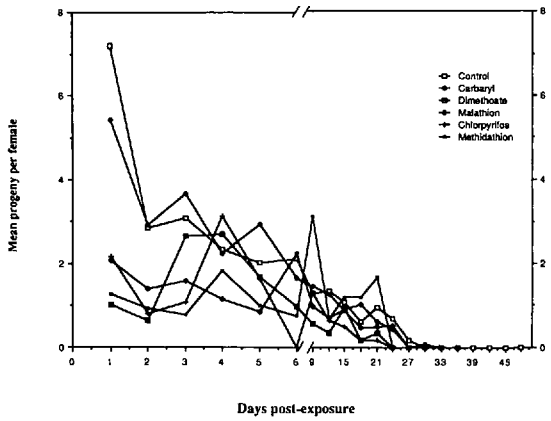

Fig. 2. Sublethal effects of five insecticides on the progeny production schedule of *A. melinus*. Mean number of progeny produced per female-day is plotted versus time since the end of the exposure.

aging. The significant interaction of time and insecticide ($F = 4.03$; df = 15, 57; $P = 0.0001$) indicated that the shapes of the curves differed significantly. The significant interaction of the linear component of time × insecticide ($F = 2.98$; df = 5, 57; $P = 0.0374$) confirmed that the slopes of the linear components of the different progeny production curves were not equal; the curves decreased more rapidly for the control and carbaryl treatments than for the OP treatments. The quadratic trend component, which tests for a "hump-shaped" component in the curves, also interacted significantly with insecticide ($F = 8.38$; df = 5, 57; $P = 0.0003$), reflecting the increasing progeny production by "recovering" OP-exposed parasitoids after the initially depressed levels of days 1–2. It is difficult to distinguish between two possible explanations for this recovery—there may have been a physiological recovery of intoxicated individuals within each replicate, or the recovery may have been caused simply by the increased relative weighting of the progeny production levels of the less intoxicated parasitoids that occurred when the most highly intoxicated individuals died.

All offspring sex ratios were strongly female-biased, as is normal for *A. melinus*, except for that of females exposed to chlorpyrifos. In the chlorpyrifos treatment, a significant increase in the proportion of males occurred ($F = 5.80$; df = 5, 11; $P = 0.0073$ [the result for chlorpyrifos is based upon 150 progeny produced over 21 d]) (Table 1). Results of linear regression analyses for each treatment indicated that the sex ratio was independent of parasitoid age for the control and all the experimental treatments except for methidathion, which showed an increasing proportion of female offspring as wasps aged (control, $r^2 = 0.08$, B (slope) = -0.79 ± 0.42 ($\bar{x} \pm$ SD), $P > 0.05$; carbaryl, $r^2 = 0.02$, $B = -0.30 \pm 0.37$, $P > 0.25$; dimethoate, $r^2 = 0.001$, $B = -0.09 \pm 0.63$, $P > 0.10$; malathion, $r^2 = 0.01$, $B = 0.37 \pm 0.89$, $P > 0.25$; chlorpyrifos, $r^2 = 0.02$, $B = -0.50 \pm 0.95$, $P > 0.25$; methidathion, $r^2 = 0.50$, $B = 1.71 \pm 0.44$; $P < 0.01$). Thus, the divergent offspring sex ratio observed for the parasitoids exposed to chlorpyrifos did not simply reflect their reduced longevities. The mechanism of chlorpyrifos action on offspring sex ratio is not clear but might include effects on the viability of stored sperm, maternal behavioral control of the primary sex ratio, or a sex-specific mortality during progeny development.

The five insecticides did not change the size, as measured by hind tibia length, of male or female progeny produced on day 1 or 2 after exposure ($F = 0.73$; df = 5, 10; $P = 0.6151$ and $F = 2.12$; df = 5, 42; $P = 0.0818$, respectively).

Discussion

Our investigation has revealed significant sublethal effects of four OP insecticides (chlorpyrifos, dimethoate, malathion, and methidathion) on the longevity and progeny production rates of *A. melinus*. One insecticide, chlorpyrifos, also shifted the offspring sex ratio away from the strong female

Table 2. Repeated-measures ANOVA of progeny production per female-day, days 1–12, for *A. melinus* exposed to residues of five insecticides and a water control

Source	Sum of squares	Degrees of freedom	Mean square	*F*	*P*
Insecticide	28.79	5	5.76	4.81	0.0052
Error	22.73	19	1.20		
Time	29.77	3	9.92	15.45	<0.0001
Time (1)[a]	29.39	1	29.39	28.43	<0.0001
Time (2)	0.09	1	0.09	0.22	NS
Time (3)	0.28	1	0.28	0.59	NS
Time × insecticide	38.87	15	2.59	4.03	0.0001
Time (1) × insecticide	15.42	5	3.08	2.98	0.0374
Time (2) × insecticide	17.30	5	3.46	8.38	0.0003
Time (3) × insecticide	6.14	5	1.23	2.56	NS
Error	36.62	57	0.64		

[a] Main effect sums of squares for time (days) and time × insecticide interaction are orthogonally decomposed into linear, quadratic, and cubic trend components. The number in parentheses following "Time" indicates the order of the orthogonal polynomial: (1) indicates the linear polynomial, (2) the quadratic polynomial, and (3) the cubic polynomial (Dixon 1985, 367–379).

bias characteristic of the species (Hoffman & Kennett 1985). No effects on the size of progeny produced during the first 2 d after exposure to any insecticide were observed. The magnitude of the combined sublethal effects of the OPs on longevity, progeny production rate, and sex ratio was great. Exposure to residues of a dimethoate solution (1.20 mg/liter) caused 24-h mortality of 50.7% (a lethal effect) but actually reduced the production of female offspring by 93.4% compared with the controls. (The figure of 93.4% was obtained from Table 1 by multiplying the proportional reduction in total progeny production by the proportional change in the percentage of females produced.) Analogous figures (percent 24-h mortality and total percent reduction in female progeny) for malathion, methidathion, and chlorpyrifos are 56.7% and 91.3%, 47.5% and 94.5%, and 48.6% and 95.8%, respectively (Table 1). In contrast to the OPs, carbaryl did not cause any detectable sublethal effects, a 24-h mortality of 62.8% causing only a 58.4% reduction in the number of female offspring produced. Variation among different insecticides, combined with the magnitude of the effects of the OPs, indicates that sublethal effects must be considered to evaluate accurately the selectivity of pesticides towards *A. melinus*.

Previous laboratory studies suggest that highly variable and potentially strong sublethal effects may be general features of the impact of synthetic organic pesticides on parasitoids. Flanders (1943) observed that contact with sublethal sulfur residues on citrus leaves caused *Metaphycus helvolus* (Compere) to lose permanently its ability to recognize hosts. Grosch (1970, 1975) found that topical applications of the chlorinated hydrocarbon (CHC) heptachlor on *Bracon hebetor* Say at about the LD_{25} produced a slight decrease in longevity and a small, temporary depression of fecundity, but applications of carbaryl at the LD_{50} yielded a slight decrease in longevity and a large (> 50%), permanent decrease in fecundity. Irving & Wyatt (1973) found that nonlethal residues of two fungicides, benomyl and dichlofluanid, and two CHC insecticides, tetradifon and lindane, reduced the host stabbing behavior of *Encarsia formosa* Gahan, while the carbamate pirimicarb had the reverse effect. Abdelrahman (1973) found that *Aphytis melinus* exposed for 24 h to residues of a LC_{50} of malathion continued to suffer delayed mortality during 3 d after exposure, a result confirmed in our study. Plewka et al. (1975) and Krukierek et al. (1975) found progressively reduced longevities for *Trichogramma evanescens* Westwood exposed to increasing doses of metasystox (an OP), DDT (a CHC), and methoxychlor (a CHC). Jacobs et al. (1984) found no sublethal effects on the number of eggs deposited per host egg or the resulting offspring sex ratio for *Trichogramma pretiosum* (Riley) exposed to up to an LC_{55} of endosulfan (a CHC) or an LC_{90} of permethrin (a pyrethroid). Similarly, no sublethal effects on longevity or fecundity were detected by Hsieh & Allen (1986) for *Diaeretiella rapae* (M'Intosh) exposed as immatures within aphid mummies to a LC_{7-16} of methomyl (a carbamate), LC_{22-29} of acephate (an OP), or LC_{28-51} of permethrin. Hsieh (1984) found that *D. rapae* exposed to acephate residues as an adult suffered no sublethal effects, but that exposure to a LC_{60} of methomyl resulted in a 50% reduction in longevity and a 93% decrease in fecundity. Finally, O'Brien et al. (1985) found that chronic exposure of *Bracon mellitor* Say to an LC_5 of azinphosmethyl (an OP) or chlordimeform (a formamidine) caused moderate decreases in fecundity and a significant shift of the sex ratio toward more females.

From these examples we cannot discern any clear patterns of the type or magnitude of sublethal effects based upon the specific compound, class of insecticide, or parasitoid species in question. The total number of studies performed to date is small, however, and it is possible that additional investigations will reveal patterns not yet apparent. Most field studies and many laboratory studies combine acute mortality and sublethal effects (e.g., Hassan et al. 1987) and therefore cannot be used to evaluate the isolated impact of sublethal effects.

The unpredictability of potentially significant sublethal effects has prompted the 28-member working group "Pesticides and beneficial organisms" of the International Organization for Biological Control of Noxious Animals and Plants to adopt bioassays which are relatively long-term (generally $\geq$7 d), and evaluate the reduction in "beneficial capacity" instead of simple mortality (Hassan et al. 1985, 1987). For parasitoids, the ability to parasitize hosts is the parameter measured. However, this approach has not been adopted generally.

In the case of *A. melinus*, our understanding of acute lethality, sublethal effects, and residue dynamics and toxicity of insecticides has not permitted the formulation of clear recommendations for the use of the least disruptive materials for California citrus IPM. All of the widely used materials appear to be highly toxic in the laboratory (Bartlett 1966, Abdelrahman 1973, Campbell 1975, Davies & McLaren 1977, Bellows et al. 1985, Morse & Bellows 1986, Rosenheim & Hoy 1986), and we are unable to predict the actual host–parasitoid–pesticide interaction that may occur in the field. The results of our study have not resolved the discrepancy between the high acute toxicity of chlorpyrifos in the laboratory (Morse & Bellows 1986, Rosenheim & Hoy 1986) and the relatively low degree of disruption in the field (Luck et al. 1986; J. Gorden and H. J. Griffiths, personal communications). In fact, chlorpyrifos produced the most severe sublethal effects of any of the materials tested in these laboratory trials. The differences between laboratory results and field experience may thus depend primarily upon the duration of residual toxicity. Because the intensity of sublethal effects may vary with the magnitude of the initial expo-

sure (Krukierek et al. 1975, Plewka et al. 1975, Hsieh 1984), it may not be appropriate to extrapolate our results to sublethal effects caused by dosages very different from the LC_{50}.

To understand fully the impact of insecticides on *A. melinus*, field studies may be necessary. However, the design of appropriate field plots is complex because movement of parasitoids is not constrained. In general, plot size will be a critical consideration for field studies and will depend on knowledge of the parasitoid's dispersal ability. Recovery of parasitoid populations following insecticide applications may depend in part upon immigration from adjacent unaffected fields. Field studies that measure host population levels and percent parasitism both before and after a pesticide application can reveal the combined impact of both lethal and sublethal pesticide effects. Field studies should also reflect the outcome of the complex interactions generated by parasitoid behavior, development, and population genetics, as well as pesticide residue dynamics and the ecological interplay of the parasitoid and host populations.

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