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Assessing effects of esfenvalerate aerosol applications on resident populations of *Tribolium castaneum* (Herbst), the red flour beetle, through direct and indirect sampling

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ABSTRACT

Small-scale field sheds were infested to establish resident populations of the red flour beetle, *Tribolium castaneum* (Herbst), and either left untreated (control) or treated every two or four weeks with an aerosol spray of esfenvalerate (Conquer®). Prior to treatments, sheds were infested by placing flour (food) patches underneath shelves in the shed, and two trials were done in separate blocks. Aerosol efficacy was assessed using pheromone traps to estimate live adults (indirect sampling) and by collecting dead adults and estimation of eggs, larvae, pupae, and adults in the food patches (direct sampling). Beetle populations readily colonized the food patches, and overall populations of each life stage in the food patches were similar in the controls and in the 2- and 4-week aerosol treatments. However, the proportion of individuals in the egg and larval stages was greater in the control versus the aerosol treatments. There were more live adults trapped in the controls than in the aerosol treatments, with lower adult numbers in the two-week aerosol spray than in the four-week sprays, and more dead adults in the food patches in the control and 4-week spray than in the 2-week spray. Indirect sampling using pheromone traps gave consistent indications of aerosol efficacy, regardless of the extent of food patch colonization; however; the presence of the food patches allowed continued population development, and as a result the frequency of aerosol application had little impact on *T. castaneum* populations in the food patches.

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1. Introduction

The red flour beetle, *Tribolium castaneum* (Herbst), is a cosmopolitan stored-product insect that can infest raw grains, mills and processing plants, and finished food products (Rees, 2004). It is a major pest of flour mills in the United States, which have relied on fumigation of structures with methyl bromide as the primary management strategy (Campbell et al., 2010a,b). The worldwide phase-out of methyl bromide has led to increased research to examine and evaluate non-fumigant options for controlling *T. castaneum*, which include spray and aerosol applied insecticides. There are a number of laboratory studies that show pyrethroid insecticides such as cyfluthrin (Tempo®) will give residual control of adult *T. castaneum* (Arthur, 1998, 2000). Similarly, insect growth regulators such as hydroprene (Gentrol®) and pyriproxyfen (NyGard®) will give residual control through inhibition of the molting and developmental processes of immature stages of *T. castaneum* (Arthur, 2001; Arthur et al., 2009).

The presence of food sources can lead to increased survival of adult *T. castaneum* after they have been exposed to contact insecticides (Arthur, 2000). Food facilities also contain refugial areas where adult *T. castaneum* can escape exposure to a residual insecticide (Toews et al., 2005a,b). Insects may escape direct exposure because populations exist in inaccessible areas where insecticide applications do not reach or because only a small relative portion of the area inside a structure is treated (e.g., spot or crack and crevice applications). Because much of the insect population is in cryptic habitats, which may or may not be exposed to insecticides and which cannot be readily sampled, it is difficult to determine the efficacy of insecticide applications applied to structures (Arthur and Campbell, 2008). Recent studies with contact insecticides applied as surface treatments to limited areas document increased adult mortality and subsequent reduction in capture in traps, but limited control of resident populations of *T. castaneum* (Toews et al., 2005a,b, 2009).

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Insecticides applied as an aerosol can disperse throughout an area and may give more complete coverage than can be achieved with residual surface treatments. However, the ability of aerosol insecticides to impact populations or the cumulative impacts of multiple applications on populations has not previously been evaluated under controlled conditions. Different aerosol formulations of synergized pyrethrins have been shown to provide effective control of adult *T. castaneum*, but also show that the related species *Tribolium confusum* (Jacqueline DuVal), the confused flour beetle, is the more susceptible of the two species (Arthur, 2008). Toews et al. (2010) evaluated aerosol formulations of either synergized pyrethrins or the pyrethroid esfenvalerate (Conquer®) for direct mortality of different life stages of *T. castaneum*. In commercial food facilities, the presence of equipment, packages and structural features may hamper aerosol distribution, and thus provide refugial areas where insects can escape exposure (Arthur and Campbell, 2008). In addition, aerosol insecticides are often applied at regular intervals, so that the cumulative effect of repeated removal of a percentage of the population or the build up of insecticide residues needs to also be taken into consideration. The objective of the current study was to evaluate how the frequency of aerosol pyrethroid insecticide applications impacts *T. castaneum* population growth under simulated field conditions.

2. Materials and methods

This study was conducted in five wooden sheds that are part of the USDA-ARS Center for Grain and Animal Health Research (CGAHR), Manhattan, KS. Three of the sheds are 5.9 m long by 2.8 m wide by 2.0 m high (sheds 1–3) and two have slightly higher ceilings at 2.2 m high (sheds 4–5). The sheds were aligned east-west with the entry door at the west end, and each shed has a heat/air conditioning unit at the east end. The thermostat on the units was set at 25 °C, but actual air temperatures inside the shed generally ranged from 22 to 27 °C. The sheds have been used for a number of studies, and their construction and method of lining the interior has been previously described (Toews et al., 2005a,b, 2009). The exterior of the sheds consisted of framed white pine and plywood, had masonite exterior siding, and an asphalt shingled roof. Floors, walls, and ceilings of each shed were insulated and covered with interior plywood. The walls were also caulked and sealed and coated with food production grade paint primer and epoxy to seal cracks and crevices. Prior to the experiment, all interior surfaces of the sheds were covered with plastic sheeting (6 ml thick) and then the floor was covered with sheetrock. The panels on the floors were replaced, primed and painted to provide a finished floor surface, using commercial products as specified in Toews et al. (2009). Between each replicate of the experiment, plastic sheeting and floors were replaced to alleviate any residual contamination. Each shed contained three metal shelves (106.7 cm long by 44.3 cm wide by 11.6 cm tall) placed one each along the north and south sides about 2 m from the east end and 0.5 m from the walls, and one shelf placed midway along the east end about 0.5 m from the wall. A complete description of these shelves, along with figures showing placement of the shelves are provided in Toews et al. (2005a,b). Temperatures were monitored by placing a HOBO temperature-RH logger (Onset Computer Corporation, Bourne, MA, USA) in the approximate center of the floor of each shed. Twenty-four hours lights-on conditions were maintained using two 100-Watt incandescent bulbs mounted in the ceiling. These bulbs give 42.0 ± 2.6 lux ($n = 20$) at ground level (Toews et al., 2009).

The experiment was conducted using a *T. castaneum* strain originating from a flour mill in the central United States and established in laboratory cultures in 2001. The strain was reared on a diet of 95% unbleached whole-wheat flour and 5% Brewer's yeast, and reared under a 14–10 (L:D) photoperiod inside an incubator that maintained 27 ± 1 °C and 60 ± 2% relative humidity. Four food patches were placed in a row underneath each shelf and positioned about one meter from the wall. Each patch consisted of the bottom half of a plastic Petri dish (62 cm^2 in total area) containing 50 g flour and 17 each of 1-week old larvae, 3-week-old larvae, pupae, and adults. A strip of filter paper ca. 7.6 cm long and 1.9 cm wide, and folded at ca. 2.5 cm, was placed with the short end inside an individual dish and the long end touching the floor. The filter paper created a ramp to facilitate movement into and out of the food patches.

The insecticide used in the trials was the pyrethroid esfenvalerate (Conquer®, 3.5% active ingredient [AI], Paragon Professional Products, Memphis, TN, USA). Label directions for aerosol application of the product used in this study were to mix 296 ml of formulation in 3.8 L of oil solvent to give a 0.25% dilute spray, and apply this dilute spray at the rate of 29.6 ml/28.3 m^3. The oil solvent used for this test was Isopar M (Exxon Mobil Chemical Company, Houston, TX, USA). Given that the label is based on the volume of the space, and slightly different amounts of spray were applied to the different sized sheds. The applications were done by using a hand-held ultra low volume (ULV) mist sprayer (E2 MLDR Chemical Dispersal Unit, MicroGen Equipment Corporation, San Antonio, TX, USA). The sprayer flow rate was calibrated so that the smaller sheds were sprayed for 72 s and the larger sheds were sprayed for 85 s, which gave a target range of 30–35 g of insecticide dispensed for a single application. The person who applied the spray stood ~2 m inside the west end of the shed, held the sprayer at ~1 m off the ground, and operated the unit for the time intervals specified above.

The experiment was performed using two blocks. The first block was initiated on 14 November 2006 and the first spray treatment was done on 16 November 2006. In the first block, shed 1 was the untreated control, sheds 2 and 5 were sprayed every two weeks, and sheds 3 and 4 were sprayed every four weeks. The final spray for this first block was done on 29 March 2007. The final samples were taken on 26 April 2007, approximately 21 weeks after the start of experiment. Before the second block, the sheds were de-constructed and re-constructed as previously described. The second block was initiated on 23 June 2008 and the first spray performed on 25 June 2008. In this block, shed 2 was the untreated control, sheds 1 and 5 were sprayed every two weeks, and sheds 3 and 4 were sprayed every four weeks. The final spraying for this block was done on 15 October, and the final sampling was done on 29 October 2008, approximately 18 weeks after the start of experiment.

The sampling procedure was the same for both blocks, and consisted of weekly enumeration of the dead adults observed outside of food patches, sub-sampling of the beetle populations in the food patches, and indirectly monitoring adult activity using pheromone and kairomone baited traps. All dead adults on the floor of each shed and underneath the shelves were collected, counted, and discarded. Live adults in the sheds were monitored using plastic pitfall traps (Dome traps) baited with a commercial oil-based food attractant and an aggregation pheromone (Trécé Corporation, Adair, OK, USA) that were placed on floor in each corner of the sheds. The traps were sampled weekly, and captured adults were removed, counted, and discarded. To determine population levels in the flour food patches, a 1 g sample was taken from each of the four food patches underneath each shelf, and replaced with an equivalent amount of new flour. The four samples for each shelf were combined for analysis. The combined samples were weighed and sieved through a standard #60 mesh brass sieve (250 micron openings) to collect immatures and adults. The number of each developmental

stage was converted to individuals per gram of flour. The totals for the samples obtained from the food patches underneath each of the three shelves were considered as sub-samples in the statistical analysis.

Data for developmental stages present in the food patches (direct sampling) were first analyzed using the General Linear Models (GLM) Procedure in the Statistical Analysis System (SAS Institute, v. 9.1 Cary, NC, USA) to determine significance of main effects sample date (week after initiation of the experiment) and treatment, and associated interactions. Samples were taken from the food patches and flour was replaced, and the same patches were sampled each week. This sampling process was considered to be a repeated measure because samples were taken from the same food patches every time. Hence, the overall analysis was conducted with date as a repeated measure, which reduced the denominator degrees of freedom for the tests, to determine significance of treatment for each life stage and the total. When necessary for a particular analysis, treatment means were separated using the Waller–Duncan *k*-ratio *t*-test under the GLM Procedure in SAS. Data for number of live adults (indirect sampling) in the four pheromone traps in each shed were totaled to obtain one value per sample date. The number of dead adults underneath each of the shelves was combined into one value, which was in turn combined with the number of dead adults on the floor inside that shed. Two variables were analyzed, the number of dead adults under the shelves and all dead adults. Data for live and dead adults obtained from indirect sampling were pooled to obtain a total value per sample date, and analyzed using the SAS Procedures as described above for direct sampling.

3. Results

3.1. Direct sampling

Data for each life stage in the food patches underneath the shelves were first analyzed for differences between control and the two aerosol treatments, with an adjusted analysis to account for date as a repeated measure. For eggs, the main effect date was significant ($F = 4.1$, df = 20, 505, $P < 0.001$), but not treatment or the interaction of date and treatment ($F = 0.3$, df = 2, 51, $P = 0.712$ and $F = 0.3$, df = 40, 454, $P = 0.875$, respectively). Both date and treatment were significant for the main effects larvae ($F = 5.7$, df = 20, 466, $P < 0.001$; $F = 3.6$, df = 2, 54, $P = 0.032$), pupae ($F = 6.0$, df = 20, 266, $P < 0.001$; $F = 7.3$, df = 2, 54, $P < 0.002$), adults ($F = 11.7$, df = 20, 467, $P < 0.001$; $F = 4.4$, df = 2, 54, $P < 0.002$), and the total of all life stages ($F = 29.5$, df = 20, 454, $P < 0.001$; $F = 4.1$, df = 2, 51, $P = 0.023$). Interactions were not significant for any of the life stages (P values ranging from 0.153 to 0.999). However; the interaction between date and treatment was significant for the total of all life stages ($F = 1.8$, df = 40, 454, $P < 0.001$). Data for the larval, pupal, and adult stages, and the overall total, were next analyzed for significant differences among treatments for each date, with no significance with respect to treatment found for any of the individual life stages ($P \geq 0.05$). Data across all treatments were combined to show trends with time (Fig. 1). Because the first block ran for 21 weeks and the second block ran for 18 weeks, the analysis was done by using data only for the first block for including the extra three weeks. There were two peaks in numbers over time, the first a lower population peak for larvae and totals of all life stages at weeks 6–8 and a higher peak at the conclusion of the experiment.

Although treatment was not significant at an individual sample week, when data were averaged across all the sample weeks there was a significant difference with respect to treatment for all life stages (Fig. 2). The total population was greatest in the control

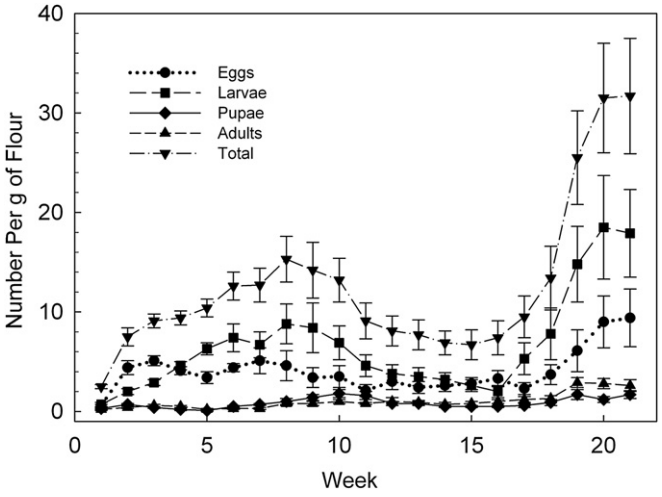

Fig. 1. Average number of eggs, larvae, pupae, adults, and total of all life stages combined, per g of flour in food refuges, with data combined across treatments. There were no significant differences for any developmental stage with respect to treatment ($P \geq 0.05$).

treatment, followed by the 4-week and then the 2-week aerosol spray treatments. For individual developmental stages, 2-week treatments were significantly lower than the controls, although differences with the 4-week treatments varied among the developmental stages (Fig. 2). Eggs and larvae were the predominant developmental stages recovered in the food patches and immature stages in total comprised about 90% of the total population in the food patches (Fig. 3). There were no differences in distribution among the developmental stages among treatments, except that the percentage of eggs was greater in 2-week treatment than in the control treatment.

3.2. Indirect sampling

The average number of adults caught in the traps differed among the treatments, with the most captured in the control treatment, and the least in the 2-week aerosol treatment (Table 1).

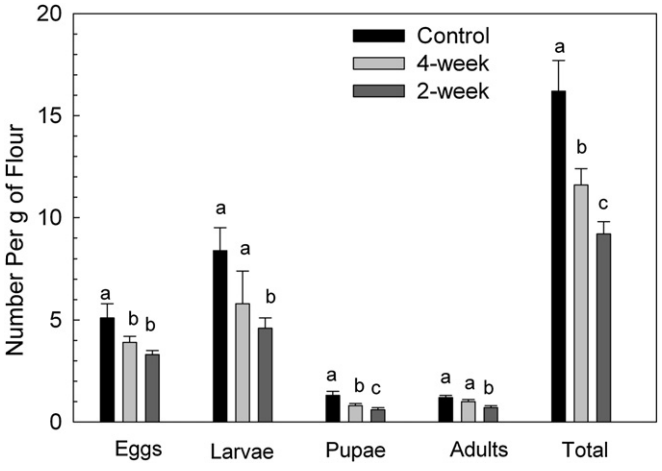

Fig. 2. Average number of each developmental stage for each treatment (control, 4- and 2-week interval aerosol sprays of esfenvalerate), averaged across sample dates (mean ± SE). Means with the same letters are not statistically different ($P \geq 0.05$). Statistical model data for eggs, larvae, pupae, adult, and totals are respectively $F = 4.1$, df = 2, 565, $P = 0.017$; $F = 7.0$, df = 2, 580, $P < 0.001$; $F = 15.2$, df = 2, 581, $P < 0.001$; $F = 6.9$, df = 2, 581, $P < 0.001$; $F = 13.0$, df = 2, 565, $P < 0.001$.

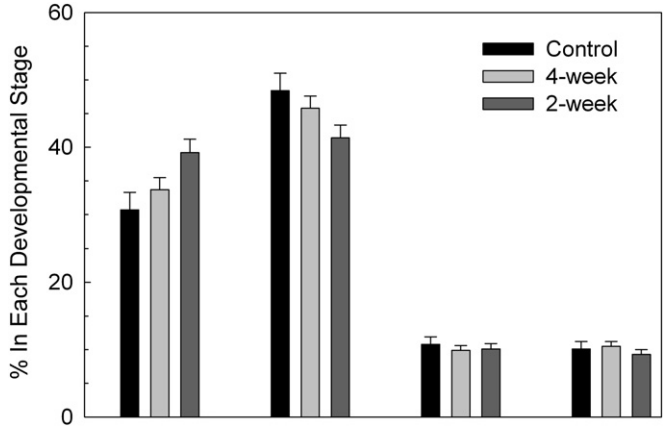

Fig. 3. Percentage of individuals in each developmental stage for each treatment (control, 4 and 2-week interval aerosol sprays of esfenvalerate), averaged across sample dates (mean ± SE). Means with the same letters are not statistically different ($P \geq 0.05$). Statistical model data for eggs, larvae, pupae, and adult are respectively $F = 3.8$, $P = 0.021$; $F = 3.7$, $P = 0.069$; $F = 0.2$, $P = 0.793$; $F = 0.8$, $P = 0.427$ (df = 2, 564 for all).

The total number of adults captured in the traps varied considerably between the two blocks of the experiment for the controls, 266 in block 1 and 723 in block 2. For the treatment sheds, the average total number captured tended to be lower in the two-week sprays (400 and 492 captures) compared to the 4-week aerosol treatment (139 and 189) for blocks 1 and 2, respectively. The temporal patterns of beetle captures were different between blocks as well. In block 1, captures were low, <2 adults per trap in all treatments, until after 15 weeks when there was an increase in captures in the controls and 4-week aerosol treatment, but not in the 2-week aerosol treatment (Fig. 4A). At the final sample week, significantly more adults were collected in the traps in the control shed, 21.5 ± 4.5, compared to 8.7 ± 3.7 and 2.9 ± 2.2 in the 2 and 4-week aerosol spray sheds, respectively. This was the only time a significant difference occurred between treatments. In block 2, captures in traps were greater from the start of the experiment and on most of the sample dates the captures in the control were greater than in either of the aerosol treatments, with a trend for the 2-week aerosol treatment to always have the lowest mean capture even though it was never significantly different from the 4-week treatment interval (Fig. 4B). In the control shed, adult captures appeared to exhibit two distinct peaks, which was similar to the population trend in the flour patches.

The numbers of dead adults in the flour patches and the number of dead adults on the floor were compared for differences among treatments by averaging over all sample dates. There tended to be more total dead adults (underneath the sheds and on the floor) found on the floor of the sheds in the 4-week aerosol compared to the control treatment, while the 2-week aerosol treatment was not different from the other two (Table 1).

Table 1
Number of adult *T. castaneum* caught in pheromone traps, number of dead adults underneath the shelves, and overall number of dead adults (mean ± SE) for each treatment (control, 4 and 2-week aerosol sprays of esfenvalerate), averaged across sample dates (mean ± SE). Means with columns followed by the same letters are not statistically different (statistical model data for captured adults, dead adults under shelves, and dead adults (on floor and underneath shelves) are respectively $F = 22.8$, $P < 0.001$; $F = 4.2$, $P = 0.017$, $F = 4.1$, $P < 0.019$ (df = 2, 192 for all)).

	Adults captured	Dead adults under shelves	All dead adults
Control	25.4 ± 3.4a	7.9 ± 1.5b	23.5 ± 4.1b
4-week	11.5 ± 1.9b	14.1 ± 1.7a	41.9 ± 4.2a
2-week	4.2 ± 1.8c	9.8 ± 1.2ab	34.2 ± 3.6ab

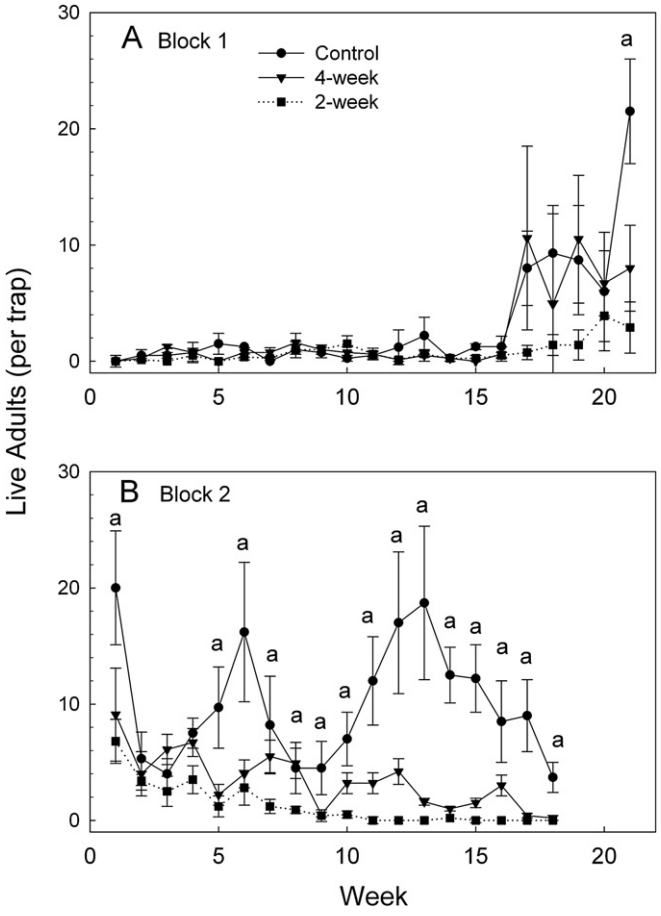

Fig. 4. Average number of live adults caught in pheromone traps for each sample week in block 1 (A) and block 2 (B). Differences among treatments ($P < 0.05$) are denoted by a lower case "a" with the control mean. No significant differences occurred between the 2 and 4-week aerosol treatments ($P \geq 0.05$).

4. Discussion

The results of this study show that the aerosol applications of esfenvalerate reduced the total population size of *T. castaneum*, with more frequent applications resulting in a greater reduction. However, the populations were highly variable among sheds and between blocks, and the overall average reduction due to treatment was moderate. The presence of greater reductions in some replicates suggests that under certain conditions the impact of these treatments can be greater, but further research is needed to determine what contributes to this variation. Beetle captures in traps and observation of dead adults in the current study tended to more accurately reflect total population trends, which is different from our earlier study in which the contact insecticide cyfluthrin was applied to surfaces in bands around shelves that contained food patches (Toews et al., 2005b). In that study, total population was not impacted by the insecticide treatment and there were generally more dead adults on the floor and fewer beetles captured in traps in the insecticide treatment compared to the control treatment. These differences could result from the aerosol applications providing more surface coverage, including drift under the shelf units. The repeated applications of the aerosol may have also been a factor, though the frequency of applications (2-weeks vs. 4-weeks) did not affect population development.

In both studies, cyclical population development was noted and generally changes in the dead adults and number of adults

captured in traps reflected these trends. However, this was not always the case and in block one captures in traps tended to be low until the very end of the experiment and dead adults on the floor were sometimes more abundant in treatments with lower total populations. Both this study and the earlier Toews et al. (2005b) study have shown that the presence of dead adults may not be a good indicator of actual population density and in addition pheromone captures may not always accurately reflect the true population size. Aerosol applications appear to disproportionately affect the adult life stage. Also, this trend of fewer dead adults in the 2-week aerosol treatment might be related to it having a lower total population size, and hence a lower number of adults, compared to the 4-week aerosol and control treatments.

There were unexpected differences between the two blocks, with greater dispersal and lower total population levels in one block relative to the other and also variation among the individual replicates within a treatment. The discrepant colonization patterns between the two blocks appear to be due to poor initial establishment in the flour patches but the cause of this cannot be attributed to a single factor. Differences may relate to dispersal patterns as a function of outside temperature, inherent differences between the colonized beetles at different times of the year, or a difference in food quality. Inside temperatures ranged from 22 to 27 °C in both blocks and hence did not appear to be a factor in the discrepant dispersal patterns. Overcrowding and depletion of a food resource can cause increased dispersal of adult *T. castaneum*, but because this pattern was observed early in the experiment, and because at each sample period flour was replaced this does not seem to be an important factor. Also, this pattern has not been observed in other experiments using a similar protocol. Female *T. castaneum* disperse among resource patches and adjust the level of oviposition in food patches to match resource availability (Campbell and Hagstrum, 2002; Campbell and Runnion, 2003). Thus differences in colonization might be related to differences in beetle assessment of resource quality between blocks.

In the current study, and in the earlier Toews et al. (2005a,b, 2009) studies, the insecticide treatments caused an increase in adult mortality, but had limited effect on the total population levels. The presence of food material in refugia not being directly treated with insecticide enabled populations to persist and develop so that adult mortality had little impact on overall populations in the experimental sheds. This could be because surviving adults compensated for the lost individuals through increased oviposition or the reduced number of adults could mean less cannibalization of earlier stages. These factors together may have resulted in increased survival of immatures to the adult stage. Another possibility is that there may have been an excess number of adults for the amount of food material and its level of exploitation; so that adults were not ovipositing in the resource patches. The amount of food material has important implications for pest population growth and the effectiveness of insecticides. In this shed study the amount of food was held constant through addition of fresh flour at each sample date. This may differ from some situations in the field where resource quality may decline as the insects exploit that resource. Several recent studies have documented that the presence of food material either during or after exposure to aerosol insecticides can lead to increased adult survival (Arthur, 2008; Arthur and Campbell, 2008; Toews et al., 2005a,b, 2009). Other patterns of flour distribution and the addition of more food material over time might have resulted in a different impact of the insecticide treatments. Improved sanitation could lead to lower populations of *T. castaneum* by reducing available food resources and increasing beetle dispersal and the corresponding increase in contact with insecticide, but complete elimination of all sources within an active commercial flour mill may not be possible (Toews et al., 2009).

Improved sanitation and aerosol insecticide treatments appear to moderate population fluctuations in *T. castaneum* and reduce the need for whole plant treatments, including fumigation (Campbell et al., 2010a,b). In the current study, regular esfenvalerate aerosol applications did not eliminate any of the populations, but appeared to compress the more extreme population fluctuations that were observed in the controls. Complete control may not have been achieved because immature life stages of *T. castaneum* escaped exposure to the aerosol because the aerosol did not disperse completely under the shelves or by moving to a lower depth in the flour food patches. Esfenvalerate applied as an aerosol may not show residual efficacy, hence any mortality would likely be due to direct exposure to the aerosol during treatment (Toews et al., 2009) and the population would have temporal refugia from exposure to the insecticide. This could also contribute to reduced impact of the insecticide treatments.

Use of aerosol insecticides with more of an impact on the hidden immature populations and/or greater residual activity might provide more of an impact on the total population. The insect growth regulator (IGR) methoprene has residual efficacy, and combination treatments of pyrethrin or pyrethroids plus methoprene are used in pest management programs for flour mills and food warehouses (Sutton et al., 2011). The commercial flour mill described in Campbell et al. (2010a,b) had for several years used at regular intervals a combination of 1% AI or 3% AI pyrethrin plus the IGR methoprene, combined with an emphasis on sanitation, as part of their pest management program. As a result, population levels of *T. castaneum* decreased so that the need for fumigations was reduced. In expanded field studies at the same site, Sutton et al. (2011) exposed whole-wheat flour and various packaging surfaces to combination treatments with 1% AI or 3% AI pyrethrin plus methoprene. Bioassays were conducted by exposing late instars of *T. castaneum* at 0–16 weeks post-application on these different treated surfaces, and the result was less than 1% emergence of morphologically normal adults for the duration of the test.

The relationship between pheromone trap catch and the true population in stored product environments, including flour mills and food warehouses, has been discussed and debated in many recent publications (Toews et al., 2005a,b; Campbell and Arbogast, 2004; Campbell et al., 2010a,b). The multiplicity of factors influencing catch of *T. castaneum*, including temperature, population density, differences in population development at different times of the year, as may have occurred in our study, and the availability of alternate food resources, makes it difficult to determine the relationship between adult trap catch and the total population at a site. In our test, the different dispersal patterns between the two blocks affected the number of live adults caught in the traps. The outcome of this difference in dispersal may have been different in the larger spatial structure of a flour mill or food warehouse which would have provided many more opportunities for dispersing individuals to find resources to infest and locations for refugial populations of stored product insects to persist (Barson, 1991; Cox and Parish, 1991; Cox et al., 1997; Campbell et al., 2010a,b). In the current study, the proportion of adult *T. castaneum* in the food patches comprised only about 10% of the total population, so pheromone baited traps that capture adults are only sampling a fraction of the total population. Thus, conclusions about the total population based on adult captures or observations of adult mortality need to be carefully considered because they can be easily misleading (Toews and Nansen, 2012).

Given the difficulties in relating captures in traps, more emphasis should be placed on examining trends in population development, rather than attempting to relate trap catch to the true

population in a stored-product environment. Consistent sampling of food patches in field sites to assess population development of *T. castaneum* would not be practical because of the emphasis on reducing the resident populations through cleaning and sanitation and the inaccessibility of the remaining infested patches. Hence, pheromone trapping of adult *T. castaneum* through some type of continuous monitoring program provides a basis by which insecticidal treatments, including aerosols, can be evaluated. Campbell et al. (2010a,b) described how a continuous monitoring program could be used to assess the prevalence of *T. castaneum* within a flour mill. They also proposed a threshold of 2.5 adults per trap per day that could be used as a risk threshold, where maintaining captures below this level was associated with less risk of large increases in captures. The impact of using aerosols to suppress fluctuations in insect abundance is consistent with the use of this type of management threshold. Our study shows that resident populations of *T. castaneum* in relatively simple storage structures could be suppressed using aerosol treatments, but the populations were clearly not eliminated. The data indicated that captures in pheromone traps provided a measure of aerosol efficacy and evidence that the *T. castaneum* populations continued to fluctuate with or without aerosol treatments. Long term continuous monitoring programs are necessary to provide the basis by which aerosol efficacy can be properly assessed.

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