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Methoprene and synergized pyrethrins as aerosol treatments to control *Plodia interpunctella* (Hübner), the Indian meal moth (Lepidoptera: Pyralidae)

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ABSTRACT

Aerosol insecticides (also known as ULV or fogging treatments) delivered through an ultra-low-volume application system, are available commercially to control insect pests such as *Plodia interpunctella* Hübner, the Indian meal moth. However, little is known about the susceptibility of eggs of *P. interpunctella* to aerosol insecticides applied in active field sites. We conducted several trials by exposing eggs of *P. interpunctella* to synergized pyrethrins, alone and in combination with the insect growth regulator methoprene. Eggs in diets and packaging materials containing the food products were directly exposed to the aerosols. There was significant variation among the food products, as assessed by adult emergence from exposed eggs, but in general there was no difference in adult emergence from eggs exposed to a 1% versus a 3% pyrethrin formulation when methoprene was included. There was no difference in efficacy between diets and diet packages placed in open areas versus areas that were in some way obstructed to the aerosol. Adult emergence was generally reduced in the treatment combinations compared to untreated controls. A partial budget analysis indicated that the combination treatment of 1% pyrethrins + methoprene represented the lowest risk, lowest cost, and would seem to be the optimum combination. Results show that field applications of aerosols could be used to control *P. interpunctella* in storage facilities.

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1. Introduction

Plodia interpunctella (Hübner), the Indian meal moth, can develop on a number of different commodities including grains, flours, beans, meals and dried fruits (Mohandass et al., 2007), and can be an economic insect pest in warehouses, elevators and commercial food processing facilities (Subramanyam and Hagstrum, 1993; Doud and Phillips, 2000; Arbogast et al., 2002). *Plodia interpunctella* can infest grain processing facilities, food warehouses, and retail stores (Buchelos, 1980; Campbell and Mullen, 2004). Infestations of food materials during processing, and infestations of finished products, can lead to rejection of products by distribution centers and consumers (Campbell et al., 2002). Historically, many flour mills have relied on fumigation with methyl bromide to manage stored-product pests such as *P. interpunctella*, but this insecticide is scheduled to be phased out under a world-wide agreement, the Montreal Protocol (Anonymous, 2004). Currently flour mills in the United States of America (USA) are receiving critical use exemptions (CUEs) for the continued use of methyl bromide.

Because of the scheduled phase-out of methyl bromide, mills and processing facilities are evaluating safer and less expensive alternatives (Mondal and Parween, 2000; Campbell et al., 2004), which include the expanded use of aerosol insecticides. Often these aerosols can be considered as ultra-low-volume (ULV) applications depending on specific formulation and particle size. A possible treatment combination is to use synergized pyrethrins combined with the insect growth regulator (IGR) methoprene. Synergized pyrethrins will often cause immediate control of all life stages but may have little residual activity. The IGR methoprene affects immature stages of insects and is stable on grain surfaces for several months, and similar results would be expected when methoprene is applied as an aerosol and is ultimately deposited on a flooring surface. Hence, methoprene would offer some level of residual control (Mondal and Parween, 2000). Both insecticides are currently labeled in the USA for use in food milling and storage facilities.

There has been some recent research regarding dispersion and spread of aerosol insecticide treatments where the target insect was either *Tribolium castaneum* (Herbst), the red flour beetle, or

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Tribolium confusum du Val, the confused flour beetle (Arthur and Campbell, 2007; Arthur, 2008). There is also some previous laboratory research showing varying efficacy of synergized pyrethrins (both in direct contact and residual activity) for control of stored-product beetles, but not for the control of *P. interpunctella* (Bernhard and Bennett, 1981; Cline et al., 1984). Aerosol droplets may be impeded by barriers such as equipment, shelving and stored products. Therefore, data regarding dispersion and coverage of aerosols in field sites is necessary to evaluate field efficacy against *P. interpunctella*. Female *P. interpunctella* may oviposit on a number of surfaces associated with food materials, and the eggs would then come into direct contact with aerosol particles, surfaces that have been exposed, and spilled food materials that have been exposed to aerosol particles.

An important aspect of any integrated pest management program is to determine the cost of a particular treatment method. Partial budget analysis can be used to compare chemical costs of control strategies and can also be used to determine levels of risk associated with each strategy (Boehlje and Eidman, 1984; Tilley et al., 2007). In the case of aerosol insecticide treatments, a partial budget analysis can compare different combinations of synergized pyrethrins and methoprene, enabling food production plant managers and warehouse managers to evaluate treatment costs. Economic analyses for other methyl bromide alternatives using enterprise budgets for specific field crops have been previously developed (Nelson, 1996; Byrd et al., 2006), but have not been done for aerosol treatments for stored products. Therefore, the specific objectives of this experiment were to: 1) compare the susceptibility of *P. interpunctella* eggs exposed directly to aerosol insecticides, to aerosol deposits in food material, and on packaging materials, 2) evaluate the benefit of using a combination of methoprene and pyrethrin versus methoprene-only and pyrethrin-only aerosol treatments, 3) examine the distribution of aerosol particles in "concealed" and "unobstructed" areas as evidenced by survival of *P. interpunctella* eggs to the adult stage, and 4) construct a partial budget analysis to evaluate the cost of insecticide treatment.

2. Materials and methods

2.1. General procedures

A laboratory colony of *P. interpunctella* was used for all studies. This colony was established in 1988 from individuals collected in Riley County, Kansas in the U. S., and periodically supplemented with wild individuals. Voucher specimens have been deposited in the Kansas State University Museum of Entomological and Prairie Arthropod Research under Lot Number 208. The colony was reared on a standard wheat-based diet. The standard rearing diet contains cracked wheat and shorts (4.4 kg), brewer's yeast (22 g), sorbic and benzoic acid (9.5 g each), honey (240 ml), glycerin (240 ml) and water (120 ml). These colonies are maintained at the USDA-ARS Center for Grain and Animal Health Research in Manhattan, KS. The colony has been maintained in environmental growth chambers (Forma-Scientific, Thermo Electron Corporation, Waltham, MA) on an enriched wheat diet at 27 ± 1 °C, approximately 40% relative humidity (r.h.), and in complete darkness (L:D = 0:24 h). Relative humidity was maintained using pans of water in the bottom of the incubator.

For each study there were three treatment methods: 1) eggs exposed directly to aerosol, 2) diet materials exposed to the aerosol with unexposed eggs added after the diet exposure, and 3) packaging materials exposed to the aerosol with the corresponding diet inside, with unexposed eggs added following treatment. Eggs that were <24 h old were exposed to the aerosol spray in 100 mm Petri dishes painted with black acrylic paint to reduce static. These eggs were transported to field sites as will be described in subsequent sections. Approximately 100 g of each diet material were exposed to aerosols in 150 mm Petri dishes and, after exposure, diet materials were transferred to clean Petri dishes of the same size. Package materials with diets inside were placed directly on the floor of the facilities. After exposure, these materials were placed in disposable plastic containers (5 cm high, 13.7 cm wide, and 13.7 cm long). Following aerosol treatments, eggs that were exposed to insecticide were placed in clean diets and allowed to mature to the adult stage under the above conditions. Packaging and diet materials exposed to the aerosol were transported back to the laboratory, where eggs placed on these materials were allowed to mature to the adult stage under the previously-described conditions. Lids on the 150 mm Petri dishes and the disposable plastic containers were altered to have a 5.1 cm-diameter vent cut in the top, covered with a standard filter paper secured with a non-toxic adhesive, to allow air movement. Temperature and relative humidity inside incubators were recorded using a HOBO data logger (Onset Computer Corporation, Bourne, MA, USA).

Diet used for both studies was standard wheat-based diet described above, commercially available corn muffin mix, peanut butter protein bars, and raisins. Package material and diet combinations were standard wheat diet inside 16.8 cm × 14.9 cm sandwich-size zipper-seal plastic bags, the protein bars inside their original laminate paper packaging, corn muffin mix inside original packaging (laminated cardboard), and two snack-size boxes of raisins taped end to end inside original laminated cardboard packaging. All sizes of packaging materials were selected so that total surface area of exposure was approximately the same for all combinations. After exposure, a sharp probe was used to make several small entry holes in each package, so as to allow neonates to enter the packages. Two field sites were used in the study, a flour mill and a processed food warehouse. Both of these sites were equipped with an aerosol/ULV compressed air application system, which dispensed insecticides at an approximate particle size of 15 μm (Entech Systems, Kenner, LA, USA). Experimental procedures for both sites will be described below in detail.

2.2. Experimental design for field trials in the flour mill

The flour mill is in central Kansas and is equipped with the aerosol/ULV system described above. One floor of the mill was chosen as the experimental site and controls were held in an unexposed office adjacent to the flour mill during the time when the insecticides were applied. This floor of the mill had approximately 20–25% of the space occupied with milling equipment and had an approximate volume of 1170 m^3.

The experimental design was a split-split-split plot experiment blocked by time. The whole-plot treatment was three replicated insecticide treatments: 1% pyrethrin plus methoprene, 3% pyrethrin only, and 3% pyrethrin plus methoprene. The 1% pyrethrin plus methoprene treatments were replicated four times with all subplot factors included, while the 3% pyrethrin plus methoprene treatments were replicated three times with exposed eggs only. The 1% pyrethrin treatment was Entech Fog-10® (Entech Systems, Kenner, LA, USA); which is 1.0% pyrethrins, 2.0% piperonyl butoxide synergist, 3.3% *N*-octyl bicycloheptene dicarboximide and 93.7% inert ingredients. The 3% pyrethrin treatment was Entech Fog-30® (Entech Systems, Kenner, LA, USA) which contains 3.0% pyrethrins, 6.0% piperonyl butoxide synergist, 10.0% *N*-octyl-icycloheptene dicarboximide and 81.0% inert ingredients. Each treatment was applied at the label rate for surface applications of 296 ml undiluted concentrate per 284 m^3. For the combination treatments, methoprene (Diacon II®, Central Sciences International, Shoenberg, IL,

USA) was added at the label rate for space applications, which is 300 mg of active ingredient [AI] per 284 m^3. The 3% pyrethrin only treatment was done only once because the normal practice of the mill is to apply the methoprene in combination with the pyrethrins. For each test, the exposure arenas described above were placed in the mill and exposed to ULV/aerosol for two hours. Materials for each block of the experiment were prepared and transported to the mill prior to each treatment period and transported back to the laboratory after exposure.

Sub-plot treatments were positioned in relation to the spray nozzle (Fig. 1), "unobstructed" or "concealed" during treatment, method of treatment, and diet/packaging combinations. For the purpose of this study, "concealed" sites within each position were fully underneath a piece of equipment in the mill. While equipment in this mill was raised up off the floor, the treatments were still partially shielded from the aerosol particles as they settled, thus simulating food patches or insects under a pallet of product or equipment. "Unobstructed" sites were in open sites not under equipment or other barriers. For each position and unobstructed/concealed sub-plot treatment, there were three exposure methods designed to simulate three possible scenarios. All three types of sites were in close proximity to each other and identical in nature. The purpose of this treatment was to compare the susceptibility of *P. interpunctella* eggs (as measured by adult emergence from those exposed eggs) when they were exposed directly to aerosol insecticide treatment, exposed to food materials that had been treated with the ULV/aerosol, and exposed on packaging materials that had been exposed to aerosol insecticide but contained untreated food materials. The final sub-plot treatment was the type of diet/packaging material. Three representative package types were used: laminate paper, laminate cardboard and plastic. Three types of diet were used for the diet exposure part of the study: standard rearing diet for *P. interpunctella*, organic protein bars, and raisins. These products were selected to represent spilled food material that could be found inside a commercial facility.

For each replicate, 20 eggs that had been exposed to the aerosol treatment were randomly selected and placed in clean food material. In addition, 20 untreated eggs were placed on each of the exposed diets and on exposed packaging materials after they had been returned to the laboratory. Test dishes were held in a 27 °C incubator with a pan of water as a humidity source (approximately 40% r.h.). Adult emergence was recorded and experiments terminated when controls reached at least 75% adult emergence or when it was determined that there was no additional emergence in the treatments, which was generally one week following the completion of adult emergence in the control dishes. Beginning with block (time-replicate) 5, only eggs were exposed to the insecticide treatment, due to the fact that adult emergence from exposed eggs in the treated diet and treated packaging materials was virtually zero. Temperature and relative humidity inside the incubators were recorded using a HOBO data logger (Onset Computer Corporation, Bourne, MA, USA) placed next to one "unobstructed" and one "concealed" area during each treatment. A HOBO was also placed in the area where controls were being held. Temperatures and relative humidity in the mill fluctuated with the season. The experiment was done from February 2007 through July 2007 and timing of application ranged from early morning to early evening. Temperatures inside the mill ranged from 22 to 34 °C, while inside relative humidity was 23–65%.

Data were analyzed using the Mixed Procedure (PROC MIXED) of the Statistical Analysis System (SAS) (SAS Institute, 2001), with blocks and replicates within blocks as random effects and all treatments as fixed effects. Percentage of adult emergence from the exposed eggs was the response variable, percentages were transformed by square root before analysis, and means for treatments were separated using the Ryan-Einot-Gabriel-Welsch Multiple Range test at $P < 0.05$ for each treatment combination.

2.3. Experimental design for field trials in the processed food warehouse

This experiment was conducted in a food storage and distribution facility equipped with the same type of ULV/aerosol system as in the flour mill described in Section 2.2. For these tests, methoprene only (Diacon II®) was applied at the label rate of 3 ml per 284 m^3. The test area was a large, relatively open warehouse room with little fixed shelving (Fig. 2). The room houses a variety of products (fresh and preserved food products, kitchen equipment and paper goods) that are moved in and out of the room frequently. The estimated occupied space (stacked goods) of this room at any given time is 10%. The volume of the room minus the 10% occupied space was approximately 15,050 m^3. The room has multiple exits to the rest of the building but no outside exit. The test room had two nozzles attached to fixed pipes along the ceiling for dispensing insecticide, and the ULV system in this food storage facility was installed such that one room can be treated separately from the others.

The experimental layout for this study was designed in a similar manner to that described for the flour mill. Three sub-replicates

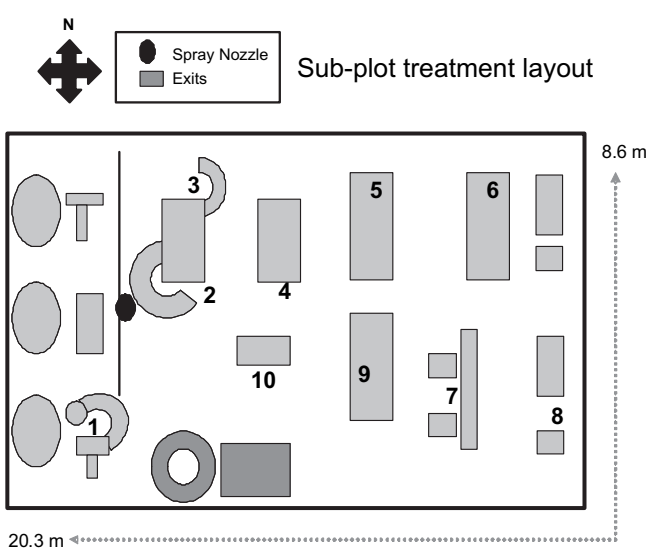

Fig. 1. Equipment and treatment layout of the flour mill used in Experiment 1. The black oval represents the position of the aerosol delivery nozzle and dark gray blocks represent exits from that floor of the mill. Drawings are not to scale.

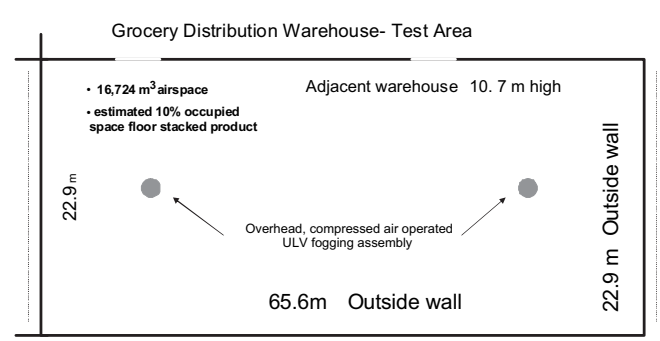

Fig. 2. Grocery warehouse used in Experiment 2. Dark gray circles represent locations of aerosol delivery nozzles. Breaks in the perimeter indicate exits from test room. Positions inside this room were chosen prior to testing periods. Locations of stacked product and shelving varied with each time period. Drawings are not to scale.

placed in different areas of the room were also done to reduce experimental variability, while controls were held in an office that was not exposed to the aerosol. The placement of packages was determined prior to the test. The same three package types were used as described in the previous experiment. For blocks (times) 1–4, standard wheat diet, protein bar and corn muffin mix were used; in blocks 5 and 6, raisins were substituted for the corn muffin mix due to low control survival. Packages were placed in the treated room and were considered either "unobstructed" or "concealed" in the same manner as in the previously described experiment. This experiment was a split–split plot with the methoprene treatment as the whole-plot factor blocked by time and the sub-plot as position in the warehouse. The sub–sub-plot treatment was two areas ("unobstructed" or "concealed") within each position. Complications with the execution of this experiment created an imbalance in the experimental design: treated package data were available for the first two blocks only; corn muffin mix was used in blocks 3 and 4, and raisins were used in blocks 5 and 6. Treatments were placed in the room and the aerosol system was activated and ran for about 20 min to dispense the required amount of insecticide for the room, and the individual treatments remained in the room for about another 70 min, for a total exposure time of about two hours. At this time the various packages were removed from the room, placed in plastic containers and transported back to our laboratory in Manhattan. There, eggs were added to the treatments and allowed to mature to the adult stage in the same manner described above for the flour mill.

Temperature and relative humidity inside incubators were recorded using a HOBO data logger placed next to treatment areas. All tests were conducted in the late afternoon during the summer of 2007; temperatures in the treatment area were about 28 °C and relative humidity ranged from 30 to 70%. Temperatures in the control room were 24 °C with relative humidity of 50–60%. All data were analyzed for this experiment using the PROC MIXED procedure of the Statistical Analysis System (SAS Institute, 2001) in the same manner as described for the previous experiment with the flour mill, with block and replicates within a block as random effects and treatments as fixed effects. Analysis was carried out on treated packaging materials in blocks 1 through 4 and 5–6, however, blocks 3 and 4 had to be eliminated because of poor survival in the untreated control.

2.4. Partial budget analysis

Chemical costs were calculated per 294 m^3 to compare costs of methoprene and synergized pyrethrin treatments (alone and in combination) for the two field sites as a control for eggs of *P. interpunctella*. Risk was calculated at three mortality levels (90, 95, and 99%) as deviations below this target goal. Tilley et al. (2007) reports a modified Target MOTAD (mortality goal) model for optimizing cost and risk, but in the case of these three experiments, time and equipment cost are fixed and the only variable cost is the cost of the chemical. Risk, in this case, is the inverse of mortality, up to the mortality target, therefore the downside risk is mortality below the target level.

Chemical and carrier oil costs (for the methoprene only treatments) were calculated based on current industry prices. Carrier oil costs fluctuate with the global petroleum market but for the purposes of this analysis were fixed to \$0.83 (US) per L or \$0.0008 per ml. Carrier costs can be especially important if comparisons are being made between chemicals with different application rates. In the case of the synergized pyrethrin applications, the formulation is premixed, so cost calculations are simply on a per unit basis. For the analysis, means from all treatments in both the flour mill study and the grocery warehouse study were used to calculate overall mortality and risk. Since grocery warehouses contain a mixture of products and package types, we attempted to get an estimate of overall mortality and risk across all scenarios (treated eggs, treated packaging, and treated diet) for each diet type.

3. Results

3.1. Flour mill experiment

For blocks 1–4 (whole-plot treatment 1% pyrethrin plus methoprene), analyses were run as if the control plates were an 11th position. Treating the control plates as a separate position was done because the controls were held in a separate room from the insecticide treatments; this allowed us to better examine the effect of position within the treatment area. Adult emergence from eggs exposed in treated diet, directly to the aerosol, or on packaging materials exposed to the aerosol was not significantly different between the unobstructed and concealed positions ($F = 0.1$, $df = 1, 849$, $P = 0.72$), indicating dispersion and penetration of the aerosol throughout the floor of the mill where the test was conducted. However, the main effects method of exposure and the specific diet used for the exposures were both significant at $P < 0.01$ ($F = 116.7$, $df = 2, 849$; $F = 63.4$, $df = 2, 849$, respectively). Main effect exposure position was not significant alone ($F = 1.1$, $df = 9, 30$, $P = 0.43$), but the interaction between position and method of treatment (treated eggs, treated package materials and treated diet) was significant ($P < 0.01$) (Fig. 3, ABC). The diet by treatment interaction was significant ($P < 0.01$), but none of the nine interactions done as part of the overall analysis were ($P \geq 0.05$).

When eggs were placed on any of the three treated diets or on the treated packaging materials, adult emergence was virtually zero. However, while treatments were significantly different from controls ($P < 0.05$), overall adult emergence was higher when eggs were exposed directly to the aerosol treatment (Fig. 3B), and adult emergence was lower in the treatments involving raisins than in the other two diets. Because there was virtually no adult emergence of *P. interpunctella* in the treated diets and treated packages portion of the experiment, these factors were omitted from the final four blocks of the experiment.

Analysis of the treated egg treatment method across all blocks (1–8) and all three whole-plot treatment methods (1% pyrethrin plus methoprene, 3% pyrethrin alone, and 3% pyrethrin plus methoprene) showed no significance in insecticidal efficacy regardless of treatment ($F = 0.8$, $df = 2, 5$, $P = 0.50$). However, in this analysis the untreated controls were eliminated from the analysis because of the obvious difference in adult emergence from eggs exposed to the insecticides versus the controls. The main effects diet and position were significant at $P < 0.01$ ($F = 174.7$, $df = 2, 467$; $F = 12.3$, $df = 9, 50$, respectively). The treatment by diet and the position by diet interactions were significant ($P < 0.01$), but none of the other nine interactions analyzed in this portion of the study were significant ($P \geq 0.05$). Overall, adult emergence from eggs exposed to the three insecticidal treatments in all three diets was significantly lower than the corresponding adult emergence from eggs in the control diet ($P < 0.05$) However, emergence in untreated controls and the diets exposed to the insecticides was generally lowest on the raisin diet compared to the protein bar and wheat diet (Fig. 4).

While assigning the data for the untreated controls to a separate position made the overall position effect highly significant, it was also necessary to determine if linear distance along the floor from a position directly below the aerosol fogging nozzle was a significant factor. In this analysis, data for untreated controls were eliminated. In addition, data for exposure of eggs to the treated diet or on the treated packaging surfaces were omitted because adult

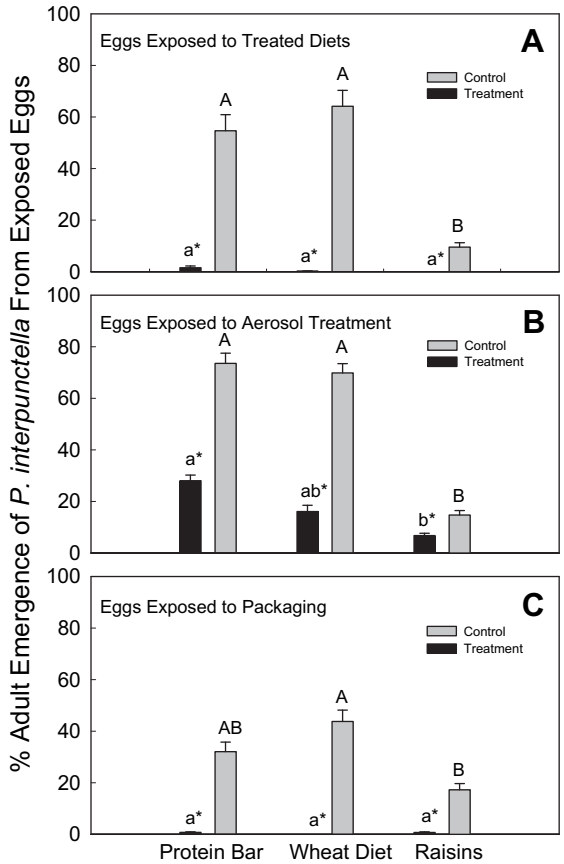

Fig. 3. Percentage of adult emergence from eggs of *P. interpunctella* exposed to an ultra-low-volume (ULV) application of 1% synergized pyrethrin + methoprene (A), direct exposure to the aerosol (B), or on packaging materials with diet inside that were exposed to the aerosol and eggs added after exposure (C). In all three graphs, capital letters indicate statistical differences between diet types and asterisks beside the mean for the treatments indicate statistical differences between the insecticide treatment and controls. Means were separated using Ryan-Einot-Gabriel-Welsch Multiple Range Test ($P < 0.05$).

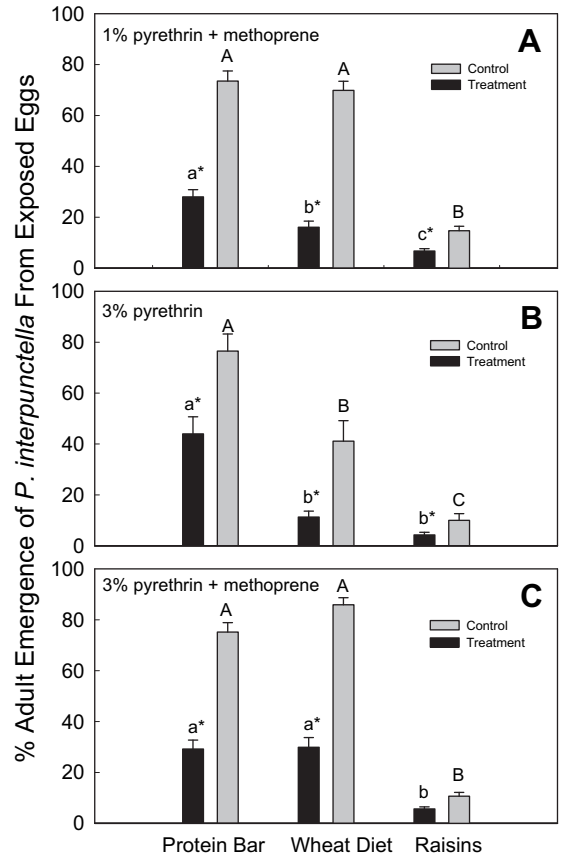

Fig. 4. Percentage of adult emergence from of eggs of *P. interpunctella* from three diets directly exposed to an ultra-low-volume (ULV) application of 1% synergized pyrethrin + methoprene (A), 3% pyrethrin only (B), or 3% pyrethrin + methoprene (C). In all three graphs, capital letters indicate statistical differences between diet types and asterisks besides the means for the treatments indicate statistical differences between the insecticide treatment and controls. Means were separated using Ryan-Einot-Gabriel-Welsch Multiple Range Test ($P < 0.05$).

emergence was virtually zero. Instead, only the data for eggs exposed along with the treated diet (reported in Fig. 2) were analyzed. The whole-plot treatment of insecticide application was not significant ($F = 0.5$, $df = 2.\ 5$, $P = 0.66$), while the main effects exposure position and diet were significant at $P < 0.01$ ($F = 16.7$, $df = 9, 45$; $F = 117.4$, $df = 2333$, respectively), along with all interactions ($P < 0.05$). Adult emergence ranged from 6.2 ± 2.3 to 33.0 ± 5.5%, and in general, as distance from the spray nozzle increased, so did adult emergence from the exposed eggs (Fig. 5).

3.2. Processed food warehouse field trial

The diets used in the first experiment were standard wheat diet inside plastic bags, commercially available peanut butter protein bar inside their original laminate paper packaging and corn muffin mix inside original packaging (laminated cardboard). Analysis was done using control data as position 4 because the tests were held in an untreated room in the same facility The only significant effect was diet ($F = 40.9$, $df = 2, 75$, $P < 0.01$, all other main effects and interactions $P \geq 0.05$). Adult emergence from eggs exposed on the wheat diet was significantly greater in the controls compared to the treatments ($P < 0.01$) but there was no difference in adult emergence of eggs put on the protein bar or corn muffin mix and exposed to methoprene, compared to the emergence of untreated controls ($P \geq 0.05$, Fig. 6).

In blocks 3 and 4 main effect diet was significant with respect to adult emergence from exposed eggs ($F = 10.3$, $df = 2, 94$, $P < 0.01$) but no other main effects or interactions were significant ($P \geq 0.05$). Adult emergence on the wheat diet and the muffin mix was low in treatments and controls, in contrast to adult emergence on the

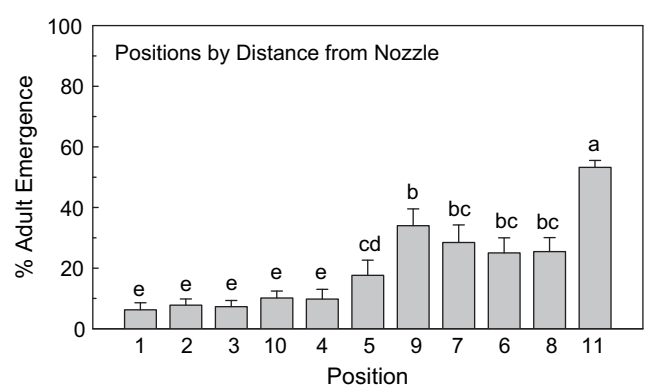

Fig. 5. Percentage of adult emergence from eggs of *P. interpunctella* exposed to an ultra-low-volume (ULV) application of 1% synergized pyrethrin + methoprene, 3% pyrethrin only, or 3% pyrethrin + methoprene (data pooled), by position of exposure inside the flour mill. Means were separated using Ryan-Einot-Gabriel-Welsch Multiple Range Test ($P < 0.05$); those means indicated by different lower-case letters are significantly different in adult emergence with respect to exposure position.

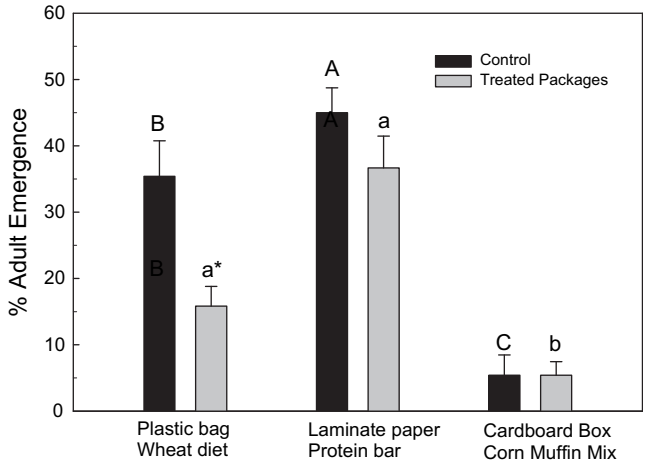

Fig. 6. Percentage of adult emergence from eggs of *P. interpunctella* from packaging/diets directly exposed to an ultra-low-volume (ULV) application of methoprene only. Means were separated using Ryan-Einot-Gabriel-Welsch Multiple Range Test; different upper-case letters indicate a significant difference between the means for different packaging/diets; different lower-case letters indicate a significant difference between the means for different packaging/diets for the methoprene treatment, and means denoted with an asterisk are significantly different between the controls and methoprene treatment for that particular packaging/diet combination ($P < 0.05$).

protein bar. When the eggs were exposed to the treated diets (Fig. 7A) or on the treated packaging (Fig. 7C), adult emergence was lower in the methoprene treatment than in the controls, but not when eggs were exposed directly to the ULV aerosol (Fig. 7B). In blocks 5 and 6 raisins were substituted for the muffin mix. The overall analysis showed that main effect method of treatment and diet were both significant at $P < 0.01$ ($F = 116.2$, $df = 2, 95$; $F = 174.19$, $df = 2, 95$), but not exposure position ($F = 1.4$, $df = 2, 3$, $P = 0.27$) or whether exposures were done in unobstructed or concealed positions ($F = 0.9$, $df = 1, 95$, $P = 0.34$). The exposure position by diet interaction and the method of treatment by diet interactions were both significant ($P < 0.01$) but no others were ($P \geq 0.05$). When eggs were exposed to the treated diets, adult emergence was lower in the methoprene treatments than in the controls on the protein bar and wheat diets (Fig. 8A). However, when eggs were directly exposed to the methoprene ULV, adult emergence was 73–80% on protein bar and wheat diets in treatments and controls. Adult emergence from eggs exposed on packaging was lower in treatments than in the controls on the wheat diet (Fig. 8C).

3.3. Partial budget analysis

Efficacy in our partial budget analysis is measured by failure of exposed eggs and larvae to emerge as adults (mortality is then the inverse of adult emergence). The results of the partial budget analysis shows that as the target mortality increases from 90 to 95 and then to 99%, risk levels increase, however the overall risk decreases as the observed mortality in the first column increases (Table 1), for each of the three treatments, diet, egg, and packaging. The cost of the 3% pyrethrin + methoprene application is estimated as $5.85 US dollars, compared to $3.14 for the 1% pyrethrin + methoprene application (Table 1). Although only the eggs were exposed to the 3% pyrethrin + methoprene, there was no increase in mortality from this higher rate of pyrethrin, hence the additional cost was not justified by a reduction in risk levels. Regardless of whether or not methoprene or pyrethrin was applied alone or in combination, the cost of the carrier was still the same, therefore the cost of adding the second insecticide was offset somewhat by the reductions in risk at each of the three mortality levels.

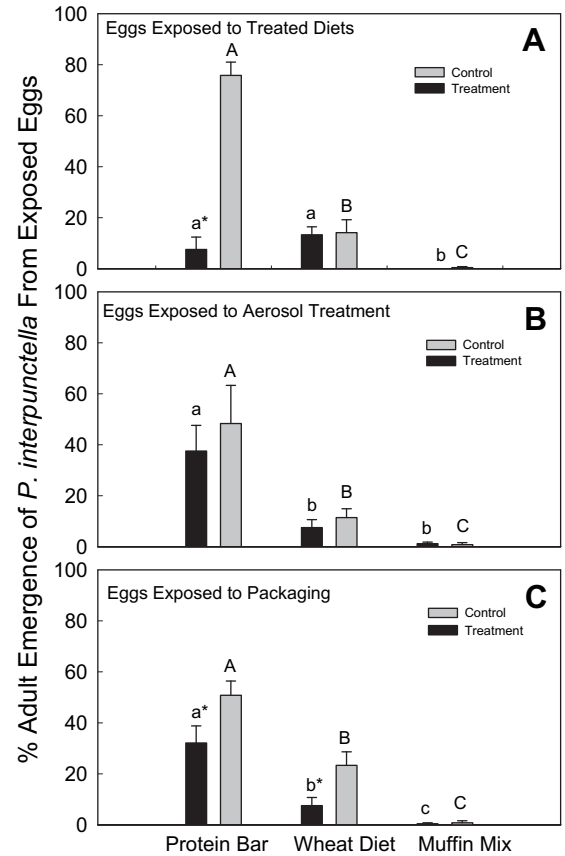

Fig. 7. Percentage of adult emergence from eggs of *P. interpunctella* exposed to an ultra-low-volume (ULV) application of methoprene only (A), direct exposure to the aerosol (B), or on packaging materials with diet inside that were exposed to the aerosol and eggs added after exposure (C). In all three graphs, capital letters indicate statistical differences between diet types and asterisks beside the mean for the treatments indicate statistical differences between the insecticide treatment and controls. Means were separated using Ryan-Einot-Gabriel-Welsch Multiple Range Test ($P < 0.05$).

Field trials with methoprene only were conducted in the grocery warehouse. Mortality of eggs on treated diet, exposed directly to the aerosol, or on treated package were the variables in the analysis. The partial budget analysis was done to show the differences between treatments, as reflected in Figs 6–8. Survival of *P. interpunctella* was greater on the wheat diet compared to the protein bar and raisin diets, reflecting a greater preference for the wheat diet. As mortality increased on the protein bar and raisin diets, the risk values at each mortality level decreased correspondingly (Table 2). Survival was also higher when treated eggs were placed on the wheat diet and protein bar compared to raisins, and on treated laminate paper compared to the plastic bag and cardboard surfaces (Table 2). All chemical costs are the same because only the methoprene treatment was evaluated, but in cases where there was little difference from the untreated controls, comparisons of the risk values emphasize the lack of control (Table 2).

4. Discussion

Reviews of previous research indicate reduced adult emergence when eggs and larvae of *P. interpunctella* feed on diets which have had methoprene incorporated in some manner into them (Oberlander et al., 1997). Our study showed that when the diets used in our study were exposed to methoprene, there was also reduced adult emergence from eggs exposed on various diets, with the exception of the wheat diet, the standard rearing medium for

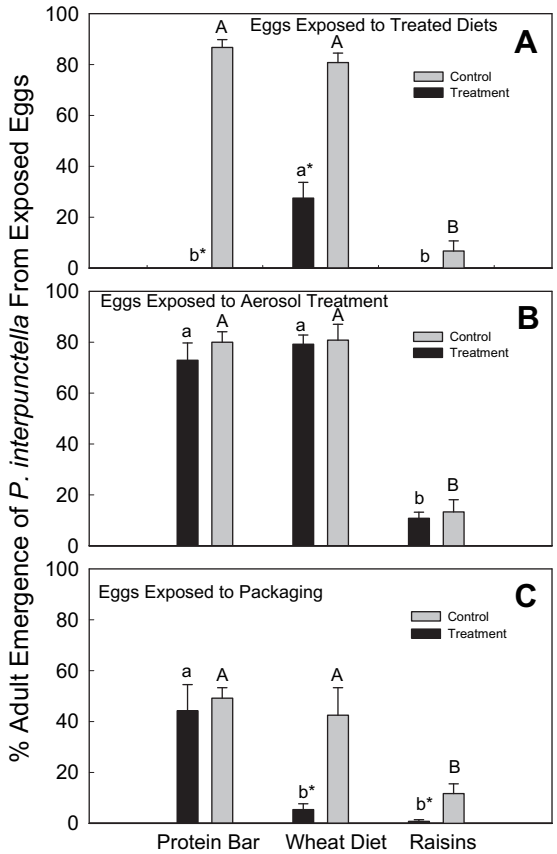

Fig. 8. Percentage of adult emergence from eggs of *P. interpunctella* exposed to an ultra-low-volume (ULV) application of methoprene only (A), direct exposure to the aerosol (B), or on packaging materials with diet inside that were exposed to the aerosol and eggs added after exposure (C). In all three graphs, capital letters indicate statistical differences between diet types and asterisks beside the mean for the treatments indicate statistical differences between the insecticide treatment and controls. Means were separated using Ryan-Einot-Gabriel-Welsch Multiple Range Test ($P < 0.05$).

the colony of *P. interpunctella* used in the tests. Adult emergence, and hence survival of *P. interpunctella* is also reduced when eggs and larvae are exposed to packaging materials or aerosol treatments of methoprene (Jenson et al., 2009). Our results also demonstrate that aerosol particles can be distributed beneath stacked products and machinery in commercial environments, and the results also showed better efficacy and distribution of aerosol synergized pyrethrins than in previous experiments (see Bernhard and Bennett, 1981; Cline et al., 1984). The results we obtained for synergized pyrethrins are also similar to other laboratory studies involving corn and wheat and exposures of *Corcyra cephalonica* (Stainton), the rice moth, and *P. interpunctella* (Huang and Subramanyam, 2003, 2005).

Overall feasibility of the combination aerosol treatments was demonstrated by the partial budget analysis. Mortality of the egg stage of *P. interpunctella* (or the inverse of adult emergence) across all treatments was between 70 and 85%, so these treatments would be expected to significantly alter population dynamics of *P. interpunctella*. Additionally, our results indicated that the most expensive treatment option does not always carry the lowest risk. For example, the 3% pyrethrin plus methoprene treatment did not reduce survival to the adult stage as much as the other treatments. However, our results represent the efficacy of these chemicals for eggs of *P. interpunctella* only, and consideration of other pest species and particular needs of each facility must be carefully assessed before insecticide application. In the processed food warehouse portion of our tests, eggs that were directly exposed to the methoprene-only aerosol treatment had a much higher survival to the adult stage than eggs exposed to pyrethrin-alone or to the combination.

Field trials are especially important when attempting to assess insecticides that are currently being used in food processing facilities. This study also shows aerosol insecticides can be effectively distributed inside commercial milling and food storage facilities

Table 1
Summary of costs and risk levels for the pyrethrin + methoprene treatments for the flour mill; % mortality is the inverse of adult emergence from exposed eggs. The different diet types and treatment methods described in the Results and in Figs. 3 and 4 are also listed. Risk is presented as three thresholds; 90, 95 and 99% mortality above which risk is set equal to zero. Costs are based in US dollars per 280 m^3. C = controls, P = pyrethrin, M = Methoprene.

Diet	Treatment	% Mortality	90% Risk	95% Risk	99% Risk	$ Cost
Wheat	C-diet	35.9	0.56	0.60	0.63	0.00
Protein Bar	C-diet	43.4	0.47	0.51	0.54	0.70
Raisins	C-diet	90.5	0.04	0.07	0.09	3.14
Wheat	1% P + M	99.8	0.00	0.00	0.00	3.14
Protein Bar	1% P + M	98.5	0.00	0.01	0.01	3.14
Raisins	1% P + M	100	0.04	0.07	0.09	0.00
Wheat	C-eggs	30.2	0.60	0.65	0.69	0.00
Protein Bar	C-eggs	26.5	0.65	0.69	0.73	0.00
Raisins	C-eggs	85.3	0.08	0.11	0.14	0.00
Wheat	1% P + M	83.9	0.11	0.13	0.15	3.14
Protein Bar	1% P + M	72.0	0.20	0.24	0.27	3.14
Raisins	1% P + M	93.2	0.02	0.04	0.06	3.14
Wheat	C-packages	56.2	0.36	0.40	0.43	0.00
Protein Bar	C-packages	68.0	0.25	0.28	0.31	0.00
Raisins	C-packages	83.0	0.11	0.14	0.17	0.00
Wheat	1% P + M	100	0.00	0.00	0.00	3.14
Protein Bar	1% P + M	99.2	0.00	0.00	0.00	3.14
Raisins	1% P + M	99.3	0.00	0.00	0.00	3.14
Wheat	C-eggs	14.1	0.77	0.81	0.85	0.00
Protein Bar	C-eggs	24.8	0.66	0.71	0.74	0.00
Raisins	C-eggs	89.3	0.03	0.06	0.10	0.00
Wheat	3% P + M	71.1	0.22	0.26	0.29	5.85
Protein Bar	3% P + M	71.8	0.21	0.25	0.28	5.85
Raisins	3% P + M	94.3	0.02	0.03	0.05	5.85

Table 2
Summary of costs and risk levels for methoprene treatments for the grocery warehouse; % mortality is the inverse of adult emergence from exposed eggs. Data for corn muffin mix were not used for the cost analysis because of low adult emergence from eggs on untreated controls. The data for the other three different diet types and treatment methods described in the Results and in Figs 6–8 are listed. Risk is presented as three thresholds; 90, 95 and 99% mortality above which risk is set equal to zero. Costs are based in US dollars per 280 m^3. C = controls, M = Methoprene.

Diet	Treatment	% Mortality	90% Risk	95% Risk	99% Risk	$ Cost
Wheat	C-diet	49.6	0.42	0.46	0.50	0.00
Protein Bar	C-diet	21.7	0.68	0.73	0.77	0.00
Raisins	C-diet	93.3	0.03	0.04	0.06	0.00
Wheat	M	80.0	0.12	0.16	0.20	0.71
Protein Bar	M	96.2	0.02	0.03	0.04	0.71
Raisins	M	100	0.00	0.00	0.00	0.71
Wheat	C-eggs	57.7	0.34	0.38	0.41	0.00
Protein Bar	C-eggs	35.8	0.55	0.60	0.63	0.00
Raisins	C-eggs	88.0	0.06	0.09	0.11	0.00
Wheat	M	52.2	0.37	0.41	0.44	0.71
Protein Bar	M	44.8	0.47	0.51	0.54	0.71
Raisins	M	89.2	0.03	0.07	0.10	0.71
Wheat	C-packages	56.2	0.36	0.40	0.43	0.00
Protein Bar	C-packages	68.0	0.25	0.28	0.31	0.00
Raisins	C-packages	83.0	0.11	0.14	0.17	0.00
Wheat	M	100	0.00	0.00	0.00	0.71
Protein Bar	M	99.2	0.00	0.00	0.00	0.71
Raisins	M	99.3	0.00	0.00	0.00	0.71

and can be part of a comprehensive pest management program. By utilizing other integrated pest management techniques such as sanitation, the risk of infestations in spilled food as mimicked by our treated diet scenario would seem to be decreased. Also, pheromone traps can be used to monitor *P. interpunctella* populations, and data could be used to determine the necessity of insecticide application (Doud and Phillips, 2000; Campbell et al., 2002).

This study provided a unique opportunity to evaluate aerosol applications in actual working commercial facilities, and thus data were obtained regarding chemical control of *P. interpunctella* in a large-scale environment. One limitation of field research of this nature is that live insects cannot normally be brought into an active commercial facility. We were able to evaluate control of the egg stage of *P. interpunctella* but not any other life stage. Another limitation of using commercial field sites is that the timing of sprays, insecticide concentrations and specific combinations are determined by the field cooperator. Nevertheless, data from field sites that store finished stored products are vital in understanding how insecticide efficacy differs from laboratory research, and how pests can be managed safely in situations where food is stored for human consumption. Due to the complex nature of grocery warehouses (variation of product, frequent rotation of product, little control over product in transit) field experiments also help to clarify specific needs of industry in developing integrated pest management strategies. Further research into methods of safely containing other life stages and insect species should be conducted so that overall population reduction can be assessed in large-scale facilities.

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This paper reports the results of research only. Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U. S. Department of Agriculture or by Kansas State University. The authors thank B. D. Barnett and C. Smith for technical assistance with the research. We also thank K. H. Zhu for reviewing the paper prior to journal submission. This paper is contribution number 09-310-J from the Kansas Agricultural Experiment Station.

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