Stored-Product

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Research

Effects of Aerosol Insecticide Application Location on the Patterns of Residual Efficacy Against *Tribolium confusum* (Coleoptera: Tenebrionidae) Larvae

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Abstract

Aerosol insecticides are one tool that pest management professionals can utilize as a spatial treatment inside food facilities and storage warehouses. Methods of aerosol application can vary significantly and can affect the spatial pattern of efficacy achieved. We investigated how the location from which an aerosol insecticide is applied inside a mill influenced the spatial dispersal of the insecticide. Treatments were performed using two commercial formulations, pyrethrin + pyriproxyfen (insect growth regulator [IGR]) and pyrethrin + methoprene (IGR), applied at one of three static locations or a fourth application comprising of splitting the application among all three locations. Concrete arenas were placed out at different locations within the mill during applications. At 2, 4, and 6 wk post-aerosol application, *Tribolium confusum* Jacquelin du Val, confused flour beetle, larvae were added to the concrete arenas and monitored for development and efficacy was evaluated based on percent adult emergence and an efficacy index that ranged from 1 (low) to 21 (high). The spatial pattern of aerosol coverage varied between insecticide formulations and the aerosol application location. Areas of the mill near walls, corners, equipment, and farthest away from the application location had larger zones of low efficacy index values among all four application locations. This study illustrated that the aerosol insecticide formulation, application location, and delivery method all significantly influenced residual efficacies of the insecticides. To increase the overall spatial coverage and IGR efficacy, targeting these areas of a mill floor with the aerosol or additional intervention techniques would increase uniform coverages and overall effectiveness.

Key words: aerosol dispersal, residual efficacy, contour mapping, flour mill, spatial coverage

Aerosols insecticide treatments disperse a liquid insecticide in small droplets or particles for use as a spatial treatment for insect control (Peckman and Arthur 2006). Aerosol insecticides are differentiated from other dispersed insecticides based on the particle size range: aerosol particles range from 0.1 to 50 µm, whereas mists range from 50 to 100 µm and fumes and smoke range from 0.00 to 0.1 µm (Snell 1997). The small particle size of aerosol insecticides allows for the movement of the particles throughout a space, both vertically and horizontally (Scheff et al. 2019). When aerosols are dispensed, the larger particles, 10–12 µm, settle out first and the smaller particles, 4–6 µm, remain suspended in the ambient air for a longer duration before settling out (Arthur et al. 2018). Small-scale laboratory studies using a specialized aerosol exposure chamber, which regulates aerosol particle sizes, have evaluated the effects of aerosol particle size on efficacy using several stored-product insect species exposed on concrete surfaces (Arthur et al. 2014, 2017, 2019; Lanka et al. 2019). These tests have shown that particle size was the most important factor influencing efficacy, with larger 16-µm aerosol particle sizes being more efficacious than smaller 2-µm particles. However, the facility structure, aerosol formulation, and delivery method all affect the movement of the aerosol particles of different sizes and the resulting deposition on surfaces and efficacy on stored-product insects.

The use of aerosol insecticides can provide a more complete coverage of surfaces throughout mills, warehouses, or processing facilities compared to other application methods (Campbell et al. 2014). The aerosol deposition onto surfaces and the residual effect on juvenile stages of insects is highly important because only a small percentage of individual insects are directly exposed during an aerosol insecticide application because a large proportion of the existing insect population is in hidden refugia where food accumulates, such as inside machinery or in cracks and crevices (Toews et al. 2010). Aerosol insecticides have no penetration capability and therefore will not directly affect insects inside packaging material, machinery, or large accumulations of grain/food spillage. However, the power of aerosol insecticides is from the extensive coverage the aerosol particles provide by particle deposition onto surfaces which increases the opportunities for insects, especially larvae, to come into contact with the insecticide as they move among resource patches (Campbell et al. 2014).

Given that pyrethrins applied in aerosol formulations have poor residual persistence (Arthur et al. 2019), pyrethrins applied are often paired with an insect growth regulator (IGR), which has much longer persistence across different surfaces (Arthur and Fontenot 2012). Arthur et al. (2019) previously reported no effect of the pyrethrin component of a pyrethrin + methoprene aerosol after 7 d post-treatment on adult *Tribolium confusum* Jacquelin du Val, confused flour beetle, exposed on treated concrete arenas. However, the methoprene component remained effective on *T. confusum* larvae up to 6 wk post-aerosol treatment, with adult emergence <2.2% for a 20-min treatment at a 16-µm particle size (Arthur et al. 2019). IGRs are highly effective on the juvenile stages of insects because they disrupt the normal development between life stages, but are not toxic to adult insects (Phillips and Throne 2010). The multiple modes of action due to using pyrethrins and IGRs may also help to mitigate the development of insecticide resistance (Scheff et al. 2018).

Small-scale studies are beneficial to understanding the fundamental concepts of how aerosols adversely affect stored-product insects; however, they do not adequately simulate the temporal and spatial complexities that exist during aerosol applications in commercial food processing facilities (Toews et al. 2009). Research using equipment to measure particle size distributions during aerosol applications have shown that there is spatial variation in particle size distribution and concentration at different locations within a facility (Arthur et al. 2018; Scheff et al. 2018, 2019). The larger aerosol particles, >5 µm, settle out of the ambient air within the first ~30 min of a treatment and can account for >90% of accumulated aerosol particle depositions (Arthur et al. 2018). Arthur et al. (2018) also reported the aerosol mass concentration (mg/m^3) decreased with distance from the release point. The combination of distance aerosol particles have to travel, from that release point, and time after application, will affect the aerosol dispersion and particle deposition and contribute to variation in efficacy against stored-product insects. Physical barriers will also affect aerosol deposition. Toews et al. (2010) reported that the mortality of *Tribolium castaneum* Herbst (Coleoptera: Tenebrionidae), red flour beetle, adults decreased when testing arenas were positioned underneath a pallet compared with arenas held in an open environment. Campbell et al. (2014) and Scheff et al. (2018) also found when evaluating spatial pattern in aerosol efficacy inside a pilot-scale mill distance and obstructions resulted in reduced efficacy (Campbell et al. 2014, Scheff et al. 2018).

Because of the effects of distance and physical barriers on aerosol distribution and spatial pattern of efficacy, the position of releasing the aerosol may have a large effect on treatment efficacy. To evaluate this factor, we have compared the impact of releasing two different aerosol formulations, pyrethrin + pyriproxyfen and pyrethrin + methoprene, applied from three locations or by splitting the application equally among those three locations. The effects of these application strategies on direct mortality of adults exposed during the application, a measure of the pyrethrin distribution, was evaluated by Scheff et al. (2018). The application location had a significant influence on the spatial pattern of efficacy, with aerosols released from multiple locations throughout a floor leading to more consistent *T. confusum* adult knockdown and mortality compared with single aerosol application location. Here, we evaluate these insecticide applications for the spatial variation in residual efficacy provided by the IGR component of the aerosol treatments which was not evaluated previously. Because IGRs typically have greater efficacy at lower concentrations than pyrethrins, spatial variation in particle deposition on surfaces might result in less spatial variation in efficacy than was reported for the pyrethrins (Campbell et al. 2014, Scheff et al. 2018). The objective of this research was to determine how the aerosol insecticide application location affects the residual efficacy of two different IGRs up to 6 wk post-aerosol treatment. The results from this study can be used in conjunction with previous research on aerosol insecticides to determine how to most effectively apply aerosols to get the most consistent efficacy and coverage within a milling facility.

Materials and Methods

Research Location

All aerosol insecticide applications occurred over a 3-day span during the summer of 2016 at the pilot-scale Hal Ross flour mill at Kansas State University, Manhattan, KS. The mill was previously described by Campbell et al. (2014) and Scheff et al. (2018), but a brief description follows. The pilot-scale mill was a concrete structure containing five floors, and the third floor of the mill was used for experimentation due to its highly congested layout and would be similar in complexity to a large-scale facility (Fig. 1) and the first floor was used as a control floor. The third floor of the mill was approximately 1,504 m^3 and was laid out in a L-shape: with the main area measuring 13.5 m × 21.0 m and a small offshoot to the north, 7.5 × 6.5 m, created the L-shape. The height of the third floor was 4.3 m. During the testing period all doors, except the main entrance, were sealed off with plastic sheeting and the air ventilation system was turned off. During treatments, temperature and relative humidity sensors (HOBO Data Logger, Onset Computer Corporation, Bourne, MA) were placed on the first and third floors. The range in temperature and relative humidity during the testing period on the first floor was 22–28°C and 50–72% RH and the third floor was 24–33°C and 50–70% RH, respectively.

Aerosol Treatments

All aerosol insecticides were applied by a commercial applicator using label rates for both aerosol insecticides tested. The first aerosol tested was TurboCide Py-75 with IGR (Chem-Tech Ltd., Des Moines, IA). This aerosol insecticide was a combination of pyrethrins and the IGR pyriproxyfen (0.7% pyrethins, 5.0% piperonyl butoxide [PBO], 0.3% pyriproxyfen, and 94% other ingredients) and will henceforth be called pyrethrin + pyriproxyfen. Pyrethrin + pyriproxyfen was formulated as a cylinder release with a CO_2 carrier, and the target release rate was ~900 g based on the label rate and volume of the space. The second aerosol insecticide used was pyrethrin (BP-100, BASF Corp., Research Triangle Park, NC) with the IGR methoprene (Diacon IGR, Central Life Sciences, Schaumberg, IL). The BP-100 contained 1.0% pyrethrin, 5.0% PBO, and 94% other ingredients. The Diacon IGR contained 33.6% (s)-methoprene and 66.4% other ingredients. The pyrethrin and methoprene were mixed together at a ratio of 795 and 16 ml and was applied using a handheld fogger (Fogmaster 7401, Fogmaster Corporation, Deerfield Beach, FL). Henceforth, this aerosol insecticide will be called pyrethrin + methoprene.

Each aerosol was applied in one of three different static locations (Fig. 1) or by applying 1/3 of the total dosage (~300 g) at each location (moving application). The aerosol was directed towards the interior

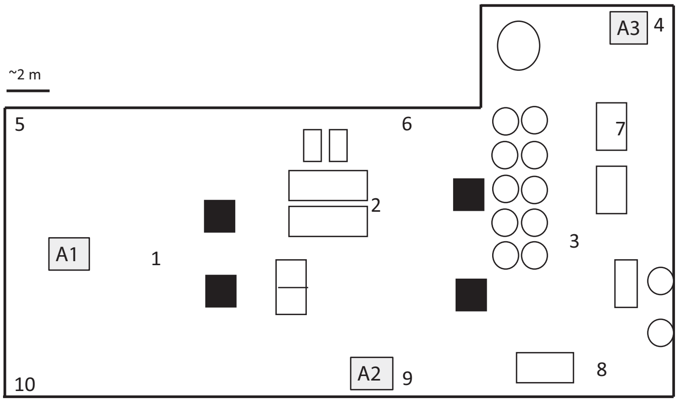

Fig. 1. General schematic of the third floor of the pilot-scale flour mill used for all experiments. The black boxes, white circles, and rectangles represent large structural features on the third floor such as support columns, milling equipment, sifters, and large storage bins. The bioassay area positions are numbered 1–10. The location of each aerosol application position is denoted as A1, A2, and A3 inside the gray squares. Aerosol application 4 was released from all three locations A1, A2, and A3 (1/3 dose at each position). Source: Scheff et al. (2018), used by permission.

of the mill at an approximate 45° angle and applied using a sideways sweeping motion toward the left and right sides of the floorspace. The total aerosol application time was approximately 2–5 min, followed by a 1-h exposure period. After the 1-h exposure, the air ventilation system was turned on for approximately 10 min to remove any residual aerosol particles that may be present in the ambient air. The next step was to pick up all bioassay arenas that were exposed to the aerosol insecticide treatment and replace with new bioassay arenas for the next aerosol treatment, which took approximately 5–15 min. The aerosol application position was changed after each treatment and each aerosol application location was repeated twice for each aerosol formulation. Due to logistical constraints of the milling facility (time available for testing) and time required for each aerosol application the pyrethrin + pyriproxyfen aerosol treatments were conducted first, followed by the pyrethrin + methoprene aerosol treatments. Day 1 of testing had five trials, day 2 had six trials, and day 3 had five trials, for a total of 16 aerosol applications.

Bioassays

The *T. confusum* larvae used in the study were from a pesticide-susceptible strain maintained at the United States Department of Agriculture–Agricultural Research Service–Center for Grain and Animal Health Research (USDA-ARS-CGAHR, Manhattan, KS). *Tribolium confusum* colonies are reared on 95% organic whole-wheat flour and 5% brewer's yeast at 27°C, 60% RH, and 0:24 (L:D) h in an environmental chamber. These colonies have been maintained at the USDA-ARS-CGAHR for more than 30 yr.

Testing arenas used in this study were individual 60 × 15 mm (~22 cm^2) Petri dishes partially filled with concrete and placed inside larger 150 × 20 mm (~137 cm^2) plastic Petri dishes. Concrete dishes were prepared based on Arthur (2015). Briefly, a dry powder driveway patching material (Rockite, Hartline Product Co., Inc., Cleveland, OH) was mixed with water to create a thin slurry, poured in the bottom of Petri dishes to a depth of ~0.5 cm, and held at ambient conditions for approximately 7 d. Inside each Petri dish, four concrete arenas were placed. Three of the arenas were used in the current study for residual bioassays at 2, 4, and 6 wk post-aerosol treatment and contained no diet at time of exposure to aerosol. The other arena was used as described by Scheff et al. (2018).

These groups of testing arenas were placed at ten different positions on the third floor (Fig. 1). Nine positions also had aerodynamic particle sizer units (APS 3321, TSI Inc., Shoreview, MN) placed to collect data on aerosol particle concentration and size distribution. Two additional testing arenas were placed on the first floor of the mill during each aerosol treatment and served as untreated controls. Arenas were placed in each of the four major corners of the mill floor (arenas 4, 5, 8, 10). Bioassay arenas along walls were placed approximately 0.5 m away from the wall (arenas 4, 5, 6, 8, 9, 10). Bioassay arena 2 was placed in between two large pieces of milling equipment and pneumatic conveying ducts. Bioassay arena 7 was placed underneath a piece of milling equipment. Relative to the application locations, bioassay arena 1 was placed directly in front of aerosol application location 1 and bioassay arenas 9 and 4 were placed next to aerosol application locations 2 and 3, respectively.

After aerosol applications, each bioassay arena was covered and transported back to the USDA-ARS-CGAHR and held at 27°C, 60% RH, and 0:24 (L:D) in an environmental chamber. At 2, 4, and 6 wk post-aerosol application, five (3–4 wk old) *T. confusum* larvae along with ~400 mg of diet were added to one concrete arena from each bioassay arena position. Number of larvae available for bioassays was limited, but five larvae per dish does provide sufficient resolution to evaluate IGR effects on development. Larvae were examined twice weekly, up to 4 wk, for adult emergence. Emerged adults were removed from dishes to prevent cannibalism.

At the end of 4 wk, all five individuals were classified as larvae, pupae, or adults. Means and SEs were calculated for adult emergence and data analyzed using statistical analysis software (version 9.4, SAS Institute, Cary, NC). Adult emergence data were transformed to angular values prior to analysis (Zar 2010) before using a three-way analysis of variance based on bioassay position, application position, and residual week as the main effects.

Aerosol Dispersal Patterns

To assess the strength of the effect of the aerosol application, an efficacy value index was created to convert the three morphological states (larvae, pupae, adult) to a single value for comparison (Campbell et al. 2014). The efficacy index ranged from 1, the weakest efficacy response with five adults, to 21, the strongest response with five larvae. All of the index values with the corresponding numbers of adults, pupae, and larvae indicated in brackets were the following: 1 [5,0,0], 2 [4,1,0], 3 [4,0,1], 4 [3,2,0], 5 [3,1,1], 6 [3,0,2], 7 [2,3,0], 8 [2,2,1], 9 [2,1,2], 10 [2,0,3], 11 [1,4,0], 12 [1,3,1], 13 [1,2,2], 14 [1,1,3], 15 [1,0,4], 16 [0,5,0], 17 [0,4,1], 18 [0,3,2], 19 [0,2,3], 20 [0,1,4], 21 [0,0,5].

To visualize the aerosol dispersal patterns' residual effect on *T. confusum* larvae, contour maps of the efficacy index values at each bioassay location were developed based on Kriging using Surfer software (Surfer 16, Golden Software, Golden, CO). Kriging is an interpolation method used to predict intermediate values using calculations where nearby points are given more weight than those further away. Contour maps were created for each application position and post-aerosol treatment week. To facilitate analysis efficacy index was divided into three levels: areas of low efficacy were defined as areas with index values between 1 and 7, areas of medium efficacy were defined as index values between 8 and 14, and areas with high efficacy values were defined as index values between 15 and 21. Contour maps are only presented for the efficacy index data and not adult emergence. Both measures of treatment effects are useful, but the efficacy index captures more of the range of the responses across multiple insects and summarizes into a single response variable that can be more easily mapped.

Results

Adult Emergence after Pyrethrin + Pyriproxyfen Aerosol Application

For the controls, the overall average adult emergence was >97% when all replicates at each residual week and application location were combined (n = 48). Therefore, no corrections for control mortality were made and significant differences were determined based on treatment arenas only (Arthur 2008; Arthur et al. 2008, 2019). For the treatment arenas on the third floor, all main effects and interactions were not significant (P > 0.05, Table 1). Specifically looking at each week, there was no adult emergence of exposed larvae after 2 or 4 wk after pyrethrin + pyriproxyfen aerosol treatment. At 6 wk post-aerosol treatment, there were only three bioassay arenas that had a single adult emergence of exposed larvae among all aerosol application locations and bioassay arena positions (application location 3, bioassay positions 1 and 10 and application location 1, bioassay position 10).

Adult Emergence after Pyrethrin + Methoprene Aerosol Application

For the control arenas, the overall average adult emergence of exposed larvae was >95% when all residual weeks and application locations were combined (n = 48). Therefore, no corrections for control mortality were made (Arthur 2008; Arthur et al. 2008, 2019). For the treatment dishes, all main effects and the interaction between bioassay position and application location were significant at P < 0.05, but all other interactions were not significant (Table 2). In general, as the time after aerosol application increased, adult emergence increased (Fig. 2). Among the combinations of aerosol application locations and bioassay positions, the impacts of treatment on percentage of adult emergence was highly variable, ranging from 0 to 100% (Fig. 2A–C).

After 2 wk post-aerosol treatment, application location 3 produced the largest variability in adult emergence, ranging from 0 to 100%, and the largest mean adult emergence, >60%, indicating that most bioassay positions had poor efficacy. After 2 wk, application location 2 had the lowest mean percent adult emergence (<25%) among all locations, but as the post-treatment interval increased, the mean percent adult emergence increased to ~40% at 6 wk post-treatment. In general, application 2 was the application location that had the lowest mean percent adult emergence and 75% of the bioassay arenas had <60% adult emergence of exposed larvae. This was in stark contrast to the low levels of adult emergence observed in arenas treated with pyrethrin + pyriproxyfen. Among all application locations, bioassay positions, and post-treatment weeks, there was only one bioassay position where there was no adult emergence of exposed larvae. This was aerosol application location 2 and bioassay position 2. Bioassay positions directly in front of aerosol application locations, in open or obstructed areas, and along walls all had adult emergences.

Contour Mapping of Efficacy Index Values

The pyrethrin + pyriproxyfen aerosol application had more even efficacy value distribution among all aerosol application locations and post-treatment times (Fig. 3) than the pyrethrin + methoprene formulation (Fig. 4). This can be observed by the range in efficacy values depicted for each insecticide as they varied over time and between application positions. At 2 wk post-aerosol treatment, the range in values is approximately 17–21 for all pyrethrin + pyriproxyfen application positions (Fig. 3). The range in values for the pyrethrin + methoprene formulations varies from 1 to 21 (Fig. 4). The high efficacy values and a narrower range in values across the mill floor is an indication that pyrethrin + pyriproxyfen had uniform coverage across all areas of the floor space and sufficient amounts of insecticide were deposited in those areas to adversely affect larval development. In contrast, the pyrethrin + methoprene insecticide had larger amounts of the floor space with low efficacy values, which indicated that there were arenas within the mill floor that did not receive enough pyrethrin + methoprene insecticide deposition to adversely affect the larval development. These locations were near the

Table 1. Three-way analysis of variance for the percentage of adult emergence after the pyrethrin + pyriproxyfen aerosol application the for the main effects of bioassay position, application location, and residual week

Factor	F	df	P
Bioassay position	0.78	9	0.6372
Application location	1.22	3	0.3047
Residual week	3.00	2	0.0535
Bioassay position × application location	0.98	27	0.5075
Bioassay position × residual week	0.78	18	0.7222
Application location × residual week	1.22	6	0.2996
Bioassay position × application location × residual week	0.98	54	0.5311

Overall control emergence was >97% among all arenas, and therefore, control data were not included for analysis.

Table 2. Three-way analysis of variance for the percentage of adult emergence after the pyrethrin + methoprene aerosol application and the main effects of bioassay position, application location, and residual week

Factor	F	df	P
Bioassay position	5.27	9	<0.0001
Application location	23.95	3	<0.0001
Residual week	18.83	2	<0.0001
Bioassay position × application location	6.02	27	<0.0001
Bioassay position × residual week	1.27	18	0.2188
Application location × residual week	1.34	6	0.2431
Bioassay position × application location × residual week	0.98	54	0.5254

Overall control emergence was >95% among all arenas, and therefore, control data were not included for analysis.

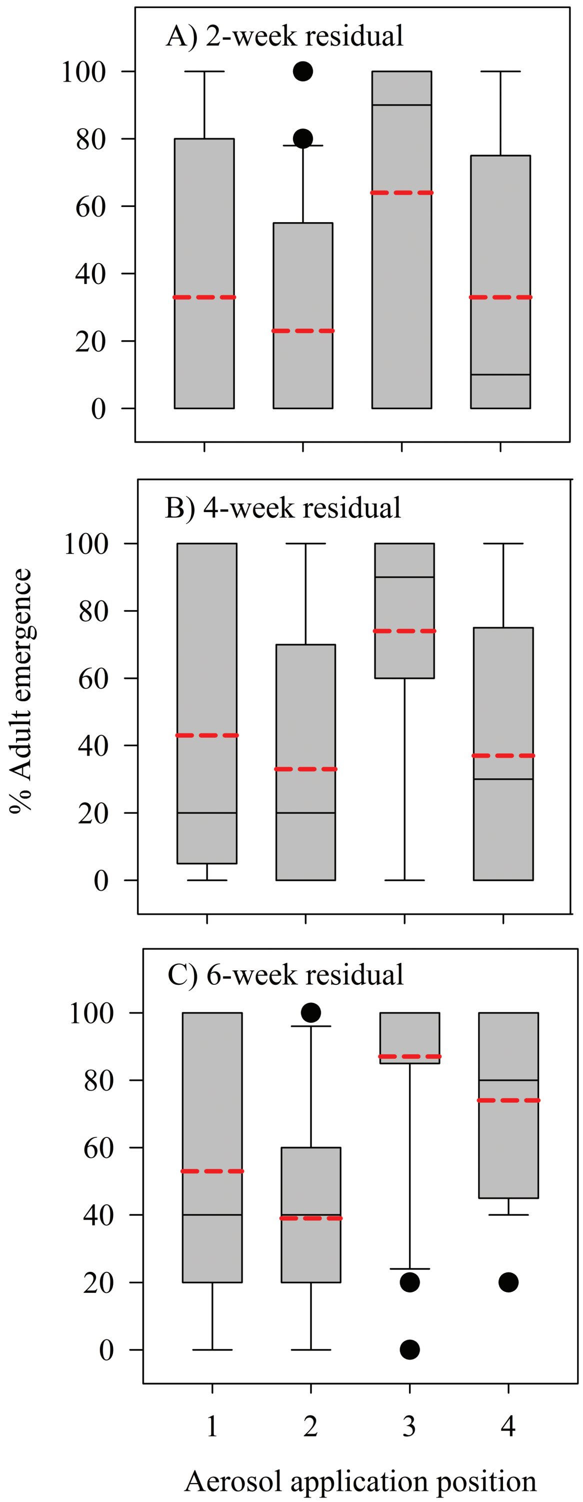

Fig. 2. Box plots of the mean percentages of *T. confusum* adult emergences after (A) 2 wk (*n* = 20); (B) 4 wk (*n* = 20); (C) 6 wk (*n* = 20) after pyrethrin + methoprene aerosol treatment among all bioassay position for each aerosol application location. The solid gray box represents the interquartile range, the solid black line represents the median (and if no line is shown the median is 0), the dashed line represents the mean, the whiskers above/below the gray box are the maximum and minimum percent adult emergences, and the black dots represent any outliers (1.5 times greater or lesser than the interquartile range).

most highly congested area of the floor, in corners, and areas farthest from the application position. As the post-aerosol application interval increased from 2 to 4 to 6 wk, we can observe the range in efficacy values changed among each aerosol insecticide formulation and application location. For the pyrethrin + methoprene aerosol application 4, the area of lower efficacy values (<7) increased from ~10% at 2 wk to 100% at 6 wk post-treatment. In comparison to the pyrethrin + pyriproxyfen formulation applied in the same way, the area of high efficacy (>15) was 100% of the floor space up to 6 wk post-aerosol treatment. Similar trends were observed for all other application positions.

The use of contour mapping helps aid in the understanding of how each aerosol insecticide performed over time when applied at specific location(s). This study illustrated that the pyrethrin + methoprene applied using a handheld fogger at multiple locations had very little effect on larvae after 6 wk post-treatment since 100% of the mill floor had efficacy values < 7. A value of <7 means at least two adults emerged at every bioassay location. In contrast, the pyrethrin + pyriproxyfen applied in multiple locations had an efficacy score >16 on 100% of the floor space at 6 wk post-aerosol application. This leads to the conclusion that using a multiple release application method for a cylinderized pyrethrin + pyriproxyfen aerosol formulation is more effective than a static location. Conversely, the multiple release application method using a handheld fogger performed the worst because not enough insecticide is being deposited to negatively affect larval development and further evaluation will be needed on ways to improve the coverage with this type of system. However, the pyrethrin + methoprene insecticide applied with a handheld fogger from position 2 had a range in efficacy values from 1 to 17, but approximately 75% of the floor space had a range of efficacy values of 7–16% or 2 or less emerged adults. Compared with multiple release application method, the static application of the insecticide was the most effective for this specific formulation and device. Ultimately, both the method/location of aerosol application and device used to deploy the aerosol play a significant impact on the residual component of the aerosol and how much product is being deposited around the floor space.

Discussion

The spatial distribution of the IGRs effect on *T. confusum* larvae was similar to the pattern of the pyrethrin's effect on adult *T. confusum* reported previously (Scheff et al. 2018). Adult *T. confusum* exposed directly in front of the aerosol or in open arenas of the floor space had greater adult knockdown or mortality compared with hidden areas or bioassay positions farthest from the aerosol discharge point (Scheff et al. 2018). The same trend was observed in the present study, whereby lower efficacy values were observed in locations where there was adult *T. confusum* recovery. Although we had predicted that spatial variation in IGR efficacy would be less than that for the pyrethrins, given the great sensitivity of the insects to IGRs, this was not the case. Variation in efficacy was most likely due to variation in amount of insecticide being deposited on surfaces resulting from how aerosol particles moved through the space. Areas of the mill floor near walls, corners, under heavily congested areas, or farther away from application location are likely getting less deposition. Arthur et al. (2018) reported a general decrease in estimated total deposition (mg/m^2) and % relative deposition (mg/m^2) as the distance increased from 4.3 to 13.5 m using the same two aerosol insecticides (pyrethrin + pyriproxyfen and pyrethrin + methoprene)

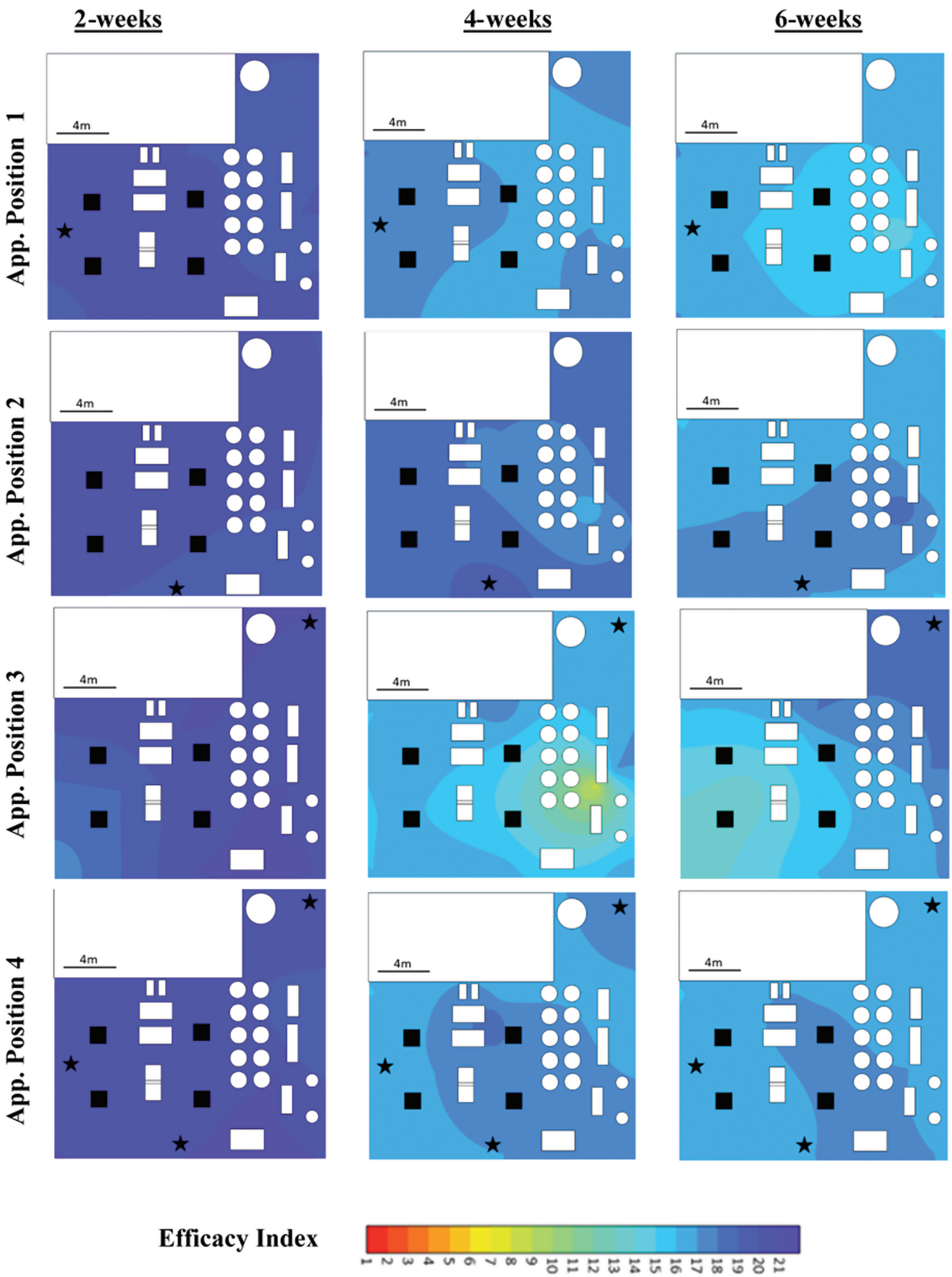

Fig. 3. Contour maps of the efficacy index values, range of lowest efficacy value of 1 to highest efficacy value of 21, for dishes containing five *T. confusum* larvae after 2, 4, or 6 wk after pyrethrin + pyriproxyfen aerosol application. The black boxes, white circles, and rectangles represent large structural features on the third floor such as support columns, milling equipment, sifters, and large storage bins. The black star represents the location of each aerosol application location.

used in the present study. Larger aerosol particles were deposited at the 4.3-m location compared with the 13.5-m location, and thus the total mass concentration was greater at the 4.3-m distance compared with the 13.5-m distance (Arthur et al. 2018). As aerosol particle size decreases, the effect on *T. confusum* larvae (or adults) also decreases because there is corresponding reduction in deposition of aerosol particles on a surface (Arthur et al. 2019). Taking this into consideration, the pyrethrin + pyriproxyfen aerosol application produced

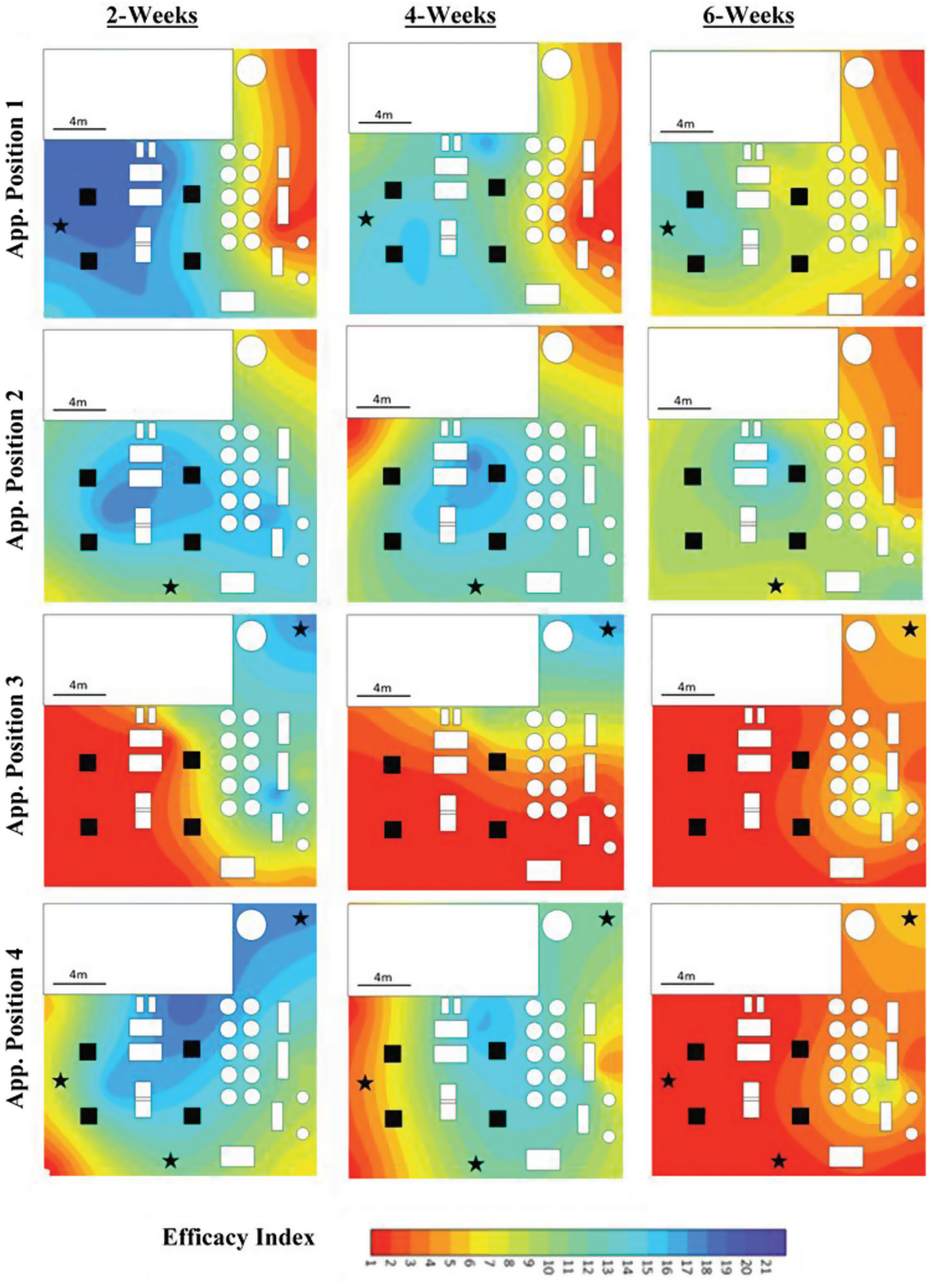

Fig. 4. Contour maps of the efficacy index values, range of lowest efficacy value of 1 to highest efficacy value of 21, for dishes containing five *T. confusum* larvae after 2, 4, or 6 wk after pyrethrin + methoprene aerosol application. The black boxes, white circles, and rectangles represent large structural features on the third floor such as support columns, milling equipment, sifters, and large storage bins. The black star represents the location of each aerosol application location.

particles sizes that not only deposited directly in front of the aerosol release location but could travel distances ~20 m away or in congested areas of the mill and deposit on surfaces in concentrations that were sufficient at inhibiting adult emergence. However, this was not the case for the pyrethrin + methoprene aerosol application. The most effective application position was at location 2, where distances within 13 m or unobstructed areas had the greatest efficacy.

The contour mapping approach used to report the effect of each aerosol formulation and application location was previously used by Campbell et al. (2014), to illustrate the effect of two different insecticide formulations. The first was pyrethrin + pyriproxyfen (Aerotech with NyGard, Chem-Tech, Des Moines, IA), which contained 0.7% AI pyrethrins, 5.0% PBO (synergist), and 0.2% pyriproxyfen. The second was pyrethrin + methoprene (Pyrocide 100, MGK, Minneapolis, MN), which contained 1.0% AI pyrethrin, 2.0% PBO, and 3.0% *N*-octyl bicycloheptene dicarboximide (synergist) and mixed with Diacon II (Wellmark, Schamburg, IL), which contained 33.6% AI *S*-methoprene. Each aerosol formulation was tested on exposed adult *T. confusum* ambient (22.7–28.7°C) and high temperatures (36.2–43.2°C), across three different floors of the same pilot-scale flour mill. Aerosols in the earlier study were applied from approximately the same location as aerosol application location 2 in the present study. Similar results were seen between the two previous studies (Campbell et al. 2014, Scheff et al. 2018) and the present study, whereby areas of low efficacy on larvae and adult *T. confusum* were near walls and locations farthest from the release position. These concepts can now be applied in other facilities that are conducting aerosol insecticide treatments. Aerosol application locations can be chosen within a floor space after pest management professionals identify areas with potential low efficacy areas and also use additional treatment options to control insects that may be found in those locations where aerosol cannot be deposited at levels that provide adequate efficacy.

The device by which each aerosol insecticide was applied can have an important impact on the movement of the particles and distance the particles are capable of dispersing. Each delivery system produces different particle size distributions, spray patterns, and release velocities, which will influence insecticide deposition over a given area and thus the residual efficacy on insect populations. These factors will in turn affect how the particles are distributed within a space. The pyrethrin + pyriproxyfen was formulated with a carbon dioxide (CO_2) carrier and held in a pressurized cylinder. Once the valve was release, the aerosol was quickly discharged at high pressure and the range in aerosol particle sizes could vary based on nozzle size, number of nozzles, height of application, and angle of application. The high pressure gives the aerosol particles greater inertia and would permit the larger particles to travel a greater distance before gravity pulls them to the ground. The contour maps highlighted this effect, by the fact that the range in efficacy index values was small which indicates there was sufficient insecticide deposited on testing arenas at even the greatest distances from the application location.

In contrast, the pyrethrin + methoprene was applied using a handheld fogger, which uses a motor and fan to apply the insecticide and as a result is likely to have larger particle sizes that fall out of the air faster compared with the cylinderized system of the pyrethrin + pyriproxyfen aerosol. The fan and motor system do not provide enough force to push the aerosol particles through the air and thus larger particles would deposit on only arenas nearest to the release point of the whereas the smaller particles would travel further before setting out due to gravity. This phenomenon could explain the differences between the resulting contour maps for each insecticide. The pyrethrin + methoprene application had significant areas of the floor space with low efficacy values, and as the post-exposure time increased, the areas of the floor space increased. A possible way to increase the distance the particles can travel before deposition on surfaces is to increase the angle at which the aerosol is applied. Particles will cover greater distances under an arc trajectory compared with a straight line. This could be a solution to increase deposition in hard to reach places or locations farthest away. Further evaluations as to the particle size ranges and distances particles can travel for each delivery system is needed to further understand their impact on particle deposition and result biological impacts. Understanding the distances the particles can travel in conjunction with published contour mapping could help pest management professionals to identify areas of the mill that might not get enough insecticide deposition because the distance is too great.

Conclusion

Ultimately, the multiple modes of action offered by a pyrethroid + IGR aerosol formulation are the key to managing populations of stored-product insects in a facility. By using a combination of bioassays and contour mapping, we can begin to understand how the complexity of the internal structure of food processing facilities combined with the application methodology and equipment used by pest management professionals affects treatment efficacy. Understanding the spatial variation and deposition of aerosol particles in a given space is valuable information for pest professionals, food quality and safety professionals, mill managers, and researchers. This study found that a multiple release application method provided the greatest residual effect on *T. confusum* larvae for the pyrethrin + pyriproxyfen aerosol. But for the pyrethrin + methoprene aerosol, applying the aerosol from a centralized location whereby most areas of the mill are <13 m away and have little obstructions to be the most beneficial application position, but further management techniques are needed in highly congested areas. This study, as well as other previous research, points out there are still areas of a facility that are hard to reach and control. Understanding that this can happen and determining where these locations are likely to occur can lead to improved application methods in order to obtain more consistent efficacy or the application of additional management tactics to target areas that do not receive adequate aerosol efficacy. These areas may also require additional spot treatments or more focused monitoring and sanitation. Ultimately, this can lead to more effective treatments with more consistent coverage and potentially use of less insecticide. In addition to further research into position of application on spatial patterns of efficacy and particle deposition, should also determine how coverage could be improved through changing the nozzle size or number of nozzles used and adjusting the height and angle of application.

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