



Movement of *Tribolium castaneum* within a flour mill

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ARTICLE INFO

Article history:

Accepted 15 March 2013

Keywords:

Red flour beetle
Flour mill
Mark-recapture
Dispersal
Heat treatment

ABSTRACT

The colonization of food processing plants by stored-product pests and their distribution within a facility depend, in part, on their dispersal ability. In this case study, we relied on self-mark recapture to evaluate the ability of *Tribolium castaneum*, the red flour beetle, to move among floors within a flour mill and the effects of a heat treatment on insect activity. Marking stations with pheromone and fluorescent powder were placed on each of five floors in the mill, and two techniques were used to recover marked individuals (trapping and direct collection of individuals from the floor). Considering both recovery techniques, *T. castaneum* was able to move among floors, but the majority of individuals remained on the same floor where they were marked (86%). Most individuals captured on a different floor were captured on a floor below the one they were marked (70%) and adjacent to it (87%). There was a spike in the number of beetles captured during heat treatment, but not an increase in movement of marked beetles between floors. These results suggest that the rate of heating was sufficient to prevent beetles time to move to cooler floors to escape heat. *T. castaneum* movement among floors needs to be taken into account when identifying sources of infestation and targeting pest management.

Published by Elsevier Ltd.

1. Introduction

Stored-product insects associated with food processing facilities inhabit an environment made up of resource patches that are isolated and discontinuous, both within structures and within the broader urban and/or rural landscape (Campbell, 2005). The ability to move through this environment and to find and colonize these resource patches contributes to their reproductive success in food facilities and their economic impact as a pest. As a result of this environment and behavior interaction, populations of stored-product insects in many food processing facilities are spatially and temporally patchy in distribution. Understanding these patterns of distribution and movement can improve the implementation and interpretation of monitoring programs and the targeting of pest management. A number of studies have evaluated the spatial distribution of insect captures in traps (Arbogast et al., 2000; Strother and Steelman, 2001; Campbell et al., 2002; Trematerra and Sciarretta, 2004; Trematerra et al., 2007), but those evaluating patterns of movement are much more limited.

Stored-product pests are readily trapped outside of grain storage and processing structures and often far away from anthropogenic

structures (Sinclair and Haddrell, 1985; Throne and Cline, 1989; Fields et al., 1993; Dowdy and McGaughey, 1994; Doud and Phillips, 2000). This suggests that they are highly mobile in outside environments and capable of long-distance flight, but since dispersal was not directly measured these captures may also indicate feral populations in close proximity to the traps. Mark recapture techniques have been used to measure dispersal of stored-product insects: lesser grain borer, *Rhyzopertha dominica* (F.), was shown to be a strong flyer and capable of dispersing considerable distances (Campbell et al., 2006; Mahroof et al., 2010); warehouse beetle, *Trogoderma variabile* Ballion, and Indianmeal moth, *Plodia interpunctella* (Hübner) were found to be highly mobile outside of a food processing facility (Campbell and Mullen, 2004); and Indianmeal moth was demonstrated to move into a flour mill (Campbell and Arbogast, 2004). Evaluation of movement patterns inside facilities is typically more difficult to perform, in part because of the limited numbers available to self-mark and restrictions on releasing insects. Campbell et al. (2002) used self-mark recapture to measure *T. variabile* mobility within a processing plant, and documented beetles moving across multiple floors and up to 216 m within a warehouse.

Tribolium castaneum (Herbst) is a major pest of stored grain, cereal products, and other stored commodities. This species is often found in environments where grain and grain-based products are processed and stored (Sinclair and Haddrell, 1985;

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Arbogast et al., 2000; Campbell and Arbogast, 2004). Flour mills are favored habitats because the milling process produces large amounts of flour and other byproducts that can accumulate inside equipment, on surfaces, and inside cracks and voids in the building structure. Favorable temperature conditions for development and movement are also maintained inside mills throughout the year (Campbell et al., 2010). *T. castaneum* do appear to have patchy distributions within mills (Semeao et al., 2012a), but since this species appears to disperse primarily by walking, their dispersal ability is not well understood. Flight can be initiated throughout the adult stage, but conditions such as low food or lack of conspecifics can trigger greater flight initiation (Perez-Mendoza et al., 2011a,b). While *T. castaneum* is not often observed flying inside flour mills, regular patterns of flight activity have been reported in food facilities (Ho and Boon, 1995). Ecological and molecular techniques have also been used to indicate that beetles do leave storage locations and disperse into surrounding areas (Ridley et al., 2011). Outside wheat flour mills *T. castaneum* abundance tends to be reduced, but beetles are regularly captured at low levels in outside traps targeting both walking and flying individuals (Campbell and Arbogast, 2004; Semeao et al., 2013). Semeao et al. (2012a) reported that the spatial distribution pattern of *T. castaneum* captures across floors of a flour mill changed over time, which suggests either shifts in the distribution of infestation or an ability to move among floors. Campbell et al. (2002) attempted to use mark recapture to measure *T. castaneum* dispersal, but was not successful in recovering marked beetles, presumably because densities were low.

Understanding the level of dispersal of *T. castaneum* within flour mills, particularly in terms of movement between floors, would assist in determining the spatial extent of populations, the potential for invasion and colonization, and interpreting patterns in pheromone trap capture. Here we present the results of an experiment using self-mark recapture to evaluate the ability of *T. castaneum* to move among floors within a flour mill. We took advantage of a situation where the population was large and appeared primarily confined to the inside of the mill since this would facilitate the recapture of marked beetles. In response to the large number of beetles, a heat treatment was applied during the course of monitoring. This provided an additional opportunity to measure if the increased insect activity associated with the heating up of the building increases beetle movement among floors, potentially enabling them to avoid lethal temperatures.

2. Materials and methods

2.1. Study site

This study was conducted at the pilot-scale Hall Ross flour mill at Kansas State University. The mill is a concrete structure composed of five floors (364 m² each floor). The mill is a tightly sealed structure and at the time of the study had an infestation of *T. castaneum* inside the mill. Given the tightness of the structure and the findings of Semeao et al. (2012a) that very few adults were captured in traps placed outside the mill this infestation is considered to represent a relatively closed population within the mill. Monitoring and a self-mark recapture study were conducted within the mill between July 28 and October 10, 2008. On each floor, four self-marking stations and five recapture traps were placed at locations chosen based on proximity to pieces of milling equipment or potential to be encountered by individuals walking across the floor. Five recapture traps were also placed along walls outside the mill. Temperature and relative humidity on each floor of the mill were monitored throughout the study using HOBO data loggers (Onset Computers, Pocasset MA). Average

temperature and relative humidity during the monitoring period were 27.03 ± 0.02 °C and $37.27 \pm 0.04\%$, respectively.

2.2. Self-marking stations

Self-marking stations were constructed using traps described in Semeao et al. (2013), which were a modified corrugated cardboard trap design (Likhayo and Hodges, 2000). Briefly, these stations consisted of two layers of corrugated plastic held between two metal plates arranged to form a 9×9 cm square and containing a 3×3 cm open space in the center. Approximately 2 g of fluorescent powder (Day-Glo Color, Cleveland, OH) and one *Tribolium* spp. pheromone lure (Trécé, Adair OK) was placed in the open center of each marking station. Marking stations on the same floor were filled with the same color fluorescent powder, but each floor had a unique color [1st floor: green (Signal Green pigment, A-18-N); 2nd floor: yellow (Saturn Yellow pigment, A-17-N); 3rd floor: orange (Fire Orange pigment, AX-14-N); 4th floor: blue (Horizon Blue pigment, A-19) and 5th floor: magenta (Corona Magenta pigment, A-21)]. On August 29, 2008 all marking stations were removed from the mill but the recapture traps were left in place until October 10, 2008.

2.3. Recapture traps

Recapture traps were Dome™ pitfall traps (Trécé, Adair, OK, USA) containing a pheromone lure for *Tribolium* spp. attached to the underside of the lid. The interior floor of the trap bottom, instead of containing a food based oil as is usually added, was coated with Tangle-Trap sticky coating (Tangle Foot Co., Grand Rapids, MI). The sticky coating was used to restrain the captured insects to avoid cross contamination of marking powder and to avoid the marking powder migrating into the kairomone oil. While the kairomone oil does increase insect response to the trap, the pheromone contributes to the majority of the insect response (Campbell, 2012). Traps were changed every week, except as noted below. The traps were taken to the laboratory where beetles were inspected under long wave (365 nm) ultraviolet light (Black Ray Lamp Model UVL-21, UVP, Upland, CA) for the presence of fluorescent powder. Observations were made under a dissecting microscope (Wild M3Z, Heerbrugg, Switzerland) at 40× magnification to detect small amounts of the fluorescent powder.

2.4. Heat treatment

A heat treatment was applied to the flour mill beginning at ~4 pm on August 13 and ending at ~1 am on August 17, 2008. Maximum temperatures achieved at data logger locations were 48 °C, 47 °C, 47 °C, 50 °C, 47 °C for 1st through 5th floors, respectively, and were reached during the evening of August 16 and held for 2, 3, 6, 4, 2 h, respectively (Fig. 1). All traps in the mill were replaced with new traps immediately before the beginning of the heat treatment and these traps were replaced immediately after the heat treatment finished.

2.5. Collection of dead beetles

Before and especially after the heat treatment, dead beetles were observed on the floors of the mill. Samples of these beetles were collected before and after the heat treatment, and presence or absence of fluorescent marking powder was determined as described above. Before the heat treatment, because of lower numbers, beetles were collected off the floor wherever they were observed. After the heat treatment, beetles were much more

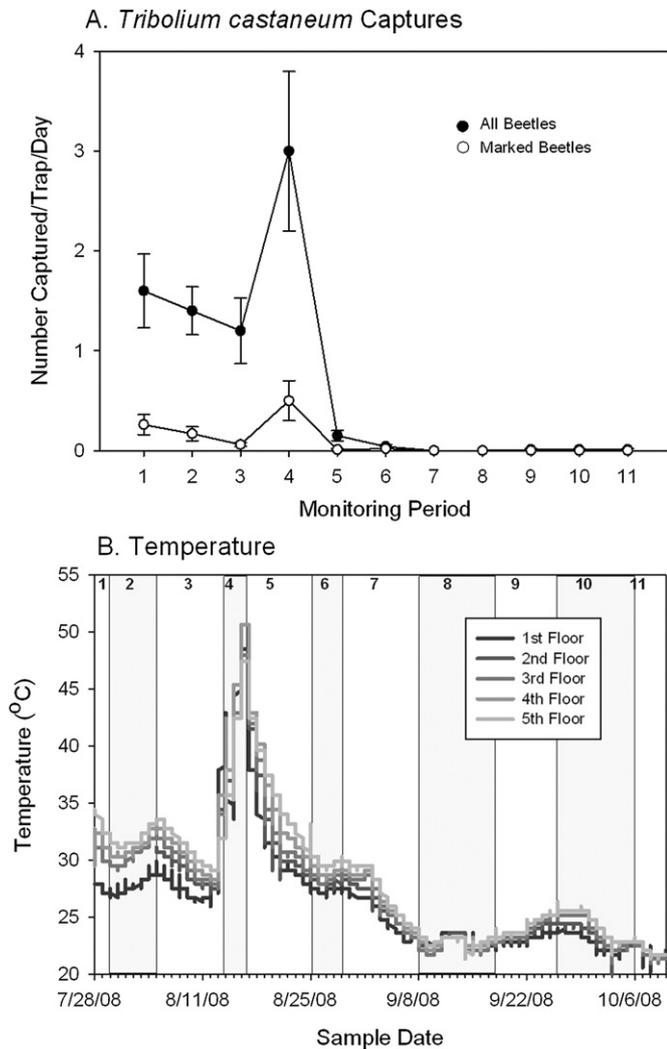


Fig. 1. The number (mean \pm sem) of marked or unmarked *Tribolium castaneum* captured per pheromone and kairomone baited trap per day during the different monitoring periods (A) and the temperatures recorded on each of the floors during the study (B), with the numbers and alternating gray highlighted areas indicating the different monitoring periods, with monitoring period 4 representing time a heat treatment was applied to the mill.

abundant and each floor was divided into 10 zones with equal numbers of beetles collected from each zone.

2.6. Statistical analysis

Beetle captures per trap, both marked and unmarked, were converted to number captured per day for analysis of trends over time. Only data from the first four monitoring periods was used since most of the beetles were captured during this period. General Linear Models (GLM) procedure with Tukey's multiple range test for means separation (SAS software v. 9, SAS Institute, Cary, NC, USA) and *t*-tests or Mann–Whitney Rank Sum tests (SigmaPlot software v. 12, Systat Software, San Jose, CA, USA), depending on normality of the data, were used to compare the total number of beetles captured/trap/day (both marked and unmarked). Pearson correlation between marked and total beetle captures in traps were performed using SigmaPlot software. Total numbers of marked and unmarked individuals over the whole monitoring period were used to determine percentages moving between floors for both captured beetles and dead beetles collected off the floor.

3. Results

The floors did not differ from each other in the total number of beetles, both marked and unmarked, captured (GLM: $F = 2.25$; d.f. = 4, 15; $P = 0.1125$): 1.5 ± 0.2 , 3.5 ± 1.4 , 2.0 ± 0.5 , 1.1 ± 0.2 , and 0.8 ± 0.2 beetles/trap/day for the 1st, 2nd, 3rd, 4th, and 5th floors, respectively. However, the floors did differ from each other in the number of marked beetles recaptured (GLM: $F = 3.18$; d.f. = 4, 15; $P = 0.0442$). The average number of marked beetles captured was 0.0 ± 0.0 , 0.1 ± 0.0 , 0.5 ± 0.2 , 0.5 ± 0.1 , and 0.2 ± 0.2 beetles/trap/day for the 1st, 2nd, 3rd, 4th, and 5th floors, respectively. The trend was that third and fourth floors had greater captures of marked beetles than first and second floors, with the fifth floor being intermediate, but Tukey's means separation test did not indicate significant differences. No beetles marked on the 1st floor were recaptured in traps. Few beetles were captured outside and no marked beetles were recovered (data not shown), so outside traps were excluded from analysis.

A total of 1007 beetles were captured in traps and of these 83 were marked (8%) (Table 1). There was a significant positive correlation between the number of marked beetles captured and the total number of beetles captured (Pearson Correlation, $r = 0.856$, $n = 11$, $P < 0.001$). Most marked beetles (93%) were recaptured in traps on the same floor on which they had been marked, with only beetles marked on the 3rd and 4th floors being recovered on other floors. Of the six marked beetles recaptured on different floors, all but one were recovered on a lower floor and three were recovered two floors below where marked. The total number of beetles captured while variable was relatively similar among the floors, but captures of marked beetles on the 3rd and 4th floors were more than twice that of other three floors. This trend suggests that marking stations on these floors were marking more individuals or marked individuals were less likely to disperse, the former of which is consistent with the greater detection of movement among floors for beetles from these floors.

The heat treatment appeared successful in reducing *T. castaneum* infestation since captures in traps were significantly lower following treatment (Mann–Whitney Rank Sum Test comparing monitoring periods immediately before and after treatment, $U = 76.5$, d.f. = 25, $P < 0.001$) (Fig. 1A). There was a spike in beetle captures during the heat treatment, which is consistent with the increasing temperatures driving beetles from hidden refugia, but due to variation among individual traps this was not statistically different (Mann–Whitney Rank Sum Test, $U = 234.5$, d.f. = 25, $P = 0.132$). Most of the increase in beetle captures in traps during the heat treatment occurred on the 2nd floor, where number of beetles captured per trap per day increased from 2.0 ± 1.0 before to 7.8 ± 6.5 during the heat treatment. The 2nd floor was the only floor with a significant increase (*t*-test, $t = -1.998$, d.f. = 8, $P = 0.0404$) in captured beetles during the heat treatment (for all other floors the *t*-test or Mann–Whitney Rank Sum test, depending on normality of the data, was not significant, $P > 0.05$). On the 2nd floor, three of the traps were responsible for the increase, with captures of 12–13 beetles per trap per day over the two days of the treatment.

Collecting dead *T. castaneum* off the floors of the mill resulted in greater recovery of marked beetles because of the much larger sample size than obtained by using the traps (Table 1). Before heat treatment, 2.4% of the collected beetles were marked, and after heat treatment, 4.1% were marked. There was a significant increase in the proportion of marked individuals when collected after the heat treatment (Log-likelihood test for contingency tables, $G = 19.9$, d.f. = 1, $P < 0.001$). As with the trapping data, most of the marked beetles were collected on the same floor on which they were marked. Before the heat treatment, 12.9% of the marked beetles were collected in a different floor and after heat treatment this

Table 1
Recovery of *Tribolium castaneum* marked on a given floor (columns) on one of the five floors (rows) of a flour mill in pheromone and kairomone baited traps, on the floor prior to a heat treatment and after a heat treatment, or total of all three groups. Total number marked beetles recovered per group are shown and in brackets is the percentage of recovered beetles marked on given floor (columns within a group) recovered among the different floors (rows within a group).

	Floor	<i>n</i>	Marked 5th floor	Marked 4th floor	Marked 3rd floor	Marked 2nd floor	Marked 1st floor	Total marked
Captured in traps (28-Jul–10-Sept- 2008)	5th	163	12 (100)	0 (0)	0 (0)	0 (0)	0	12
	4th	270	0 (0)	27 (87)	1 (3)	0 (0)	0	28
	3rd	150	0 (0)	2 (6)	32 (94)	0 (0)	0	34
	2nd	264	0 (0)	0 (0)	0 (0)	6 (100)	0	6
	1st	160	0 (0)	2 (6)	1 (3)	0 (0)	0	3
	All floors	1007	12	31	34	6	0	83
On floor before heat treatment (12-Aug-08)	5th	780	12 (100)	1 (3)	0 (0)	2 (25)	0 (0)	15
	4th	673	0 (0)	32 (91)	3 (10)	1 (12)	0 (0)	36
	3rd	752	0 (0)	1 (3)	25 (86)	1 (12)	0 (0)	27
	2nd	741	0 (0)	1 (3)	1 (3)	4 (50)	0 (0)	6
	1st	593	0 (0)	0 (0)	0 (0)	0 (0)	1 (100)	1
	All floors	3539	12	35	29	8	1	85
On floor after heat treatment (19-Aug-08)	5th	1103	47 (90)	2 (3)	0 (0)	0 (0)	0 (0)	49
	4th	1245	5 (10)	72 (96)	7 (7)	0 (0)	0 (0)	84
	3rd	1204	0 (0)	1 (1)	64 (65)	0 (0)	0 (0)	65
	2nd	1475	0 (0)	0 (0)	27 (27)	25 (100)	0 (0)	52
	1st	1287	0 (0)	0 (0)	1 (1)	0 (0)	6 (100)	7
	All floors	6314	52	75	99	25	6	257
Totals	5th	1945	71 (93)	3 (2)	0 (0)	2 (5)	0 (0)	76
	4th	1993	5 (7)	131 (93)	11 (7)	1 (3)	0 (0)	148
	3rd	2072	0 (0)	4 (3)	121 (75)	1 (3)	0 (0)	126
	2nd	2480	0 (0)	1 (1)	28 (17)	35 (90)	0 (0)	64
	1st	2040	0 (0)	2 (1)	2 (1)	0 (0)	7 (100)	11
	All floors	10,530	76	141	162	39	7	425

percentage was 16.7% (not significantly different based on log-likelihood test for contingency tables, $G = 0.716$, d.f. = 1, $P > 0.05$). This suggests that while many more dead beetles were present on the floor after the heat treatment, consistent with the treatment driving the beetles from hidden refugia, there was not an increase in movement between floors.

Most of the marked beetles collected that did move between floors were originally marked on the 2nd, 3rd, and 4th floors (Table 1). Beetles moved both upward and downward between floors, but a greater percentage moved downward (65%). Much of this downward trend was due to the post-heat treatment beetles marked on the 3rd floor. The majority of the movement of marked beetles was between adjacent floors: out of a total of 54 beetles moving between floors, 91% ($n = 49$) moved to an adjacent floor, 6% ($n = 3$) moved two floors away, and 4% ($n = 2$) moved three floors away.

For all the collection methods and dates, a total of 425 marked beetles were collected (Table 1). Of these marked beetles, a total of 60 (14%) were recovered on a different floor from which they were marked. Of those moving between floors, 87% ($n = 52$) moved to adjacent floor, 7% ($n = 4$) moved two floors, and 7% ($n = 4$) moved three floors. Overall, beetles were more likely to move downward (70%). There were differences between floors at this mill in terms of marked insects recaptured, even though the total number of beetles recovered on each floor were similar. The first floor was unusual in that only 11 beetles marked on that floor were recovered. Most marked *T. castaneum* activity appeared focused on the 3rd and 4th floors, which had a greater number of beetles marked and greater movement between floors. Temperatures prior to the heat treatment tended to be cooler on the first floor compared to the other floors, which might result in less beetle movement and marking, but the remaining floors had similar temperatures so this would not explain the greater dispersal from the 3rd and 4th floors (Fig. 1B).

4. Discussion

The findings of this study indicate that although *T. castaneum* is widely considered to be less mobile than many other pest species

found in mills, movement among floors occurs even in a relatively tightly sealed new facility. Although no significant difference among floors was detected in terms of total number of marked and unmarked insects captured, indicating similar numbers of beetles on each floor, the floors did differ from each other in the number of marked beetles recaptured. More beetles tended to be marked on the third and fourth floors. Temperature differences among floors do not seem to explain these differences, but it is possible that differences in physical layout, equipment or trap placement among the floors caused the pattern.

Most of the marked beetles were recaptured on the same floor they were marked, but beetles were detected moving between floors of the mill. In addition to having the highest captures of marked beetles, the third and fourth floors generated the majority of the beetles marked and captured on different floors. Additionally, most beetles marked on one floor and found on a different floor were found on a lower floor. This suggests that within a mill certain locations are more likely to be foci of dispersing beetles (in this case the 3rd and 4th floors) and that dispersal downward would tend to generate new infestations below the original source. Tendency to move downward also suggests that a component of the dispersal between floors is due to beetles falling through gaps in the floor. This phenomenon has been observed in other locations where beetle activity or capture in traps is associated with source infestations in duct work or equipment located above where beetles were recovered (JFC, personal observation). The relatively tight sealing may have also contributed to this finding, since flying upward between floors would be more difficult with fewer openings. As with *T. castaneum*, *T. variable* marked on the fourth floor of a food processing facility, were primarily caught on the same floor as the marking station, and most of those recovered on different floors had moved downward (Campbell et al., 2002). Semeao et al. (2012a) reported shifts in *T. castaneum* distribution that suggested movement upward and downward within the mill through the season, but this mill was open from basement to top floor along one side of the structure and had many more openings cut into the floors which could facilitate both upward and downward movement. These

combined findings suggest that individuals more consistently move downward in facilities, but further research is needed before general conclusions can be drawn.

Heat treatments have been used historically for pest management and have seen increased interest in recent years as an alternative to fumigation. Typically, heat treatments involve slowly heating the structure (5 °C/h) to a target temperature of 50 °C and holding for 24–36 h (Beckett et al., 2007). While insects typically die within minutes at this temperature (Fields, 1992), the longer exposure time is needed to allow structure and equipment to absorb the higher temperatures. Heat treatments reaching less than 50 °C can have insect survival, and during the heat treatment reported here most floors did not reach this target temperature, at least at the data logger locations (Fig. 1B). However, the heat-up and cool-down during the heat treatment were relatively slow allowing for a longer exposure period to elevated temperature. *Tribolium castaneum* was still active after the heat treatment, although the numbers captured were dramatically reduced. This is consistent with other studies showing reductions in captures in traps following heat treatments (Roesli et al., 2003).

Heat treatments can reveal the locations of hidden infestations since as the structure is heated, insects are driven out from harborage and a halo of dead insects can frequently be observed around these points of origin. Beetles have also been reported aggregating in zones of lower temperature, such as can occur on the ground floor. *Tribolium castaneum* does respond to temperature gradients and moves to preferred temperatures (Jian et al., 2005). What is less well known is if beetles can move downward across the floors to find these cooler zones. The heat treatment reported here had a relatively slow rate of heating, which could maximize the potential for behavioral avoidance of treatment. While there was a trend for beetle activity to increase during heating, measured in both captures in traps and collection of dead beetles off the floor, there was not an increase in movement of marked beetles between floors of the mill. This suggests that potential for behavioral avoidance by moving to cooler locations may be limited.

The red flour beetle is well adapted to heterogeneous environments of spatially separated food patches, and it readily disperses from food patches and visits multiple resource patches over its lifetime (Campbell and Hagstrum, 2002; Campbell and Runnion, 2003; Romero et al., 2009). Our findings indicate that these resource patches can be located on different floors within a food facility and still be interconnected by beetle movement. In addition to beetle's own active dispersal, individuals can be transported between floors and among different zones within a floor with the movement of product and during sanitation activities. Given the limited activity of the mill and sanitation during the period of this study it appears likely that most of the reported movement was due to activity of the beetles. However, this combination of active dispersal and human aided movement may both be responsible for patterns of distribution and movement observed within facilities (Campbell et al., 2002; Semeao et al., 2012a) and at broader spatial scales outside of facilities measured either directly (Sinclair and Haddrell, 1985; Subramanyam and Nelson, 1999; Ridley et al., 2011) or using molecular markers to evaluate gene flow (Drury et al., 2009; Ridley et al., 2011; Semeao et al., 2012b). While there is a growing body of evidence that *T. castaneum* may be more highly mobile than originally hypothesized there are still important fundamental questions about their mechanisms and patterns of movement and the implications for pest management that need to be addressed.

Acknowledgments

We thank the personnel at the Hall Ross Flour Mill, Department of Grain Science and Industry, Kansas State University and Dr. Bh.

Subramanyam for facilitating study and Dr. R. N. C. Guedes for providing comments on an earlier version of the manuscript. This study was supported in part by USDA RAMP (Agreement No. 2007-51101-18407) and USDA Methyl Bromide Alternative (Agreement No. 2011-51102-31125) grants. Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U. S. Department of Agriculture or Kansas State University. USDA is an equal opportunity provider and employer. Contribution number 13-182-J from the Kansas Agricultural Experiment Station.

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