Particle Films for Suppression of the Codling Moth (Lepidoptera: Tortricidae) in Apple and Pear Orchards

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ABSTRACT Studies were conducted in 1997and 1998 to evaluate the effects of three particle film formulations consisting of kaolin and adjuvants on neonate larvae, ovipositing adult females, and eggs of the codling moth, *Cydia pomonella* (L.). Neonate larval walking speed, fruit discovery rate, and fruit penetration rate on apple host plants coated with particle films were significantly lower than on host plants without particle films in laboratory assays. Females oviposited less on host plants covered with a particle film residue than on untreated plants in laboratory choice and no-choice tests. Hatch rate of codling moth neonate larvae was unaffected by particle films sprayed on host plants either before or after oviposition. Fruit infestation rates were significantly reduced on particle film-treated trees compared with untreated trees for both first- and second-generation codling moth in field trials in both apple and pear orchards. Particle films appear to be a promising supplemental control approach for codling moth in orchards where moth density is high, and may represent a stand-alone method where moth densities are lower.

KEY WORDS *Cydia pomonella,* apple, pest management, particle film, kaolin

CODLING MOTH, *Cydia pomonella* (L.), is the most important pest of apple worldwide and is of critical concern in western North America (Barnes 1991, Beers et al. 1993). Recent demonstration of resistance to azinphosmethyl, the major insecticide used for its control (Varela et al. 1993, Knight et al. 1994) and the passage of the Food Quality Protection Act in 1996 have prompted research on ways to reduce organophosphate insecticide use against codling moth. Mating disruption of codling moth (Vickers and Rothschild 1991, Howell et al. 1992) and its areawide implementation (Calkins 1998) have allowed reductions of 50–75% of azinphosmethyl for codling moth control in the orchards using this control approach in the northwestern United States. Unfortunately, mating disruption may fail to provide adequate control when orchard topography is uneven, where wind exposure is high, or where codling moth densities are high. Applications of azinphosmethyl are often required to supplement mating disruption, and alternatives to this organophosphate would be valuable for both organic and conventional pome fruit growers.

Particle films were recently introduced as a novel way to suppress arthropod and disease pests of food crops (Glenn et al. 1999). When crops are dusted or sprayed with hydrophobic particles, a protective barrier against both plant pathogens and plant-feeding arthropods is created (Glenn et al. 1999, Puterka et al. 2000). Kaolin, the foundation of the experimental particle film formulations tested herein, is a white, nonabrasive, inert aluminosilicate mineral that is widely used in a variety of industrial applications including in paints, cosmetics, and pharmaceuticals (Dean 1998). Recently, USDA–ARS and Engelhard Corp., Iselin, NJ, formed a partnership to develop both hydrophobic and hydrophilic particle films for use in agriculture (Glenn et al. 1999, Puterka et al. 2000).

Previous experimental trials with hydrophilic kaolin clays and other particles in pest management were only moderately effective (Driggers 1929, Alexander et al. 1944, David and Gardiner 1950). In contrast, recent studies have shown that experimental hydrophobic formulations of kaolin-based particle films can effectively protect host plants from pear psylla, *Cacopsylla pyricola* Foerster (Puterka et al. 2000); pear rust mite, *Epitrimerus pyri* (Nalepa) (Puterka et al. 2000); spirea aphid, *Aphis spireacola* Potch; twospotted spider mite, *Tetranychus urticae* Koch; and the potato leafhopper, *Empoasca fabae* (Harris) (Glenn et al. 1999). Pest populations were significantly reduced by repellency, disruption of feeding and oviposition, and increased mortality on treated versus untreated foliage in greenhouse and field trials caused by hydrophobic (Glenn et al. 1999) and hydrophilic (Puterka et al. 2000) particle films. Similar studies against tortricid leafrollers showed significant reductions of early-season shoot infestation rates in particle film-treated trees in field trials and reduced oviposition, larval feeding, and larval survival on treated foliage in laboratory and field cage studies (Knight et al. 2000). Herein, we examine the effects of three particle film formulations on the behavior of the codling moth

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in the laboratory, and measure protection from codling moth damage in apple and pear orchards.

Materials and Methods

Material Formulation and Application. Hydrophobic (M96–018, M97–002) and hydrophilic (M97–009) particles (Engelhard) were applied at a standard rate of 0.3 kg/l. M96–018 and M97–002 were first slurried with 0.04 liters of methanol and sufficient water was added to bring volume to 1 liter (1×). M97–009 was added directly to water containing 2 ml of a proprietary surfactant sticker (NL48; Engelhard) to facilitate dispersion of particles. Continuous agitation was required to keep the material in suspension. Half (1/2×) and twofold (2×) rates of particle film were formulated as described above by adjusting particles and methanol or particles and surfactant sticker concentrations. Formulated materials were applied in the small-plot trials described below with an engine driven, 95-liter sprayer (Rears Manufacturing, Eugene, OR) equipped with a handheld spray gun (Gunjet No. 2, Teejet, Boise, ID) running at 7.0 kg/cm^2. Greenhouse-grown, ≈6-mo-old plants, and field-collected foliage used for laboratory studies were treated with a 2-liter hand-pump sprayer with an adjustable nozzle.

Particle Residue Measurement. Particle film residues were measured gravimetrically during a field study in late summer 1997. Leaves were sampled from 'Fuji' apple test trees at weekly intervals through three biweekly spray cycles: before application, several hours after application, and 7 d after application. One fully expanded leaf from the midbranch of the current season's wood was removed from each of five branches of a single tree and placed in a plastic bag. Three trees from each treatment type, including control trees, were sampled on each date. Leaves were refrigerated at 2°C until used (<2 wk). Leaves were individually washed in 25 ml of methanol in the bottom of a 9-cm glass petri plate. A short-bristled 1-cm-wide natural hairbrush was used to remove kaolin from the leaf surfaces. Methanol was replenished as needed to clean off all five leaves from a given tree in the same plate. Subsequently, methanol was evaporated from plates for 48 h in a fume hood, and plates were weighed, cleaned, dried, and reweighed. Particle weights were derived by subtraction. Areas of cleaned leaves were measured with a LI-3000 area meter (Licor, Lincoln, NE), and milligrams of residue per square centimeter were obtained by dividing residue by twice the measured surface area. Residue was corrected to that caused by particle films alone by subtraction of corresponding values from untreated control trees. Quadratic regression was used to determine the influence of day from last treatment and rate applied on residue amount (PROC RSREG, SAS Institute 1996). We infer by visual comparisons that these residues were fairly typical of those seen in all field studies reported herein and provide an indication of residues encountered by codling moth adults and neonate larvae in both small-plot field and laboratory studies.

Field Efficacy Trials. The effect of particle films on damage to fruit was tested against both first and second generations of codling moth in apple in 1997 and 1998. Apple trials used 5–10 replicate plots, arranged in completely random designs. Plots consisted of either one each of adjacent, 5–6-yr-old Fuji, 'Gala', 'Red Delicious', and 'Golden Delicious' trees (mixed), or three adjacent Fuji trees (Fuji). Second-generation damage was estimated on trees following the removal of first-generation damage and thinning trees to contain ≈50 and 125 undamaged fruit in 1997 and 1998, respectively. In 1998, a trial was conducted in pear with a randomized block design and eight replicates of single 40-yr-old 'Bartlett' trees. Details of the five field trials follow.

Trial 1. M96–018 at the 1× rate was applied to 10 replicates of mixed apple trees on 8, 16, and 30 May and 12 and 26 June; fruit were assessed on 10 July 1997.

Trial 2. M96–018 and M97–002 at 1/4, 1/2, 1, and 2× rates were applied to five replicates of Fuji apples on 23 July, and at 1/2, 1, and 2× rates on 6 and 22 August and 5 September; damage was assessed on 5 October 1997.

Trial 3. M96–018 and M97–009 at 1× rates were applied to mixed apples on 5 and 22 May and 1, 11, and 22 June: damage was assessed on 27 June 1998.

Trial 4. M96–018 and M97–009 at 1× rates were applied to mixed apples on 7 and 21 July, 3 and 17 August, and 9 September; damage was assessed on 16 September 1998.

Trial 5. M96–018 and M97–009 at 1× rates was applied to pear trees on 27 March, 20 April, 15 May, 11 June, and 7 July for low-frequency applications and on those dates and on 7 and 28 April, 4 and 22 June, and 21 July 1998 for high-frequency applications. Various water plus adjuvant controls were applied on all 10 dates. Fruit damage was assessed as the proportion of total fruit damaged by codling moth in all apple studies and as the number of damaged fruit per tree in the single pear study. Factorial analysis of variance (ANOVA) of arcsine-transformed proportions (or square root [count +1] for pears) was used for analysis with particle film formulation and control treatments representing levels of a single-treatment variable. In apple trials, the influence of fruit load variation among varieties on damage proportions was assessed by analysis of covariance (ANCOVA) and corrected when necessary (PROC GLM, SAS Institute 1996). In trial 2 where rate of particle film was varied, damage was analyzed by quadratic regression (PROC RSREG, SAS Institute 1996). In trial 5, frequency of application varied as did formulations; these were treated as levels of a single categorical variable in the factorial ANOVA. Planned comparisons among treatments were made with orthogonal contrasts.

Laboratory Assays. The effect of particle films on codling moth was examined for three behaviors: adult oviposition, neonate larvae walking speed, and fruit penetration ability by neonates. Also hatching rate of larvae from eggs laid on or covered by particle films was examined. Both choice and no-choice tests of effects of particle films on female oviposition were performed.

Adult choice test. Small bouquets (≈20-cm lengths) of fruit-bearing (fruit 3–4.5 cm diameter) branches of Red Delicious were pruned from trees in an unsprayed orchard in mid-June and inspected to ensure they were free of codling moth eggs. Bouquets were thinned to contain two fruit and then sprayed to drip with 1× or 1/2× rates of M96–018, or methanol–water and allowed to dry. One centimeter was cut from branch ends and bouquets were placed in a 500-ml Erlenmyer flask containing water. Flasks and were wrapped in window screening to deter oviposition on this substrate. When 24 h old, adults were collected from a laboratory colony and were confined for an additional 24 h in 0.5-m^3 screen cages to allow mating. Females were assumed to be mated when isolated and randomly allocated to treatments. Two bouquets, one from each of the three treatment levels, were placed in 60-liter Styrofoam ice chests, previously lined with sheets of organdy. A second sheet of organdy was draped over each ice chest, and five mated codling moth females were released below the sheet. The cover for the ice chest, perforated previously to allow ventilation, was secured with tape. Hence, plants with codling moths were completely encased in coarse organdy except for the leaf and fruit substrates provided. After 72 h, the eggs were counted on each substrate, including leaves, fruit, branches, and the organdy covers. Nine replicates of each treatment comparison were used. Data were analyzed by paired *t*-tests (1× versus control, 1/2× versus control, 1/2× versus 1×) (PROC MEANS, SAS Institute 1996).

Adult No-Choice Tests. Single greenhouse-grown Red Delicious apple seedlings, sprayed with 1/2× or 1× M96–018 or control formulation as described above were enclosed with a cylinder of standard window screening. Three codling moth females and three males (24–48 h old) were released into the cylinder before it was attached with duct tape to a pot (9 by 9 cm) containing the apple seedling. After 48 h, eggs were counted on leaves, branches, soil, pot, and screen cover. A second experiment was conducted comparing 1× rates of M96–018, M97–009, and control formulations (both methanol-water and spreader in water). In this experiment, five mated codling moth females were confined for 72 h. Ten replicate plants for each treatment were used, and results were analyzed by one-way ANOVA (PROC GLM, SAS Institute 1996).

Larval No-Choice Test. No-choice experiments also were conducted with neonates on single particle film- and adjuvant-treated fruit (3–6 cm in diameter). Fruit were sprayed to drip twice with full rates of M96–018 or M97–009 and allowed to dry overnight. Fruit were placed individually in plastic vials (200 ml), and a single active neonate larva was transferred with a fine paint brush to the inner wall of the vial and a vented lid placed on the vial. Three to four days after infestation, the number of neonates that successfully penetrated the fruit was evaluated. One hundred and twenty replicates for each treatment was performed, and results were analyzed with a chi-square test (PROC Freq, SAS Institute 1996).

Larval Mobility Test. We examined the walking speed of codling moth larvae on apple shoots collected in the field in mid-September. Leaves were removed from current season shoots, and shoots were then dipped for 10 s into either 1/2× or 1× M96–018 or in methanol–water control while the suspension was agitated in a large graduated cylinder on a magnetic stirrer. After drying, shoots were hung horizontally on two loops of twine and the midpoint of each shoot was marked with a waterproof marking pen. Neonate larvae were released on the branches at this midpoint, and the distance 20 larvae crawled in 5, 30, and 120 s was measured for each treatment. Distance walked in each time class was analyzed as a one-way ANOVA, with treatment rate as the classification variable (PROC GLM, SAS Institute 1996).

The influence of host fruit-seeking behavior also was examined in the presence of particle film residues and control formulations. A single particle film-treated fruit (4–6 cm in diameter) was affixed to a branch (free of leaves and treated as above) with a No. 3 insect pin a few centimeters below the branch end. The cut end of each branch was placed vertically in a flask of water and a single neonate larvae was placed on it at a point 20 cm below the fruit. Larvae were allowed 24 h to locate and enter fruit. One hundred replicates for each treatment type were conducted, and infestation rates were analyzed by a chi-square test for independence.

Larval Hatch. The effect of particle films on codling moth egg viability was estimated from hatching rates of larvae from eggs laid on apple leaves previously treated with particle film or control solutions, and from hatch rates of larvae from eggs deposited on untreated foliage and subsequently treated with particle film or control solutions. In all cases, seedlings were sprayed or left untreated, and three female and male codling moths (24–48 h old, as described above) were confined to single plants in screen cylinders. Leaves containing eggs were isolated and placed in brown paper lunch bags and these placed in larger, plastic bags. Leaves were incubated at 22°C for 10 d and the number of hatched and dead and sterile eggs were counted. Ten replicates of each treatment were used. Chi-square tests were used to detect significant differences in hatching rate (PROC FREQ, SAS Institute 1996).

Results

Residues. No difference between particle film formulation M96–018 and M97–002 on residues was observed ($P = 0.92$) and the two were pooled. Multivariate quadratic regression analysis explained 88% of the variation in the leaf residue data and showed a highly significant linear effect ($P < 0.0001$), and a moderate quadratic effect ($P = 0.02$) of rate and days

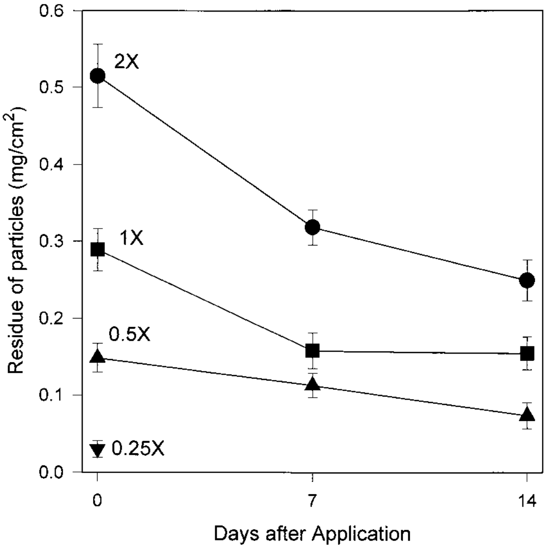

Fig. 1. Residue (mg/cm^2 ± 2SE) found on apple leaves in relation to rate applied and days after applications. See *Results* for detailed statistical description.

after application (Fig. 1). Because there was a significant interaction among rate and days after application ($P < 0.0001$), each rate was analyzed separately by quadratic regression of days after application and residue. Linear terms were highly significant at all three rates ($P < 0.0015$ in all comparisons) and the quadratic term was significant only at the 1× rate ($P = 0.016$), which is also evident in Fig. 1. At all three rates, day 14 residues approach but do not reach 50% of day 0 residues, suggesting the half life of residues on apple foliage is greater than the 14-d cycle of the spray applications. Similar studies were not conducted on fruits.

Small-Plot Trials. *Trial 1.* Codling moth damage was reduced by 87% after the first generation of 1997 by five applications of M96–018 compared with methanol/water-treated control trees. Specifically, 3.4 ± 4.2% of fruit were infested in M96–018 treated trees and 32.9 ± 3.3% were infested in untreated control trees. The difference was highly significant *($P <$ 0.0001)*.

Trial 2. There were highly significant linear ($P <$ 0.0001) and quadratic ($P < 0.0001$) terms for the regression of codling moth damage between 0×, 1/2×, 1×, or 2× rates of particle films applied biweekly for the second flight (Fig. 2). Particle film formulation had only a modest effect on the analysis ($P = 0.09$; Fig. 2). Analysis of simple effects by one-way ANOVA showed no difference in damage among rates of particle films ($P > 0.5$) and damage was significantly lower than in the methanol–water treated trees ($P < 0.0001$; Fig. 2).

Trial 3. In the first generation of 1998, fruit damage was low (<2% in all plots) and was significantly effected ($P = 0.0002$) by particle film treatments. M96–018 and M97–009 compared with several control formulations reduced damage by 53–87% (Table 1). Apple variety did not influence proportion of fruit damaged ($P_{\text{Variety}} = 0.13$; $P_{\text{Variety*Treat}} = 0.71$), hence, results are pooled over variety.

Trial 4. In the second generation of 1998, codling moth damage was higher (0.6–11%) and particle film treatments were highly significant ($P < 0.0001$). M96–018 and M97–009 compared with several control formulations reduced damage 82–95% (Table 2). Methanol–water or spreader control formulations had slightly less damage than unsprayed controls, enough to be marginally significant in two of the four fruit

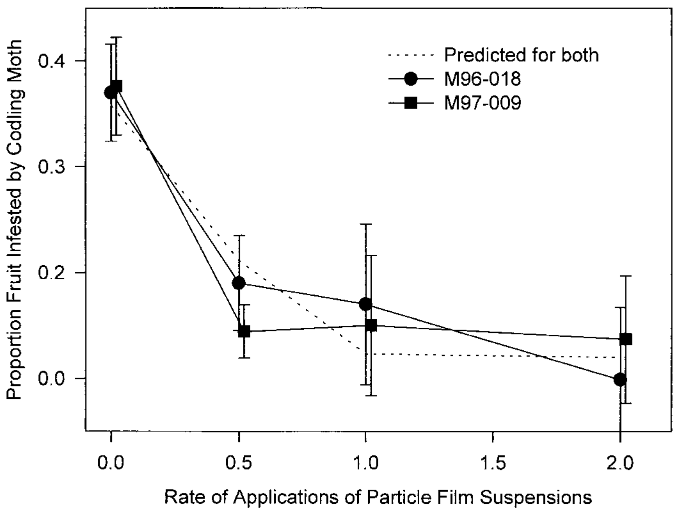

Fig. 2. Proportion of apple fruit infested by codling moth in trees sprayed with four rates of two formulations of particle films. The predicted quadratic regressions for each formulation also are plotted. See *Results* for detailed statistical discussion.

Table 1. The proportion of fruit damaged by codling moth assessed on 27 June 1998 from mixed varieties of apple trees receiving six applications of M96-018, M97-009 (0.03 kg/l), or spreader, methanol, or unsprayed controls applied by handgun at ≈2 liters per tree

Treatment	Proportion infested[a]
Control	0.0085 ± 0.0023a
Methanol	0.0090 ± 0.0026a
Spreader	0.0145 ± 0.0041a
M96-018	0.0010 ± 0.0005b
M97-009	0.0018 ± 0.0011b

[a] Mean percentages of fruit displaying codling moth entries followed by a different letters are significantly different ($P < 0.05$, Student-Neuman-Keuls).

Table 3. Number of pear fruit damaged by codling moth on 29 July 1998 from >50-yr-old Bartlett trees receiving 5 (L) or 10 (H) applications of M96-018, M97-009, or 10 applications of spreader or methanol (0.03 kg/l) applied by handgun at ≈4 liters per tree, or unsprayed controls

Treatment	No. damaged fruit[a]
M96-018 L	0.1250 ± 0.13a
M97-009 H	0.5000 ± 0.28a
M96-018 H	0.6250 ± 0.32a
M97-009 L	1.1250 ± 0.35a
Methanol	11.000 ± 2.67b
Unsprayed	17.437 ± 3.98b
Psyllicides[b]	19.625 ± 7.66b
Spreader	21.2500 ± 7.43b

[a] Means followed by a different letter are significantly different ($P < 0.05$, Student-Neuman-Keuls).

[b] Trees received Comply and Agrimek at maximum label rates on 29 February and 7 June, respectively.

varieties if these are analyzed separately (data not shown). Fruit load among apple variety generally did not influence proportion of fruit damaged [$P_{\text{Variety}} = 0.07$; $P_{\text{Variety*Treat}} = 0.09$] except for the aforementioned effects among controls, and results are pooled over variety for clarity.

Trial 5. In pear in 1998, cumulative damage over both generations showed a 90–99% reduction compared with unsprayed or adjuvant-sprayed control trees (Table 3). Particle film treatments versus controls was a highly significant source of variation in codling moth damage ($P < 0.0002$) in all small-plot trials. Notable was the lack of difference among 10 versus five applications in reducing codling moth damage. Finally, there was no effect on efficacy of formulations of the particle films in either comparisons between two hydrophobic formulations nor between hydrophobic and hydrophilic formulations (orthogonal contrasts; $P > 0.5$).

Throughout the field trials, foliage and fruit were examined for phytotoxic effects stemming from repeated particle film applications. We found no evidence of leaf burn, premature leaf drop, staining, or bronzing of fruit, or within-season effects on fruit set and size. Potential positive horticultural effects of particle films on fruit size and color are reported elsewhere (Glenn et al. 2000).

Laboratory Trials. *Adult Choice Tests.* Codling moth showed no statistically significant preference for oviposition onto fruit clusters treated with half or full rates of M96–018 in paired-choice tests (paired $t = 1.35$; $P > 0.23$). Hence, we pooled these two rates in comparisons with methanol–water controls. Females laid almost three tmes fewer eggs on kaolin-treated fruit (31.2) versus control fruit (8.9) (paired $t = 3.12$; $P = 0.01$), and ≈40% fewer eggs on kaolin-treated leaves (60.3 eggs per bouquet) compared with control leaves (35.2 eggs per bouquet) (paired $t = 1.87$; $P = 0.09$). No differences were observed on stems ($P > 0.8$) where fewer than two eggs per bouquet were laid on average. Summing all substrates, kaolin-treated clusters received half as many eggs than did methanol–water controls (93 versus 45.9; paired $t = 3.21$, $P = 0.008$).

Adult No-Choice Tests. Two separate experiments were conducted with foliage (Table 4). In the first, 60–80% fewer eggs were laid by females confined for 48 h on bouquets treated with full or half rates of M96–018 compared with those confined on methanol–water treated control ($P = 0.0001$). In the second experiment, full rates of M96–018 and M97–009 received 70–85% fewer eggs after 72 h than control-treated bouquets ($P = 0.0003$) (methanol–water and spreader controls were similar and pooled).

Fruit Penetration Rate. Neonate larvae liberated in vials containing a single treated fruit were 43% less

Table 2. Proportion of fruit damaged by codling moth assessed on 5 October 1998 for fruit from four varieties of 6-yr-old apple trees receiving seven applications of M96-018, M97-009 (0.03 kg/l) after 1 July, or spreader, methanol, or unsprayed controls applied by handgun at ≈2 liters per tree

Treatment	Proportion infested[a]
Control	0.071 ± 0.008a
Methanol	0.114 ± 0.039a
Spreader	0.097 ± 0.021a
M96-018	0.013 ± 0.002b
M97-009	0.006 ± 0.002b

[a] Means of fruits displaying codling moth entries followed by a different letter are significantly different; comparisons within fruit varieties ($P < 0.05$, Student-Neuman-Keuls).

Table 4. Codling moth eggs laid on kaolin-treated plants in no-choice tests

A[a]		B[b]	
Treatment	Eggs/seedling	Treatment	Eggs/seedling
Control	28.55a	Control	90.64a
M96-018 1X	7.05b	M97-009	33.18b
M96-018 ½X	5.14b	M96-018	15.33b

Means followed by the same letter are not significantly different, ($P < 0.05$, Student-Neuman-Keuls).

[a] Two rates of M96-018 were compared with control with three females ovipositing for 2 d.

[b] M97-0009 and M96-018 were compared with controls with five females for 3 d.

successful in penetrating particle film-treated fruit (38–46%) than various control formulations (66–81%) ($\chi^2 = 57.7$, df = 1, $n = 570$, $P = 0.001$). There were no observable differences between M96–018 and M97–009 treated fruit ($\chi^2 = 1.3$, df = 1, $n = 245$, $P = 0.249$). Differences among the three control formulations was moderately significant ($\chi^2 = 6.23$, df = 2, $n = 325$, $P = 0.044$) but was of little biological interest.

Hatching Rates. Particle films sprayed onto leaves containing codling moth eggs that were 24–48 h old did not effect hatching rate, nor were rates reduced for eggs laid on leaves with a 6-h-old Kaolin residue, compared with hatching rates on unsprayed leaves. Specifically, larvae did not hatch from 6.25% of eggs laid on M96–018 residue versus 3.7% in controls ($\chi^2 = 3.17$, $P = 0.08$, $n = 931$); 2% did not hatch when eggs were over-sprayed with M96–018 versus 2.75% in controls ($\chi^2 = 1.27$, $P = 0.24$, $n = 2{,}146$). Although there appears to be a slight tendency to reduced hatching when eggs are laid onto residues, the effect was so slight as to be of little biological significance.

Walking Speed. Distance walked by neonate codling moth larvae in 2 min was reduced threefold in the presence of M96–018 on leafless apple shoots ($F = 15.8$; df = 2, 27; $P < 0.0001$; $R^2 = 0.55$). Larvae walked 17.5 ± 2.5 mm in 2 min on control shoots, but only 4.7 ± 1.5 mm or 5.2 ± 1.5 mm on shoots treated with full or half-rates of M96–018, respectively. A similar pattern was observed for shorter observation times but these were not statistically significant ($P = 0.58$ for 10 s, $P = 0.05$ for 30 s).

Host-Finding Ability. Neonate larvae liberated on a 20-cm branch below a single terminal fruit showed that kaolin residues impeded host finding by 64%. Six and 9% of larvae (100 each) found and penetrated the fruit in 1× and 1/2× treatments of M96–018, respectively, whereas 21 of 100 larvae found and penetrated the fruit in methanol–water controls ($\chi^2 = 12.8$, $P = 0.016$; no differences were evident between the two rates). These results are in accord with walking rate studies and fruit penetration rates.

Discussion

Kaolin particle film residues, applied in water-based formulations, have significant detrimental effects on codling moth in both adult and neonate stages. Specifically, residues reduced neonate walking speed, rate at which neonates infest fruit, and oviposition by adults in both choice and no-choice assays. In contrast, residues did not influence the hatching rate of larvae. These results are similar to those from studies with the obliquebanded leafroller (Knight et al. 2000). Our results also agree with preliminary studies by Glenn et al. (1999) wherein they show even more dramatic effects on behavior of *Cacopsylla pyricola* and *Aphis pomi* when confined on substrates dusted with particle films.

Roughly 50–70% reductions in both adult codling moth oviposition and in fruit penetration rates by neonates may be sufficient to explain 50–90% reductions in fruit damage by codling moth seen in the assorted field trials. However, we do not know the influence particle films may have on adult survival, and behaviors such as mating, orientation within orchards for oviposition, and persistence in orchards. These behaviors also may be important in producing our field results, but characterizing them in laboratory and cage studies is difficult as evidenced by the work with obliquebanded leafroller (Knight et al. 2000).

Conventional management of codling moth with azinphosmethyl entails two or three cover sprays for each generation with the intention of killing neonate larvae for a 2–3 wk period with each spray (Beers et al. 1993). Particle film residues may be used in a similar fashion. This is suggested by four observations: a half-life of particle film residues exceeding 15 d; equal efficacy between 1× and 1/2× rates in oviposition no-choice assays; similar efficacy of season-long control with five or 10 applications in pear; and no effects of rate (1/2×, 1×, or 2×) on adult suppression in apple studies. However, irrespective of rate, particle films are less effective in suppressing codling moth than is azinphosmethyl. But particle films may be an important supplement to mating disruption or other insecticides in future codling moth management strategies. A formulation similar to M97–009 is now registered for pome fruits under the label Surround, and further evaluations of its timing and efficacy are underway.

Abrasive mineral particles have been tested and used for insect control for many decades; their efficacy rests on disrupting cuticle integrity and subsequent desiccation. White washes also have been studied and can be effective in disrupting insect orientation to plants by making them reflect different wavelengths of light (reviewed by Glenn et al. 1999). The particle films addressed herein are highly processed, nonabrasive minerals that are similar to those used in paint and paper manufacture. It was hypothesized that a more or less continuous film of particles would represent a physical barrier between plant surfaces and pest arthropods and diseases. Because infection by many plant diseases requires water at the plant surface, original formulations of particle films were chemically treated to make them hydrophobic (Glenn et al. 1999), but now it is known that hydrophilic films (Puterka et al. 2000) also may provide disease control. Our studies with codling moth show no significant difference in hydrophobic or hydrophilic preparations of the particle films in those behavioral assays and field efficacy studies where they were compared.

Particles in the form of dusts from unpaved roads, tillage, and mining operations have long been thought to reduce beneficial insect activity and cause insect and mite outbreaks (DeBach 1951). DeBach (1969) showed a nearly 40% reduction in *Aphytis* oviposition (eggs per female) into California red scale on dusty versus clean fruit. Similarly, he showed California red scale increased after intentional, repeated application of soil dust onto *Citrus* trees (DeBach 1965). The airborne soil dusts studied by DeBach (1969) are undoubtedly different from the highly refined kaolin (alumina silicate) particles used in our studies, but the potential for reduced beneficial insect activity from kaolin particle films should not be ignored. In an ancillary grower trial with seven applications of M96–018 in Red Delicious apples, we observed a twospotted spider mite outbreak early in the summer following the trial (T.R.U., unpublished data). Knight et al. (2000) described increased levels of the western tentiform leafminer, *Phyllonorycter elmaella* Doganlar & Mutuura, as well as significantly lower parasitism of this pest in apples treated with M96–018 compared with untreated trees. Based on perception of behavior disturbances caused by particle films, we believe disruption of natural enemies will be most significant with small species that actively search the plant surface to locate their host or prey. Future efficacy studies and implementation trials with particle films also should include evaluations of natural enemy activity and pest resurgence problems.

Our behavioral studies suggest that disorientation of the neonate codling moth larvae and avoidance by ovipositing adult females are key modes of action of this barrier film. It is likely that the behaviors of many insects and mites will be similarly affected (e.g., species in Glenn et al. [1999] and Puterka et al. [2000]. Also recent studies show that particle films can have significant beneficial horticultural effects when used on pome fruits (Glenn et al. 1999, 2000). These properties, together with the mechanical mode of action for insect control, suggest that particle films are a highly promising control measure that is suitable for integration into tree fruit production and pest management.

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