Long-Term Monitoring of *Tribolium castaneum* Populations in Two Flour Mills: Rebound After Fumigation

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ABSTRACT Structural fumigations of food processing plants to manage stored-product insects has been a major component of pest management programs, but limited information on field efficacy is available. Efficacy, based on pheromone trapping data, consists of initial reduction in captures after treatment and rebound in trap captures over time. Pattern of *Tribolium castaneum* (Herbst) rebound was evaluated after 21 fumigations in two flour mills. Rebound in mean number of beetles captured and the probability of a trap capturing one or more beetles was evaluated. Rebound to a threshold mean beetle capture of 2.5 beetles per trap per 2-wk period took 174 ± 33 d and rebound took longer after fall (248 ± 50 d) than spring (104 ± 21 d) fumigations. Rebound to the probability of capture threshold of 0.50 was 120 ± 21 d, but there was no significant effect of season. Improvement in integrated pest management (IPM) practices in one of the mills was associated with an increase in time to reach mean beetle capture threshold (49 ± 15 d before and 246 ± 71 d after) but not in time to reach the probability of capture threshold (38 ± 14 d before and 165 ± 46 d after). There was a negative correlation between number captured after fumigation and time to rebound to threshold. After improved IPM there was a significant reduction in the number of beetles per trap immediately after fumigation. Above these two thresholds the degree of change in trap captures is significantly greater than below, which suggests they might be useful in evaluating risk in a pest management program.

KEY WORDS *Tribolium castaneum*, flour mill, population dynamics, pheromone trapping, fumigation

Evaluation of tactics for managing pest populations in food facilities such as mills, processing plants, and warehouses is challenging. Pest populations are spatially and temporally patchy with many individuals exploiting cryptic habitats. In addition, insect harborages are often unknown and inaccessible, so that evaluation of population trends is difficult (Campbell 2006). Pheromone trapping programs are widely used to determine temporal and spatial patterns in pest populations in food facilities (Arbogast et al. 2000, Doud and Phillips 2000, Campbell et al. 2002, Roesli et al. 2003, Campbell and Arbogast 2004, Campbell and Mullen 2004, Toews et al. 2006, Trematerra et al. 2007), even though the relationship of trap capture to total abundance or spatial distribution of pest populations is difficult to define (Toews et al. 2009). It is also difficult to replicate treatments to evaluate efficacy in commercial food facilities because each facility has unique characteristics that are often not stable over time. Small-scale laboratory studies that can be replicated typically do not adequately simulate the spatial and temporal patterns of exposure to treatments that occur under more real-world conditions (Toews et al. 2009). In commercial food facilities it is also difficult to isolate the effects of a pest management tactic because a range of interventions and operational procedures are ongoing within a facility that can impact pest populations. As a consequence of these issues, pest management in the food industry often relies on calendar-based application of pesticides or other control tactics, with limited evaluation of overall pest population dynamics or use of this information to guide management decisions.

Historically, the major management tool for stored-product insects in food processing plants has been periodic structural fumigation with methyl bromide (Fields and White 2002). Although there have been laboratory evaluations of fumigation efficacy (Bell 1988), there is little published information on efficacy

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of structural fumigation of processing plants (Campbell et al. 2002, Campbell and Arbogast 2004, Toews et al. 2006, Small 2007). Methyl bromide has been identified as an ozone-depleting substance and its use is being phased out worldwide under the 1987 Montreal Protocol on Substances that Deplete the Ozone Layer. Because of the high treatment costs associated with declining supplies of methyl bromide for application under critical use exemptions (CUEs) and high costs of alternative tactics such as sulfuryl fluoride or high temperature, there is increasing interest in reducing the need for structural treatments. Baseline information on the efficacy of fumigations and the factors that impact efficacy is needed to facilitate this move away from reliance on methyl bromide.

The management of red flour beetle, *Tribolium castaneum* (Herbst), and confused flour beetle, *Tribolium confusum* Jacquelin du Val (Coleoptera: Tenebrionidae), in flour mills is one area where CUEs currently permit methyl bromide use within the United States, although other countries around the world have stopped using methyl bromide in these facilities. The primary alternative structural treatments are the fumigant sulfuryl fluoride and high temperature. Structural treatments are expensive to perform both in terms of the treatment costs and in lost productivity associated with shutting down facilities that typically run 24 h a day and 7 d a week. Integrated pest management (IPM) programs that reduce insect populations below levels where a structural treatment is needed or at least decrease the frequency of treatments, might make alternatives more economically viable and be less disruptive to production practices. Adoption of these alternatives requires a better understanding of pest population dynamics, which in turn requires better use of monitoring tools and integration of the information they generate into programs. Information on pest population trends can also help in more effectively using structural treatments, such as fumigation by optimizing fumigant applications (Chayaprasert et al. 2009), fumigating at appropriate times of year, and not fumigating unless threshold population densities are reached.

Assessment of treatment efficacy in a food facility consists of two components—the immediate reduction in insect abundance and the population rebound, or recovery in numbers over time after treatment. In Campbell et al. (2010), long-term monitoring data sets from two commercial mills were used to evaluate *T. castaneum* captures in traps and the impact of fumigation treatments on the immediate reduction in captures. Here, using the same data, we focus on how *T. castaneum* captures increased after structural fumigation to evaluate long-term population rebound. Monitoring data from 21 complete periods between fumigations is analyzed in this study. In addition, we examined how rebound rate is influenced by time of year the fumigation is performed and IPM program being used in the mill. This unique data set also enables us to explore the idea of management targets for flour mills based on the pattern of increasing risk of rapid population growth and how they might be used in guiding pest management programs.

Materials and Methods

Flour Mills. More detailed information on the mills and the management tactics used can be found in Campbell et al. (2010). Mill 1 was a wheat flour mill (≈4,500 m^3) that consisted of five floors and was attached to an elevator with bulk grain storage silos and a packaging/warehouse building. Eleven structural fumigations were performed (nine with methyl bromide and two with sulfuryl fluoride (ProFume; Dow AgroSciences, Indianapolis IN) in a period between July 2002 and December 2008, with 10 complete periods between fumigations with which to evaluate rebound. Methyl bromide fumigations typically used a rate ranging from 20 g/m^3 (1.25 lb/1,000 $feet^3$) to 26 g/m^3 (1.61 lb/1,000 $feet^3$) for 24 h, and the two sulfuryl fluoride fumigations were at a low rate of 32 g/m^3 (2 lb/1,000 $feet^3$), 19-h exposure, and a high rate of 111 g/m^3 (6.9 lb/1,000 $feet^3$), 18-h exposure. At mill 1, an improved IPM program was instituted after November 2004. This improved program included the installation of an aerosol application system with nozzles on each floor that were used to apply either 1 or 3% synergized pyrethrins (Entech Fog-10 or Entech Fog-30, Entech Systems, Kenner, LA) (1.0 ml/m^3) and methoprene (Diacon II, Wellmark International, Schaumburg, IL) (0.01 ml/m^3) at 2–4-wk intervals. IPM was further improved by enhanced sanitation that included targeting treatment of hot spots (located by trapping) through cleanup or application of insecticides. This change provided a unique opportunity to determine whether rebound rate was affected by improvements in the IPM program.

Mill 2 was a wheat processing facility (≈11,200 m^3) that consisted of five floors, with a structure for producing a grain-based product and a warehouse attached. Also located on the property were office and receiving buildings, a feed mill (operational during part of the study), and an energy production facility. Between March 2003 and December 2008, this mill underwent 12 structural fumigations, with 11 complete interfumigation periods of monitoring data. Mill 2 was fumigated twice a year with methyl bromide—in the spring and the fall (typically 24 g/m^3 [1.5 lb/1,000 $feet^3$] and ≈20-h exposure times).

Insect Monitoring Program. *T. castaneum* adults inside the mill were monitored using pitfall traps (Dome traps, Trécé Inc. Adair, OK) placed on the floor. These were baited with pheromone lures (Trécé Inc.) for *Tribolium* spp. (*T. castaneum* and *T. confusum*) and a kairomone attractant (Trécé Inc.). There were 55 trapping locations, 11 per floor in mill 1, and 32 trapping locations in mill 2, five traps per floor for the first, second, and fourth floors and six traps per floor for the third and fifth floors. Two measures of *T. castaneum* captures in traps were used: the average number of beetles captured per trap per standardized 2-wk period (beetles per trap per period) and the proportion of the traps that captured one or more beetles per

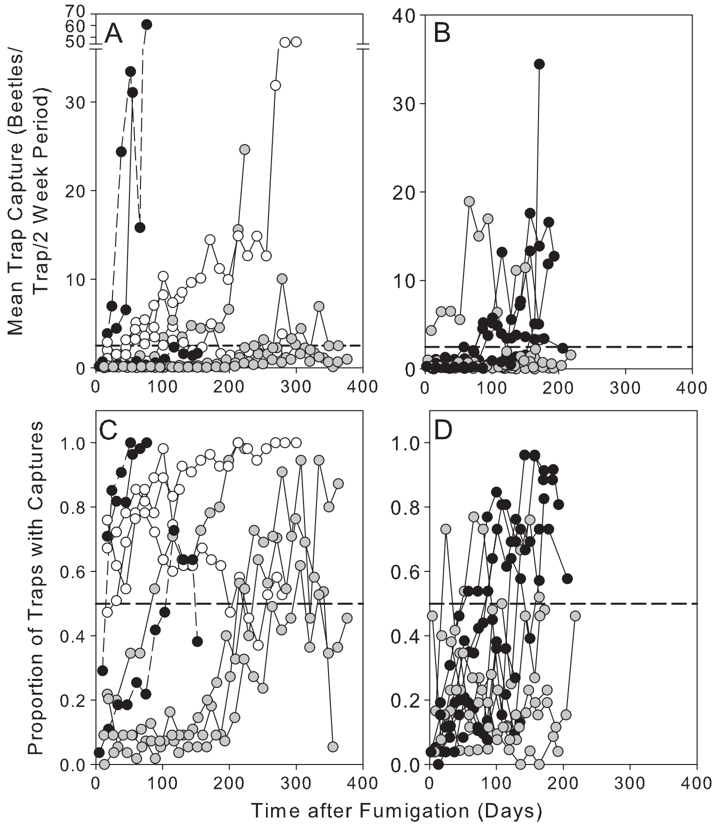

Fig. 1. Rebound in *T. castaneum* mean trap capture in mill 1 (A) and mill 2 (B) and rebound in proportion of traps with captures of one or more beetles in mill 1 (C) and mill 2 (D). Time has been standardized to d after fumigation so that different fumigations can be aligned. Black circles indicate captures after spring fumigations, white circles indicate summer fumigations, and gray circles indicate fall fumigations. Solid lines indicate rebound after methyl bromide fumigations and dashed lines indicate rebound after sulfuryl fluoride fumigations. Dashed horizontal reference lines indicate threshold values used in analysis: 2.5 beetles per trap per 2-wk monitoring period for mean trap capture (A and B) and 0.50 for the probability of capture of one or more beetles in a trap (C and D).

standardized 2-wk period (i.e., probability of capture). More detailed information on the monitoring program is provided in Campbell et al. (2010).

Statistical Analysis. Regression analysis of rebound data were performed using TableCurve 2D software (Systat Software Inc., Chicago IL). Survival or time-to-event analysis, including Kaplan–Meier analysis using the log-rank test, Cox Proportional Hazards model with likelihood ratio test, and paired tests were performed using the statistical package of SigmaPlot version 11 (Systat Software, Chicago IL). For comparison of data before and after management changes, General Linear model Procedure (GLM) was performed using SAS version 9 software (SAS Institute, Cary, NC). Proportional data were arcsine square root transformed before analysis, but untransformed data are presented. All data are presented as mean ± SEM.

Results

Rebound After Fumigation. Rebound rate in mean trap capture and probability of capture varied considerably among the fumigations (Fig. 1). As a result, there was no significant linear or nonlinear regression model that fit the combined data from all the fumigations for either trap capture measurement using either each mill separately or the two mills combined ($P > 0.05$). Looking at time periods between fumigations individually, linear and/or exponential functions typically provided a significant model fit to trap captures after fumigation, but no single function fit all fumigations well and models typically were not very predictive (i.e., low r^2 values). In some cases, poor model fit occurred because the mill was fumigated again before captures could increase sufficiently to fit a regression or because the captures fluctuated, probably due to other management tactics. Therefore, we developed threshold values and analyzed the time to reach the first monitoring period that matched or exceeded those thresholds as a measure of rebound rate. For mean trap capture the threshold of 2.5 beetles per trap per period was used, which corresponded to the median value for the combined mills of mean trap capture in the monitoring period immediately before fumigation. For probability of capture, the threshold of 0.50 was used, which corresponds to the median

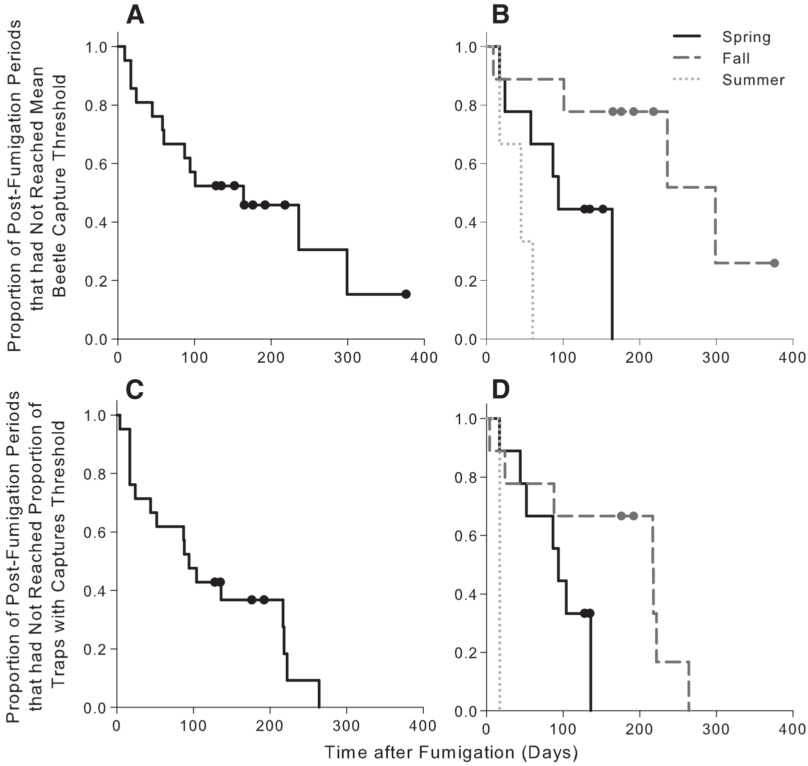

Fig. 2. Time-to-event (survival) curves for the time after fumigation for *T. castaneum* captures to reach the thresholds for (1) mean trap capture of 2.5 beetles per trap per wk (i.e., median mean trap capture before fumigation for the combined mills) (A and B) and (2) proportion of traps having a capture of one or more beetles reaching 0.50 (i.e., median proportion of traps with captures before fumigation for the combined mills) (C and D). Data are combined from both mills and in graphs B and D the fumigations are sorted by season. Circles indicate censored data (i.e., fumigations occurred before the mill reaching the threshold value).

value for the combined mills of the proportion of traps with captures of one or more beetles immediately before fumigation. Time-to-event (survival) analysis was used to analyze rebound to threshold, because fumigations sometimes occurred before threshold values were reached, resulting in what is termed censored data or data that have not reached an event before the termination of the observation (e.g., fumigation occurred before reaching threshold).

The two mills did not differ from each other in the time required to reach the mean trap capture threshold (Kaplan–Meier log-rank test: $Z = 0.702, P = 0.402$): 148 ± 46 d ($n = 10$) and 154 ± 25 d ($n = 11$), for mills 1 and 2, respectively. These means are biased, because mill 1 had two censored observations and mill 2 had six censored observations. The two mills also did not differ from each other in the time to reach probability of capture threshold ($Z = 0.242, P = 0.622$): 101 ± 31 d ($n = 10$) and 131 ± 27 d ($n = 11$), for mills 1 and 2, respectively. Mill 1 always reached the threshold value before fumigation, whereas mill 2 on four occasions was fumigated before reaching the threshold. Combined data from both mills was used for the subsequent analyses.

For rebound to the mean trap capture threshold, the biased mean (biased because maximum time was used for the censored observations, but these are less than the actual time to reach threshold if fumigation had not occurred) for the combined mills was 174 ± 33 d ($n = 21$, censored observations = 8) (Fig. 2A). Time to reach mean trap capture threshold varied among seasons (spring, summer, and fall) ($Z = 10.389, P = 0.006$) (Fig. 2B). Because summer fumigations were applied only in mill 1 and because spring and fall fumigations are more typical, further analysis was focused on just these two seasons. There was a difference in the rebound to mean trap capture between spring and fall fumigations ($Z = 4.122, P = 0.042$): 104 ± 21 d ($n = 9$, censored events = 3) and 248 ± 50 d ($n = 9$, censored events = 5) for spring and fall fumigations, respectively. Including mean trap capture before and after fumigation, percentage of reduction in trap captures, proportion of traps with captures before and after fumigation, and percentage of reduction in proportion of traps with captures as covariates in a Cox Regression Proportional Hazards model indicated that the hazard rate was significantly affected only by the mean number captured before fumigation (hazard ratio = 1.176) (likelihood ratio test statistic = 28.682, $P < 0.001$).

For rebound to the probability of capture threshold, the biased mean for the two mills combined was 120 ±

21 d (n = 21, censored observations = 4) (Fig. 2C). Time to reach threshold varied among seasons (spring, summer, and fall) (log-rank test statistic = 9.391, P = 0.009) (Fig. 2D). Focusing just on spring and fall seasons, even though the trend was similar to that for mean trap captures there was not a significant difference between seasons (log-rank test statistic = 3.752, P = 0.053) (66 ± 15 d [n = 9, censored events = 1] compared with 160 ± 37 d [n = 9, censored events = 1], for spring and fall fumigations, respectively). The Cox Regression Proportional Hazards model with the covariates described above showed that the hazard rate was not significantly affected by any of these covariates (likelihood ratio test statistic = 11.035, P = 0.087).

Two of the fumigations at mill 1 were performed with sulfuryl fluoride, although at different rates. Beetle captures after the low rate rebounded more rapidly than captures after the high rate. The time required to reach the mean capture and probability of capture thresholds was 24 and 52 d, respectively, for the low rate and 152 (censored data because a fumigation was performed before reaching threshold) and 104 d, respectively, for the high rate. A spring methyl bromide fumigation at mill 1 also rebounded rapidly; 17 d, or one monitoring period, to reach both thresholds. The rebound to mean trap capture threshold for all methyl bromide fumigations was 176 ± 34 d (n = 19, censored events = 7) and for only spring methyl bromide fumigations it was 106 ± 23 d (n = 7, censored events = 2). For the proportion of traps with captures, rebound to threshold for all methyl bromide fumigations was 124 ± 23 d (n = 19, censored events = 4) and for only spring fumigations it was 93 ± 19 d (n = 7, censored events = 2). Due to the limited replication with the sulfuryl fluoride fumigations, formal comparisons are not possible but the general trends justify the combining of two different fumigants in the overall analysis.

Impact of Change in IPM Practices on Population Rebound in Mill 1. Improvement of IPM practices in fall 2004 was followed by reduced trap capture and reduced probability of capture. The decline in mean capture during a monitoring period was from 10.8 ± 1.7 (n = 57) before to 1.2 ± 0.1 (n = 111) beetles per trap per monitoring period after improvement (F = 64.91; df = 1,166; $P < 0.001$). The probability of capture also declined significantly, from 0.80 ± 0.03 (n = 57) before to 0.36 ± 0.03 after the change (F = 111.27; df = 1,166; $P < 0.001$). There was also a reduction in the level that trap captures reached by the time of fumigation. Mean capture at time of fumigation was 30.4 ± 8.1 beetles per trap per period before improvement of IPM and 1.8 ± 0.6 beetles per trap per period after the management change (F = 9.71; df = 1,9; P = 0.012). The probability of capture was 0.96 ± 0.02 before and 0.46 ± 0.13 after the management change (GLM: F = 17.05; df = 1,9; P = 0.003).

Efficacy of the fumigations measured as reduction in mean trap capture in monitoring period immediately after fumigation compared with the level immediately before fumigation was not significantly affected by the management change: 92.2 ± 2.8% reduction in mean trap capture before versus 91.2 ± 4.0% reduction after management change ($F_{1,9}$ = 0.04; P = 0.844). However, there was a greater reduction in probability of capture immediately after fumigation after the management change (46.2 ± 9.3% before versus 82.8 ± 9.3% after [$F_{1,9}$ = 7.59; P = 0.022]). Inside temperature during the fumigation was not different before and after the management change ($P > 0.05$); data shown in Campbell et al. (2010). A consequence of these changes in pest abundance was that number of fumigations per year was reduced from two or three before the management change to one per year afterward; with this fumigation typically occurring in the fall.

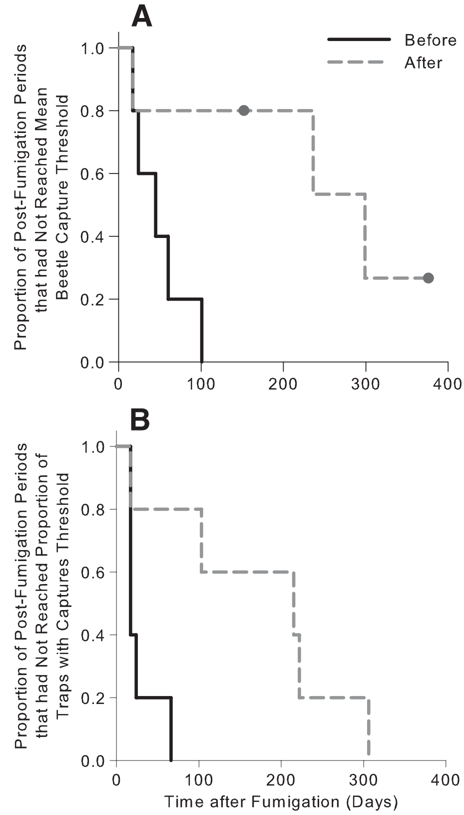

Fig. 3. Mill 1 time-to-event (survival) curves for the time after fumigation for *T. castaneum* captures to reach the thresholds for (A) mean trap capture of 2.5 beetles per trap per wk (i.e., median mean trap capture before fumigation for the combined mills) and (B) probability of capture reaching 0.50 (i.e., median proportion of traps with captures of one or more beetles before fumigation for the combined mills) before and after management changes. Circles indicate censored data (i.e., fumigations occurred before the mill reaching the threshold value).

Rebound time to both the mean capture and probability of capture thresholds was increased after the pest management changes (Fig. 3). Comparing rebound to the mean capture threshold, there was a significant increase in the time-to-event (log-rank test statistic = 4.874, $P = 0.027$): 49 ± 15 d ($n = 5$, censored events = 0) before and 246 ± 71 d ($n = 5$, censored events = 2) after the management change. Comparing rebound to the probability of capture threshold, there was also a significant difference in the time-to-event (log-rank test statistic = 5.801, $P = 0.016$): 38 ± 14 d ($n = 5$, censored events = 0) before and 165 ± 46 d ($n = 5$, censored events = 0) after the management change.

In part this increase might be explained by the reduced number and proportion of traps with captures in the monitoring period immediately after fumigation being less after the management change than before (mean trap capture after fumigation: 1.8 ± 0.6 beetles per trap per period before versus 0.1 ± 0.0 beetles per trap per period after management change ($F = 7.07$; df = 1,9; $P = 0.0261$); proportion of traps with captures after fumigation: 0.52 ± 0.09 before versus 0.08 ± 0.03 after management change ($F = 17.07$; df = 1,9; $P = 0.0026$), and as a result providing a smaller starting population. There was a significant negative correlation between the mean number of beetles per trap per period immediately after fumigation and time to rebound to mean trap capture threshold (correlation coefficient = −0.626, $P = 0.0024$, $n = 21$) and probability of capture threshold (correlation coefficient = −0.596, $P = 0.0044$, $n = 21$); i.e., as trap capture after fumigation increased the time to reach threshold decreased. The same relationship occurred between proportion of traps with captures immediately after fumigation and rebound to mean trap capture threshold (correlation coefficient = −0.530, $P = 0.0135$, $n = 21$) and probability of capture threshold (correlation coefficient = −0.553, $P = 0.0093$, $n = 21$).

Differences in rebound rate before and after management change could also result from the fumigations always occurring in the fall with the corresponding longer period of time after treatment to reach thresholds due to cooler temperatures reducing development and immigration rates. Only one fall fumigation occurred before the management change in mill 1 (66 and 88 d to reach the mean trap and probability of capture thresholds, respectively), so statistically comparing just fall fumigations before and after change is not an option. However, the rebound after fall fumigations just during the period after the management change in mill 1 can be compared between the two mills. The three fall fumigations in mill 1 after the management change had rebound to mean trap capture threshold values of 215, 222, and 306 d compared with 158, 4, 218 d in mill #2, but the difference was not significant based on *t*-test ($t = -1.633$, $P = 0.178$), but the test had low power because of the low replication. The rebound to probability of capture threshold was similar in pattern (215, 222, and 264 d in mill 1 and 176, 4, 218 in mill 2) and was also not significantly different ($t = -1.502$, $P = 0.207$) with lower power *t*-test. It is also interesting to note that the one fumigation in fall before the management change had rebound rate of less than half that after the management change.

To evaluate the impact of management change on beetle captures while controlling for season, we also analyzed the percentage change in mean capture and probability of capture between sequential monitoring periods, excluding sequential periods with a fumigation conducted between them, for mill 1 sorted by both season and before and after the changes in management. The overall GLM model including season and before/after management change as factors was significant for change in mean trap capture ($F = 2.70$; df = 1, 146; $P = 0.0476$): season was a significant factor ($F = 5.29$; df = 1,146; $P = 0.0229$), but change in management and the interaction between season and change in management tactics were not significant. Sorting data by season, the change in mean trap capture was 23.0 ± 9.0% ($n = 79$) in the cool season and 66.1 ± 15.8% ($n = 71$) in the warm season monitoring periods. For the proportion of traps with captures, the overall GLM model including season and before/after management change as factors was not significant ($F = 0.81$; df = 1,146; $P = 0.4898$).

Management Thresholds Based on Beetle Captures in Traps. There are currently no pest management action thresholds for food facilities, but visual assessment of the rebound of capture data (Fig. 1) and the good fit of exponential functions to some of the rebound data suggest that the rate of increase in trap captures over time with increase in mean trap capture follows an exponential pattern, although with considerable variation in the data. This variation is probably the result of fumigations that occurred before the pattern of variation developed, other management practices that impacted density dependent population growth, and the inaccurate relationship between trap capture and population density (Toews et al. 2009). Here, we explore the relationship between mean trap captures and the change in trap captures from one period to the next.

Assessing degree of increase in mean beetle captures in the next monitoring period as a function of the mean number captured in the current monitoring period is shown in Fig. 4A. There was not a significant correlation between these two variables (Pearson Correlation coefficient = 0.0843, $P = 0.151$, $n = 292$), probably because as mean trap capture increases it is more likely that management tactics will be increased resulting in slower rates of increase or even decreases and also some of the greatest mean captures were immediately before fumigations so had missing data for the change to the next monitoring period. In this situation, plotting the change from the previous monitoring period against the current mean trap captures may be a more informative way to look at the data (Fig. 4B). In this case, there was significant positive correlation between the two variables (Pearson correlation coefficient = 0.689, $P < 0.001$, $n = 290$). The predictive value of a high mean beetle capture is not as good as the probability that if you have a large mean capture of beetles that it was associated with a large increase in numbers in the previous monitoring period. The relationship between the proportion of the traps containing one or more beetles and change in trap captures in the next monitoring period (Pearson correlation coefficient = 0.152, $P = 0.009$, $n = 292$) (Fig. 4C)

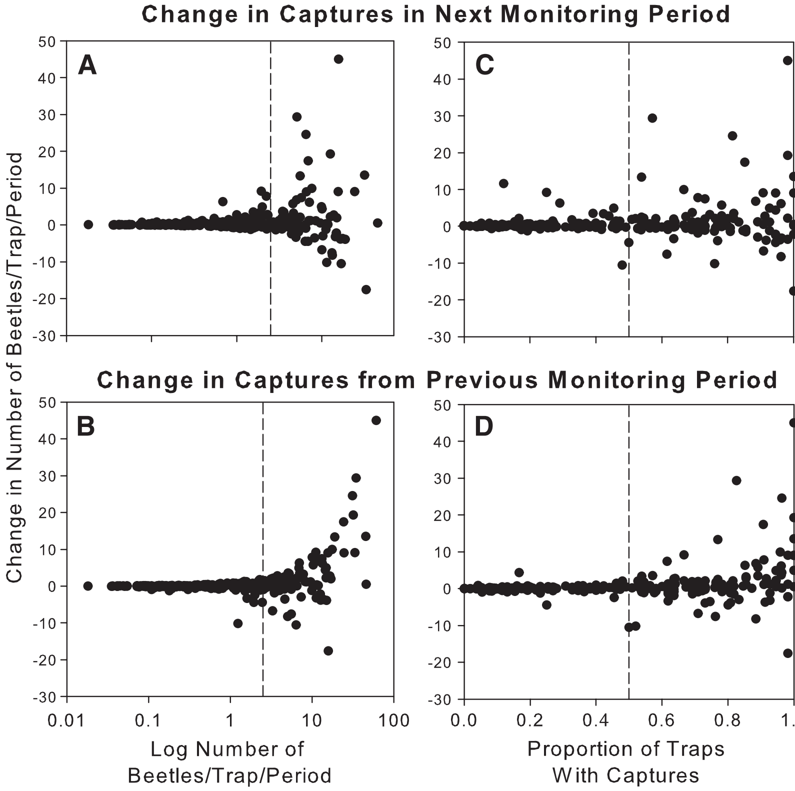

Fig. 4. Relationship between mean *T. castaneum* captures (beetles per trap per period) (A and B) and proportion of traps with captures of one or more beetles (C and D) in relation to the change in the next 2-wk monitoring period (A and C) and in the previous 2-wk monitoring period (B and D). The vertical dashed line in A and B represents 2.5 beetles per trap per period and in C and D represents probability of traps capturing of one or more beetles.

and change from the previous monitoring period (Pearson correlation coefficient = 0.272, $P < 0.001$, $n = 302$) (Fig. 4D) both had significant positive correlations.

Using the previously described thresholds of 2.5 beetles per trap per period and 50% of the traps with captures of one or more beetles (Fig. 4), the amount of change in mean number of beetles captured increased above these thresholds. Thus, these thresholds might be good indicators of increased risk. Below the mean trap capture of 2.5 beetles per trap per period, the mean increase in mean trap capture in the next monitoring period was 0.34 ± 0.08 ($n = 202$, median = 0.04, min = −1.28, max = 9.17); but above this threshold, the mean increase in mean trap capture in the next monitoring period was 1.76 ± 0.85 ($n = 90$, median = 0.33, min = −17.62, max = 45.00). The difference between these two groups was not significantly different based on Mann–Whitney rank sum test ($U = 8746.5$, $P = 0.607$); data were not normally distributed so nonparametric test was used. Focusing on the intervals where the beetle captures increased, the degree of increase was significantly greater above the 2.5 beetles per trap per period threshold (5.4 ± 1.2, $n = 51$) than below (0.9 ± 0.2, $n = 119$) this threshold (Mann–Whitney rank sum test, $U = 1185.0$, $P < 0.001$), although the percentage of intervals with an increase was similar (59 and 56%, respectively).

Below the 0.5 probability of capture threshold, the increase in mean trap capture from one monitoring period to the next was less variable then above the threshold, looking both forward and backward (Fig. 4C and D). Below this threshold, the change in mean trap capture was 0.02 ± 0.05 beetles per trap per period ($n = 173$, median = 0.02, min = −4.4, max = 4.3); and above the threshold, the change was 1.71 ± 0.56 beetles per trap per period ($n = 142$, median = 0.64, min = −17.6, max = 45.0). The difference between these two groups was significant based on Mann–Whitney rank sum test ($U = 8329$, $P < 0.001$). For intervals where the beetle captures increased, the degree of increase was also significantly greater above the probability of capture threshold (4.3 ± 0.9, $n = 71$) than below (0.8 ± 0.2, $n = 95$) this threshold (Mann–Whitney rank sum test, $U = 1314$, $P < 0.001$), although the percentage of intervals with an increase was similar, 56 and 59%, respectively.

Discussion

Fumigation efficacy, as measured using pheromone trapping, consists of two components, the initial reduction in captures after treatment and the rate at which the trap captures increase after treatment. Initial reduction in trap captures, measured and discussed in Campbell et al. (2010), reflects the initial mortality of adults, and to some extent pupae and late instars, overlain with immigration of adults into treated areas immediately after treatment. The increase in trap captures over time after treatment (rebound) reflects both individuals surviving treatment, including eggs and early instars not detectable in pheromone traps immediately after treatment, immigration, and the progeny of the survivors and immigrants; coupled with the influence of environmental conditions and management tactics. The impact of egg and larval survival after fumigation would not be detected until 1 to 2 mo after treatment, when adults emerge and disperse and can be captured in pheromone traps. Conversely, the pupae and adults surviving fumigation would be detectable within days. Rebound patterns measured in this study were highly variable, which probably reflects in part the impact of these many diverse factors on population growth. Although the relative importance of these different factors cannot be independently tested, by analyzing the data in different ways we can explore the impact of these factors. Analysis in Campbell et al. (2010) suggested that survival of fumigation was more significant than immigration for *T. castaneum* captures immediately after fumigation. Unchecked population growth in mills is predicted to be exponential given the amount of food material available. In a few cases the rebound pattern was well explained by an exponential regression, but more often the observed pattern did not fit this type of model. This is probably because other management tactics occurring within the facility are negatively impacting population growth and also that pheromone traps are imperfectly correlated with actual population levels. Small (2007) evaluated captures of *T. confusum* in four flour mills in England at periods 2, 2–7, and 8–12 wk after fumigation and generally did not find much of a change in percentage of reduction among these time periods.

The thresholds for mean capture and probability of capture provide a novel method for quantifying and evaluating rebound which is needed to deal with this highly variable data. In mills, increasing insect captures increase the probability that management interventions will increase or intensify—this is true on both an overall mill average and at individual trap locations. These interventions will impact the overall population or just the probability of an insect being captured. For example, some residual insecticides have been shown to reduce trap captures because of mortality of dispersing adults, even if not impacting total pest populations (Toews et al. 2006). Conversely, improved sanitation will increase trap captures likely as a result of increasing foraging areas due to reduced number and size of habitat patches (Toews et al. 2005).

The threshold of 2.5 beetles per trap and 0.50 of the traps with captures of one or more beetles was based on the median prefumigation levels and is not an economic threshold. Although the time to reach these thresholds has limited resolution because it is based on samples collected over monitoring periods of ≈2 wk, there were still significant differences detected among seasons and before and after management changes. These thresholds were for comparative purposes, but further analysis of the data also suggests they may indicate a level above which risk of large increases in trap captures is greater and might also be useful for guiding management decisions. Although there are a number of differences between the two mills examined in this study, the time to reach the mean trap capture threshold was not different between the mills. Other higher thresholds also could be used, the one beetle per trap per d, for example (Campbell and Arbogast 2004), and these may have greater risk of large increases between monitoring periods, but the multiple years of data collected from these two mills suggests that this lower level threshold may be more informative. Flour mills and other food facilities do not currently use such thresholds for management, but this approach holds potential for improving management programs, because it is relatively simple to calculate, can be used to evaluate success of current program, and can be easily adapted to a given facility type and its management goals. Data from other locations will be useful in determining the generality of these thresholds, but the approach could easily be customized for a given facility based on their monitoring data.

It took significantly longer to reach the mean trap capture threshold when fumigations occurred in the fall compared with the spring, although the rebound to probability of capture threshold was not significantly different. This could result from three factors—differences in the founding population size, differences in temperature between the seasons reducing population growth rate, and cooler outside temperatures reducing immigration. Campbell et al. (2010) found no significant impact of season on foundation populations as measured using pheromone trap captures immediately after fumigation. Proportional hazards analysis indicated that mean number captured before fumigation significantly impacted rebound, but because Campbell et al. (2010) found a positive correlation between number before fumigation and number after fumigation, this suggests that there is an impact of founding population on rebound rate. It seems that percentage of reduction after fumigation is proportional to the number of beetles present and not typically a reduction to a baseline level; therefore, controlling the densities reached before treatment and thus the number of founders to start rebound after treatment is important. Temperature was different within the mills between the seasons (Campbell et al., 2010). The average daily temperature difference inside the mills between the cool and warm season was 6°C in both mills, with cool season average daily temperatures of 24°C and warm season of 30°C, but there was no significant correlation between inside temperature and trap captures. Population growth rate would be different between these two seasonal mean temperatures (Howe 1962, White 1987), although there is also considerable spatial and temporal variation in temperature within the mills that might reduce these differences. No data on immigration rates is available for *T. castaneum*, but immigration of other stored-product pest species at mill 1 did vary seasonally (Campbell and Arbogast 2004). It is likely that most of the populations at these two locations are contained within the mills, but immigration from outside is a factor that will contribute to rebound less in the winter and cooler times of spring and fall. It will be necessary to use population models to fully explore the potential influences of temperature differences between seasons within a mill on pest population rebound. Although it is typically not feasible to use temperature manipulation inside a mill to manage pest population growth, this approach through the use of aeration is widely used in stored grain (Flinn et al. 1997, Arthur and Flinn 2000). The results of this research illustrate how manipulating the time of year fumigations are performed could be used to exploit seasonal patterns in temperature inside and outside that are already present.

Comparison of the rebound pattern of sulfuryl fluoride with that of methyl bromide is important, because *T. castaneum* eggs are the most resistant to sulfuryl fluoride (Fields and White 2002). Differences in efficacy against egg stages are likely to be detectable one to two months after treatment, depending on temperature, but the presence of adults immediately after fumigation, which would be continually laying eggs, could mask population increases attributable to egg survival of treatment. Although only two fumigations with sulfuryl fluoride were conducted and no large increase at the time interval when eggs should reach the adult stage was detectable, the high and low rates did have a different rebound rate. The initial reduction in trap captures of the two fumigations was consistent with methyl bromide fumigations (Campbell et al., 2010). There was rapid rebound at the low rate of sulfuryl fluoride, but rebound after the high rate was consistent with the overall average for methyl bromide fumigations. However, one of the spring methyl bromide fumigations also rebounded within 17 d, so rapid rebound is not necessarily the result of the fumigant type. Small (2007) found no difference in rebound between methyl bromide and sulfuryl fluoride, two mills for each fumigant, after 12 wk. However, more information from other locations and use of population models is needed to further evaluate the impact of egg survival and immigration on rebound rate.

The change in management tactics at mill 1 provides a unique opportunity to look at the impact of management on population rebound, although even with multiple years before and after change, this is still one replicate location. It is also difficult to determine the relative importance of the different tactics such as sanitation, spot treatments, and aerosols because multiple tactics were occurring at the same time. The regular use of aerosols was a major component of the change in management, and simulated field trials show aerosol treatments of synergized pyrethrins alone and in combination with methoprene are effective against both *T. castaneum* and *T. confusum* (Arthur and Campbell 2007, Arthur 2008). Improved management tactics did not impact fumigation efficacy in terms of initial reduction in beetle captures after fumigation, except for proportion of traps with captures immediately after fumigation, there was a significant impact on rebound in both mean and proportion of traps with captures. The ability to disrupt population growth through increased mortality (sanitation and insecticide use), reduction in availability of food patches (sanitation and structural modification), and reduced ability to colonize (exclusion and insecticide use) seems to have the ability to reduce pest populations. Mean trap captures remained at low levels after the management changes even though the proportion of traps with captures still tended to increase which indicates that population was still spreading but not increasing to densities obtained previously. The shift in time of year when fumigations occurred in mill 1 does potentially confound the evaluation of the impact of the IPM tactics, because rebound rates were slower in fall fumigations even at mill 2.

Part of the search for methyl bromide alternatives is to find economically viable alternatives. If monitoring and IPM programs can reduce the need to fumigate and reduce the number of fumigations from two to three per year to one per year, or even less frequently than that, the viability of alternatives even if more expensive can be increased. Certainly some of these fumigations at these mills were performed when population levels, as indicated by pheromone traps, seemed to be relatively low. The mill performing one fumigation per year had lower average *T. castaneum* captures than the one performing two fumigations per year. Aerosol insecticide applications are relatively inexpensive to perform compared with fumigations in both chemical costs and shut down time. A good sanitation program is essential for any food facility and critical for both its direct impact on populations and its indirect impact on insecticide efficacy (Arthur and Peckman 2005). The information presented here is a start at understanding these processes and starts to fill a large data gap on understanding pest populations in food facilities. Clearly, even more studies of this type coupled with economic analysis and population models are needed to develop a more complete understanding of these systems and how best to manage pest populations.

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References Cited

Arbogast, R. T., P. E. Kendra, R. W. Mankin, and J. E. McGovern. 2000. Monitoring insect pests in retail stores by trapping and spatial analysis. J. Econ. Entomol. 93: 1531–1542.

Arthur, F. H. 2008. Aerosol distribution and efficacy in a commercial food warehouse. Insect Sci. 15: 133–140.

Arthur, F. H., and P. W. Flinn. 2000. Aeration management for stored hard red winter wheat simulated impact on rusty grain beetle (Coleoptera: Cucujidae) populations. J. Econ. Entomol. 93: 1364–1372.

Arthur, F. H., and P. S. Peckman. 2005. Insect management with residual insecticides, pp. 167–173. *In* J. W. Heaps (ed.), Insect management for food storage and processing, 2nd ed. American Association of Cereal Chemists Press, St. Paul, MN.

Arthur, F. H., and J. F. Campbell. 2007. Distribution and efficacy of pyrethrin aerosol to control *Tribolium castaneum* (Coleoptera: Tenebrionidae) in food storage facilities. J. Stored Prod. Res. 44: 58–64.

Bell, C. H. 1988. Minimum concentration levels of methyl bromide required for full efficacy against seven species of stored-product beetle at two temperatures. J. Pestic. Sci. 24: 97–109.

Campbell, J. F. 2006. Stored product insect behavior, pp. 39–54. *In* J. W. Heaps (ed.), Insect management for food storage and processing, 2nd ed. American Association of Cereal Chemists Press, St. Paul, MN.

Campbell, J. F., and R. T. Arbogast. 2004. Stored-product insects in a flour mill: population dynamics and response to fumigation treatments. Entomol. Exp. Appl. 112: 217–225.

Campbell, J. F., and M. Mullen. 2004. Distribution and dispersal behavior of *Trogoderma variabile* and *Plodia interpunctella* outside a food processing facility. J. Econ. Entomol. 97: 1455–1464.

Campbell, J. F., M. A. Mullen, and A. K. Dowdy. 2002. Monitoring stored-product pests in food processing plants with pheromone trapping, contour mapping, and mark-recapture. J. Econ. Entomol. 95: 1089–1101.

Campbell, J. F., M. D. Toews, F. H. Arthur, and R. T. Arbogast. 2010. Long-term monitoring of *Tribolium castaneum* in two flour mills: seasonal patterns and impact of fumigation. J. Econ. Entomol. 103: 991–1001.

Chayaprasert, W., D. E. Maier, K. E. Ileleji, and J. Y. Murthy. 2009. Effects of weather conditions on sulfuryl fluoride and methyl bromide leakage during structural fumigation in a flour mill. J. Stored Prod. Res. 45: 1–9.

Doud, C. W., and T. W. Phillips. 2000. Activity of *Plodia interpunctella* (Lepidoptera: Pyralidae) in and around flour mills. J. Econ. Entomol. 93: 1842–1847.

Fields, P. G., and N.D.G. White. 2002. Alternatives to methyl bromide treatments for stored-product and quarantine research. Annu. Rev. Entomol. 47: 331–359.

Flinn, P. W., D. W. Hagstrum, and W. E. Muir. 1997. Effects of time of aeration, bin size, and latitude on insect populations in stored wheat: a simulation study. J. Econ. Entomol. 90: 646–651.

Howe, R. W. 1962. The effects of temperature and humidity on the oviposition rate of *Tribolium castaneum* (Hbst.) (Coleoptera, Tenebrionidae). Bull. Entomol. Res. 53: 310–310.

Roesli, R., Bh. Subramanyam, J. F. Campbell, and K. Kemp. 2003. Stored-product insects in Kansas retail pet stores. J. Econ. Entomol. 96: 1958–1966.

Small, G. J. 2007. A comparison between the impact of sulfuryl fluoride and methyl bromide fumigations on stored-product insect populations in UK flour mills. J. Stored Prod. Res. 43: 410–416.

Toews, M. D., F. H. Arthur, and J. F. Campbell. 2005. Role of food and structural complexity on capture of *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae) in simulated warehouses. Environ. Entomol. 34: 164–169.

Toews, M. D., J. F. Campbell, and F. H. Arthur. 2006. Temporal dynamics and response to fumigation of stored-product Coleoptera in a grain processing facility. J. Stored Prod. Res. 42: 480–498.

Toews, M. D., F. H. Arthur, and J. F. Campbell. 2009. Monitoring flour beetles in pilot-scale warehouses treated with β-cyfluthrin: are residual insecticides and trapping compatible? Bull. Entomol. Res. 99: 121–129.

Trematerra, P., P. Gentile, A. Brunetti, L. E. Collins, and J. Chambers. 2007. Spatio-temporal analysis of trap captures of *Tribolium confusum* du Val in a semolina-mill, with a comparison of female and male distributions. J. Stored Prod. Res. 43: 315–322.

White, G. G. 1987. Effects of temperature and humidity on the rust-red flour beetle, *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae), in wheat grain. Aust. J. Zool. 35: 43–59.

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