Stored-product insects in a flour mill: population dynamics and response to fumigation treatments

James F. Campbell[1,]* & Richard T. Arbogast[2]

[1]*United States Department of Agriculture, Agricultural Research Service, Grain Marketing and Production Research Center, 1515 College Ave, Manhattan, Kansas, 66502, USA;* [2]*United States Department of Agriculture, Agricultural Research Service, Center for Medical, Agricultural and Veterinary Entomology, Gainesville, FL, 32604, USA*

Accepted: 18 June 2004

Key words: Tribolium castaneum, Plodia interpunctella, Trogoderma variabile, monitoring, mark-recapture, Lepidoptera, Pyralidae, Coleoptera, Dermestidae, Tenebrionidae

Abstract

In a wheat flour mill, seasonal trends in stored-product insect trap capture, relationships between trap captures inside and outside the mill, and between pheromone trap capture and product infestation, and the impact of fumigation on pest populations, were assessed. Mark-recapture was used to evaluate the potential for movement of insects outside the mill into the mill. For *Plodia interpunctella* (Hübner) (Lepidoptera: Pyralidae) and *Trogoderma variabile* Ballion (Coleoptera: Dermestidae), pheromone trap captures outside were higher than inside the mill, and when inside and outside trap captures were correlated, both indoor and outdoor trap captures tended to cycle according to a seasonal pattern; fumigations did not consistently influence pheromone trap captures, and in only one instance were they found in product samples. Mark-recapture data indicated that *P. interpunctella* was capable of entering the building from outside. *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae) trap captures, in contrast, tended to be lower outside compared to inside, followed a pattern of sharp decline after fumigation treatment, and then steadily increased (0.002–0.005 beetles/trap/day) until the next fumigation. This pattern, other than potentially the rate of increase, was not impacted by season and outside trap capture levels. *Tribolium castaneum* was the primary species infesting the product. The information generated in this study provides some of the information needed to develop improved monitoring and management programs.

Introduction

A diverse community of arthropods is associated with environments where humans store grain and grain-based products; from on-farm bins to grain elevators, to mills and processing facilities, to warehouses, to retail stores, and ultimately to consumer shelves (Good, 1937; Evans & Porter, 1965; Zimmerman, 1990; Arbogast et al., 2000; Doud & Phillips, 2000; Campbell et al., 2002; Roesli et al., 2004). These arthropods have a major economic impact on the food industry due to the costs associated with their treatment and monitoring, rejection and return of contaminated products, loss of consumer goodwill, and failure to pass inspection or meet regulations. Many sectors of the food industry still rely on calendar-based pesticide applications that are often applied to the whole structure, but the pending loss and rising cost of many chemical tools is triggering interest in improving integrated pest management.

Ultimately, the development of pest management programs for the food industry that are targeted in both time and space will increase the effectiveness of pest suppression to acceptable levels and reduce the cost and risk of negative non-target effects (Brenner et al., 1998). For food processing facilities, however, there exists limited published information on stored-product pest population dynamics and the response of pest populations to management interventions such as fumigation or heat (Campbell et al., 2002; Roesli et al., 2003). Lack of information on pest populations is hampering the development of alternative pest management tools and integrated pest management programs.

Wheat milling is a major food industry that has a very low tolerance of insect infestation. Flour mills contain a

*Correspondence: USDA ARS GMPRC, 1515 College Ave, Manhattan, KS, 66502, USA. Tel.: +1 785 776 2717; Fax: +1 785 537 5584; E-mail: campbell@gmprc.ksu.edu

complex network of storage bins, processing equipment, and machinery for moving grain and milled material (Scott, 1951). Insects are a concern to the milling industry in two primary areas: internal feeding beetles in the whole grain before it is processed, contributing insect body fragments to flour, and external feeders infesting the structure and equipment within the mill leading to contamination of the product and potentially indicating unsanitary conditions within the mill. At flour mills, stored-product pest insects can be within, or moving between, four general areas: the bulk stored grain, the processing and circulation equipment, the structure of the building, or other resource patches outside the building (Campbell et al., 2004). Pest monitoring information primarily comes from sampling insects from the product stream (e.g., tailings samples), equipment (e.g., elevator boots) and, to a lesser extent, from pheromone trapping. Pest management relies heavily on sanitation and structural fumigation or heat treatments to remove resource patches, kill dispersing insects, and to reduce or eliminate populations within already infested patches. Methyl bromide is the most widely used whole-plant structure fumigant for mills and processing facilities (Taylor, 1994), but there is limited published data on its efficacy. Methyl bromide use for structural treatments is currently being phased out as part of the Montréal Protocol, due to its atmospheric ozone-depleting ability, and there is a major effort underway to develop alternative tools.

An important factor in developing and evaluating management and monitoring programs is to determine on what spatial scale pest subpopulations are interacting. If pest subpopulations are interacting over spatial scales larger than an individual structure, rapid pest resurgence after treatments such as fumigation may occur because only some of the subpopulations will be affected, and patches inside can be quickly recolonized. In addition, pheromone trapping may not accurately indicate the infestation level or the efficacy of the treatment within a facility because they are typically placed outside resource patches and collect dispersing individuals, some proportion of which may have originated from patches outside the structure (Campbell et al., 2002).

There is evidence to suggest that pest subpopulations are interacting over larger spatial scales than just the interior of structures. Stored-product insects have been found to be patchy in distribution, both spatially and temporally (Arbogast et al., 1998, 2000; Campbell et al., 2002), and patches of resource can be interconnected by dispersal behavior (Campbell & Hagstrum, 2002; Campbell et al., 2002; Campbell & Runnion, 2003; Campbell & Mullen, 2004). Many stored-product pest species are also readily trapped outside grain storage and processing structures (Throne & Cline, 1989, 1991; Fields et al., 1993; Dowdy & McGaughey, 1994; Doud & Phillips, 2000; Campbell & Mullen, 2004). Doud & Phillips (2000) and Campbell & Mullen (2004) have found high numbers of some pest species immediately outside food processing facilities and speculated that immigration could be important in pest dynamics inside the mill.

Here we have investigated the seasonal trends in stored-product insect capture at a wheat flour mill, compared the relationship between trap captures inside and outside the mill, compared the relationship between pheromone trap capture and product infestation, and evaluated the impact of fumigation on pest populations. Monitoring focused on the red flour beetle [*Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae)], which is the major pest of the wheat milling industry in the USA, Indian meal moth [*Plodia interpunctella* (Hübner) (Lepidoptera: Pyralidae)], and warehouse beetle [(*Trogoderma variabile*) Ballion (Coleoptera: Dermestidae)]. In addition, a mark-recapture method was used to evaluate the potential for movement of insects outside the mill into the mill.

Materials and methods

The flour mill had five floors, including a basement, of approximately 180 m^2 per floor, and was attached to an elevator with bulk grain storage silos. In the vicinity of the mill/elevator were packaging and warehouse buildings, office and receiving buildings, sheds, and another grain elevator. The property surrounding the mill was level and consisted of areas of gravel and grass and the property was bordered by a paved road on one side and residential areas in the other directions.

The mill was sampled inside from June until November 2001 and from July 2002 until December 2003. Outside the mill, traps were in place from June until November 2001, July to December 2002, and April to December 2003. Normal pest management and sanitation practices were conducted between June 2001 and December 2003, including six structural fumigations (the first with sulfuryl fluoride and the rest with methyl bromide). Five fumigations were performed while pheromone trapping, starting on 9 June 2001, 13 July 2002, 16 November 2002, 28 June 2003, and 23 August 2003, with an additional fumigation performed during December 2001, but the mill was not monitored immediately before or after.

Insects inside the mill were monitored using Dome and Pherocon II pheromone traps (Trécé Inc., Adair, OK, USA). Dome traps are 10.5 cm diameter circular traps that consist of a ramp that insects can climb and a 4 cm diameter and 2 cm deep circular pitfall area in the center (Mullen, 1992). Pheromone lures are attached inside a dome shaped plastic cover and suspended over the pitfall area. The bottom of the pitfall contained a piece of filter paper saturated with a food oil attractant. Dome traps were placed on the ground next to walls or pillars, and captured insects any that walked into the trap. In this study, the Dome traps contained pheromone lures (Trécé Inc., Adair, OK, USA) for *Tribolium* spp. [*T. castaneum* and *T. confusum* (Duval) (Coleoptera: Tenebrionidae)], an aggregation pheromone that attracts both males and females, and *Trogoderma* spp. [*T. variabile* and *T. granarium* Everts (Coleoptera: Dermestidae)], a sex pheromone that attracts males. Other species of stored-product associated insects were also frequently captured in Dome traps, either because they responded to food oil or randomly encountered the trap. Pherocon II traps are 15 cm long and 15 cm wide, with roughly diamond-shaped openings at both ends, with the interior of the trap having a sticky surface (280 cm^2) and designed to capture flying insects. Pherocon II traps were suspended between 1.5 and 2.1 m off the floor. Pherocon II traps were baited with an IMM+4 pheromone lure (Trécé Inc., Adair, OK) that attracts four different pyralid moth species, but *P. interpunctella* was the only species present at this site. This is a sex pheromone that attracts males.

Insect levels inside the mill were also monitored by collecting product samples from four locations in the product stream (3rd, 4th, and 5th mids, and purifiers) and a trash bucket where coarse materials removed from the product stream accumulate before disposal. Approximately 100 g of material were collected from each location. In the laboratory, the material was sieved and the species and number of larval and adult insects present was determined. The number of live insects present in the samples was converted to a number per 100 g for comparison, and all of the locations were totaled for analysis and presentation.

Outside the facility, Delta traps (Scentry Biologicals Inc., Billings, MT or Trécé Inc., Adair, OK) were placed on wood or metal stakes approximately 1 m off the ground. This trap type is triangle shaped (10 cm wide per side) at the ends and 18 cm long with a sticky surface on the three interior walls (540 cm^2 trapping surface). Delta traps were baited with the same type of pheromone lures as used indoors to monitor *T. variabile* and *P. interpunctella. Tribolium castaneum* was monitored using Dome traps, but with cracked grain instead of food oil in the pitfall, to prevent contamination, and held in place with a 14 × 14 cm metal mesh (11 mm diameter pore size) box attached to the ground with metal spikes.

There were 11 trapping locations on each floor of the mill, giving a total of 55 locations, with each location containing a Dome and Pherocon II trap. Nine of the locations on each floor were roughly equidistant from each other along the outer walls, and two were placed near walls, pillars, or pieces of equipment in the interior space. Eight Delta traps and four Dome traps were placed outside, around the perimeter of the mill and attached grain elevator. Traps were typically checked every 2 weeks and the pheromone lures were replaced every 8 weeks. Dome traps were replaced at each sampling date and returned to the laboratory to facilitate insect identification and counting. Stored-product insects were identified using the keys in Gorham (1987). Different trapping intervals were sometimes used, usually due to the timing of fumigations, so all capture data was converted to a daily capture rate over the interval to facilitate comparison. The mean trap capture was determined for each floor on each sample date, and the mill mean and standard error of the mean was determined based on the means of each floor.

The potential for insect immigration was evaluated using a self mark-recapture method (Campbell et al., 2002). Self-marking stations were modified from those described in Wileyto et al. (1994) and Campbell et al. (2002), and designed to enable insects to enter and leave, but also confine and protect the fluorescent marking powder from exposure to rain and wind. The marking stations consisted of a plastic bucket (17 cm in diameter and 11 cm height) with a snap-on lid (Airlite Plastics, Omaha, NE, USA) with three 2.5 × 2.5 cm flaps cut equidistant from each other on the sides. Several holes, 0.5 cm in diameter, were drilled into the bottom of the bucket to allow any rainwater collecting in the bucket to drain. A 90 mm Petri dish bottom was glued to the middle of the floor of the bucket and contained a 1–2 mm layer of Saturn Yellow fluorescent powder (DayGlo Color, Cleveland, OH, USA). Pheromone lures for *P. interpunctella* were placed on top of the powder near the center of the Petri dish. Moths entered the marking station through the flaps and landed inside. They walked around the pheromone lure as part of their behavioral response to the pheromone and in the process pick up marking powder. After a certain giving-up-time, marked moths leave the marking station through the flaps. Pheromone lures were changed at the same time as the traps, and the powder was refreshed as necessary.

Four self-marking stations were placed outside around the perimeter of the mill/elevator and warehouses. The marking stations were in place from 11 September 2002 to 15 November 2002. During this period, all the pheromone traps were replaced at each sampling period and returned to the laboratory. Captured insects from both the indoor and outdoor traps were inspected under long wave (365 nm) ultraviolet light (Black-Ray Lamp Model UVL-21; UVP Inc., Upland, CA) to determine whether they had retained any powder on their cuticle. A magnifying lens and a dissecting microscope were used to determine whether the insects had collected even small amounts of fluorescent powder.

Results

Tribolium castaneum was captured in Dome traps within the mill throughout the monitoring period (total of 14,390 beetles were captured), including during the winter months (Figure 1B). Average trap capture declined after each fumigation treatment, and then increased until the date of the next fumigation (Figures 1B and 2). The average trap capture level when fumigations were performed was 1.1 ± 0.4 beetles trap^{-1} day^{-1}, but ranged from 0.2 to 2.2 beetles trap^{-1} day^{-1}. The average reduction in trap capture after a fumigation was 88.1 ± 3.3% (n = 5).

Trap captures increased at a linear rate between 0.002 and 0.005 beetles trap^{-1} day^{-1} for at least the first 100 days after fumigation, except for the fumigation in June 2003, which rebounded rapidly (Figure 2). A seasonal effect on rebound is suggested, because the initial increased rate after fumigation in November (0.002 beetles trap^{-1} day^{-1}, based on a linear regression of trap captures within 100 days after fumigation) was less than half of that in June–August (0.004–0.005 beetles trap^{-1} day^{-1}). After two of the fumigations, a sharp increase in trap captures was observed (Figures 2C,D), in one case less than 75 days after the fumigation, and in the other case after more than 175 days.

For periods when inside and outside locations were monitored (n = 31), the mean trap capture of red flour beetles outside the mill was lower than that inside the mill (Figures 1A,B); 0.069 ± 0.02 compared to 0.47 ± 0.08 beetles trap^{-1} day^{-1} (two-tailed paired t-test: t = 4.999, d.f. = 30, P<0.001). The number of beetles captured inside and outside were correlated (Spearman rank correlation, $r_s = 0.415$ $(r_s)_{0.05(2),29} = 0.368$). For the three dates when beetles were captured outside prior to fumigation, outside trap captures declined after fumigation (decreases of 58.3%, 32.4%, and 94.7% for July 2002, June 2003, and August 2003, respectively).

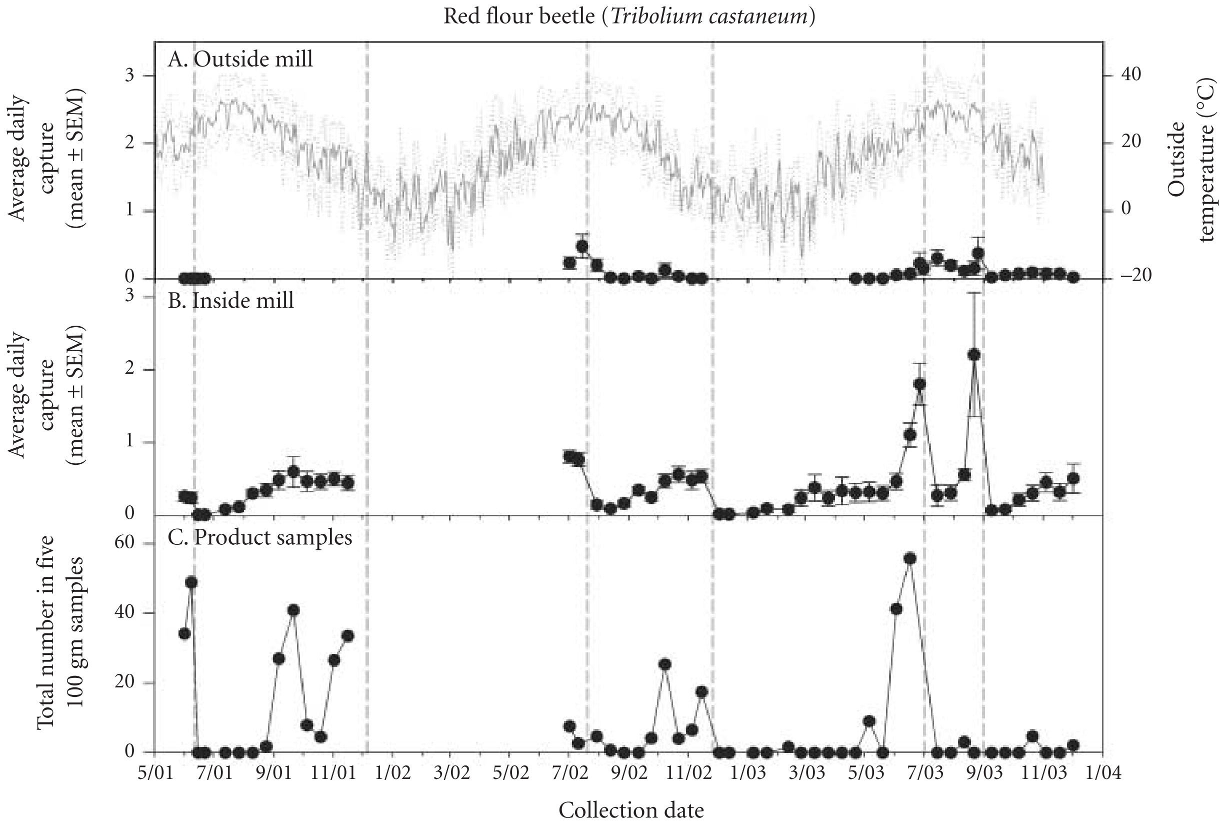

Figure 1 Changes in the number of *Tribolium castaneum*, the red flour beetle, associated with a flour mill from June 2001 until December 2003. (A) Average daily capture of beetles in pitfall traps baited with pheromone and food attractant placed outside the flour mill. Dark gray lines indicate the daily outside air temperature over the monitoring period: the solid line indicates daily mean temperature, and dotted lines indicate the daily maximum and minimum temperatures. (B) Average daily capture of beetles per trap baited with pheromone and food attractant placed within the flour mill. (C) Total number of live adults recovered per 500 g product: combined product samples collected at four locations in the product stream (3rd, 4th, and 5th mids, and purifiers) and a trash bucket. Gray vertical dashed lines indicate the dates on which fumigations of the mill were performed.

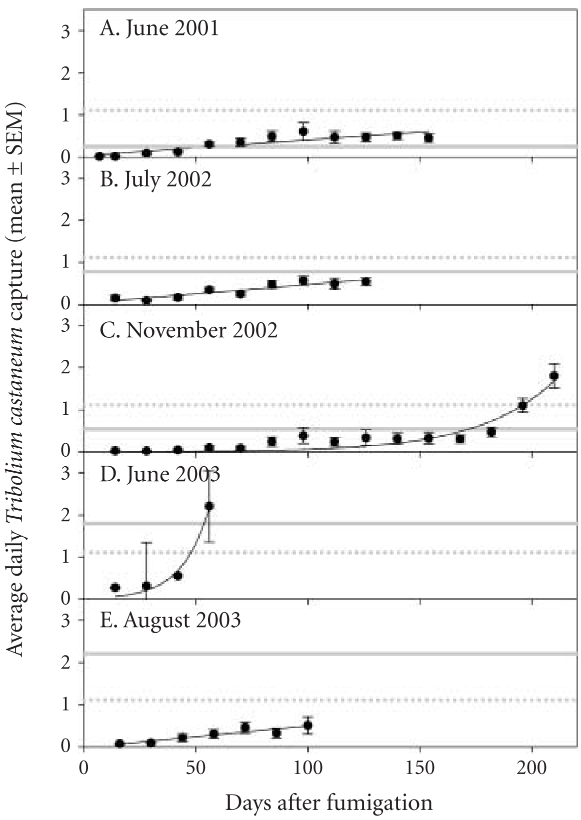

Figure 2 *Tribolium castaneum* capture in pheromone and food attractant baited pitfall traps as a function of number of days following the fumigation of a flour mill. Fumigation dates were: (A) June 2001, (B) July 2002, (C) November 2002, (D) June 2003, and (E) August 2003. In all cases, except (E) August 2003, after the last data point a fumigation was performed. Horizontal solid gray lines indicate mean trap capture level prior to that specific fumigation. Horizontal dotted gray lines indicate the average mean trap capture prior to fumigation for all five fumigations. Linear regressions (A: $y = 0.034 + 0.004x$, $r^2 = 0.769$; B: $y = 0.039 + 0.004x$, $r^2 = 0.843$; E: $y = -0.02 + 0.005x$, $r^2 = 0.859$) or exponential growth functions (C: $y = 0.0032 \times 1.03^x$, $r^2 = 0.892$; D: $y = 0.021 \times 1.09^x$, $r^2 = 0.973$) were calculated for each fumigation rebound.

Tribolium castaneum was the predominate species recovered in product samples taken from the mill equipment and trash bucket (Figure 1C). Although this data was highly variable, due in part to the relatively small volume of the samples vs. the amount of product present, the number of beetles present tended to decrease after fumigation in all cases but one, no beetles were captured immediately after fumigation, and then increased until the next fumigation. However, not all fumigations occurred when levels of beetles in the product were high. Number of beetles captured in pheromone traps and the number of live beetles recovered in product samples was correlated (Spearman rank correlation, $r_s = 0.605$ $(r_s)_{0.05(2),46} = 0.291$). In general, beetles were recovered in pheromone traps prior to being detected in product samples (Figures 1B,C).

Plodia interpunctella was prevalent inside the mill (total of 22 251 male moths captured), but was typically only captured inside when moths were also present outside the mill (Figure 3A,B). Unlike *T. castaneum*, trap capture patterns following fumigation did not show a consistent pattern of decrease after fumigation and then steady increase over time. Average trap capture prior to fumigation was 1.2 ± 0.6 moths trap^{-1} day^{-1}, and the level after treatment was variable with an average decrease in trap capture of $4.4 \pm 53.9\%$ (n = 5). In only one instance was *P. interpunctella* recovered in the product samples (Figure 3C), and this was due to the presence of larvae in the trash bucket sample that we suspected to be more susceptible to infestation than the product stream.

Regardless of fumigation schedule, *P. interpunctella* trap captures inside tended to follow the seasonal patterns in trap capture observed outside the mill: outside trap captures increasing with one or more peaks of flight activity until September, and then declining to zero by November (Figure 3A). For periods when both locations were monitored (n = 44), the mean trap capture of Indian meal moths outside the mill was greater than that inside the mill (Figure 3A,B): 16.1 ± 2.4 compared to 0.7 ± 0.1 moths trap^{-1} day^{-1} (two-tailed paired t-test: t = 6.743, d.f. = 43, $P<0.001$). The only cases when inside trap captures were higher were when outside trap captures had declined to zero in the fall/autumn, but a few moths were still captured inside. Trap captures inside and outside the mill were significantly correlated (Spearman rank correlation, $r_s = 0.901$ $(r_s)_{0.05(2),47} = 0.288$). In all three years, the captures of moths inside the mill decreased during the fall/autumn in the absence of fumigation treatment.

Like *P. interpunctella*, *T. variabile* was captured in higher numbers outside than inside the mill, and inside populations tended to follow the trends observed outside the mill and not to decrease in response to fumigation (Figure 4). The total number of beetles captured inside the mill over the monitoring period was 1196. Average trap capture prior to fumigation was 0.13 ± 0.05 beetles trap^{-1} day^{-1}, and the level after treatment was variable, with an average decrease in trap capture of $16.7 \pm 48.2\%$ (n = 5). For periods when both indoor and outdoor locations were monitored (n = 44), the mean trap capture of warehouse beetles outside the mill was greater than that inside the mill (Figure 4A,B): 12.0 ± 1.9 compared to 0.05 ± 0.01 beetles trap^{-1} day^{-1} (two-tailed paired t-test: t = 6.23, d.f. = 43, $P<0.001$). Trap capture levels inside and outside the mill were significantly correlated (Spearman rank correlation, $r_s = 0.824$ $(r_s)_{0.05(2),47}$

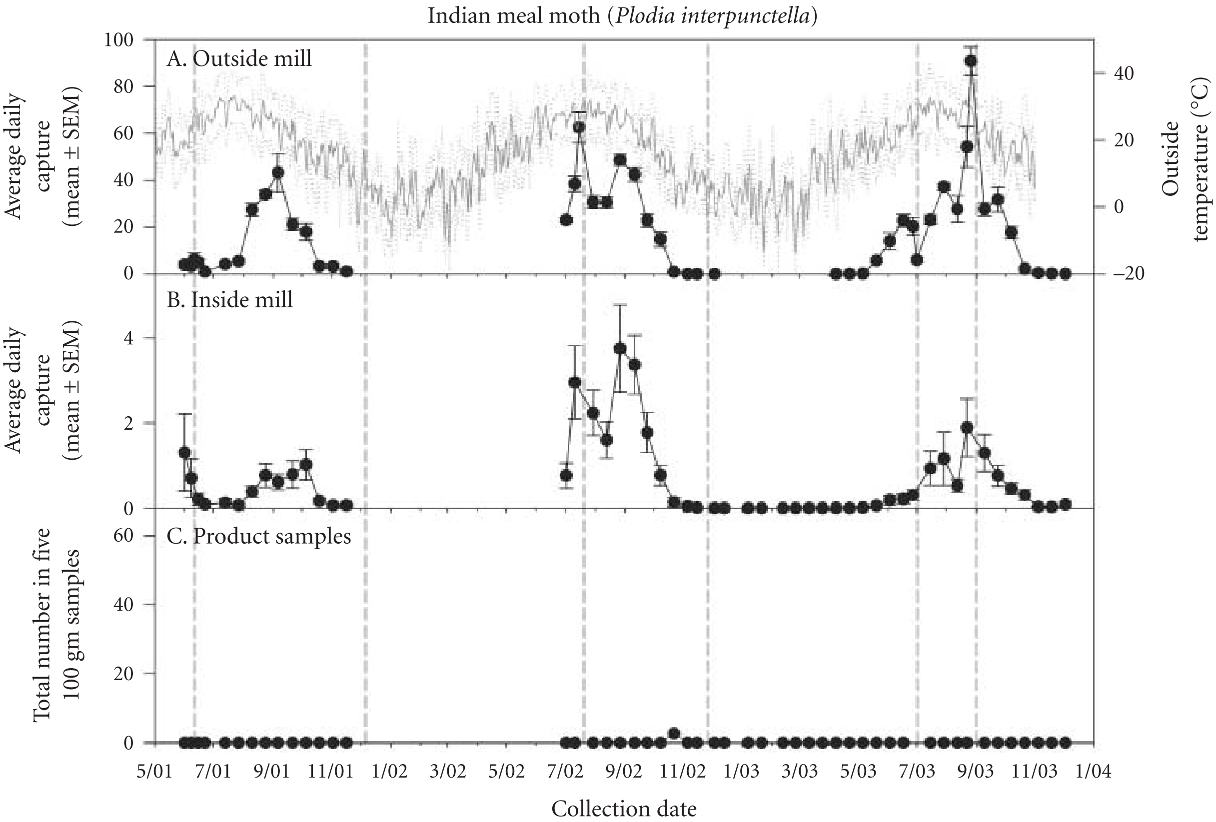

Figure 3 Changes in the number of *Plodia interpunctella*, the Indian meal moth, associated with a flour mill from June 2001 until December 2003. (A) Average daily capture of moths in traps baited with pheromone placed outside the flour mill. Dark gray lines indicate the daily outside air temperature over the monitoring period: the solid line indicates daily mean temperature, and dotted lines indicate the daily maximum and minimum temperatures. (B) Average daily capture of moths/trap baited with pheromone placed within the flour mill. (C) Total number of individuals recovered per 500 g product: combined product samples collected at four locations in the product stream (3rd, 4th, and 5th mids, and purifiers) and a trash bucket. Gray vertical dashed lines indicate the dates on which fumigations of the mill were performed.

= 0.288). This species was never recovered from the product samples (Figure 3C).

Stored-product species, other than *T. castaneum* and *T. variabile*, were also recovered in Dome traps placed inside the mill. In 2002–03, the most prevalent species were: *Typhaea stercorea* L. (Coleoptera: Mycetophagidae, n = 4427), *Cryptolestes* spp. (Coleoptera: Laemophloeidae, n = 1675), *Ahasverus advena* (Waltl) (Coleoptera: Cucujidae, n = 882), *Cryptophagus* spp. (Coleoptera: Cryptophagidae, n = 298), parasitoid wasps (Hymenoptera, n = 152), *Plodia interpunctella* (n = 89), *Litargus balteatus* Le Conte (Coleoptera: Mycetophagidae, n = 52), *Oryzaephilus* spp. (Coleoptera: Silvanidae, n = 49), *Sitophilus zeamais* Motschulsky (n = 32), *Cynaeus angustus* (LeConte) (Coleoptera: Tenebrionidae, n = 15), *Rhyzopertha dominica* (F) (Coleoptera: Bostrichidae, n = 9), *Sitophilus oryzae* (L.) (Coleoptera: Curculionidae, n = 8), *Latheticus oryzae* Waterhouse (Coleoptera: Tenebrionidae, n = 3), *Ptinus* spp. (Coleoptera: Ptinidae, n = 3), *Palorus ratzeburgii* (Wissmann) (Coleoptera: Tenebrionidae, n = 2), and *Palorus subdepressus* (Wollaston) (Coleoptera: Tenebrionidae, n = 1). Psocids (Psocoptera) and non-stored-product associated insects were also occasionally observed in the traps. Trap captures of these other species tended to follow a seasonal pattern of increasing through the summer, peaking in the fall, and then sharply declining, although the patterns for individual species or groups varied.

During the self mark-recapture experiment, 10 marked *P. interpunctella* were recaptured inside the mill and 50 marked moths were recaptured outside. If we assume that the same number of moths are marked per station as are captured per trap over an equivalent period of time, then the number of marked moths can be estimated. A total of 1370 moths were estimated to have been marked. Based on this total, we can estimate a recapture efficiency of 5.0%. The marked moths were recaptured in the basement (n = 2),

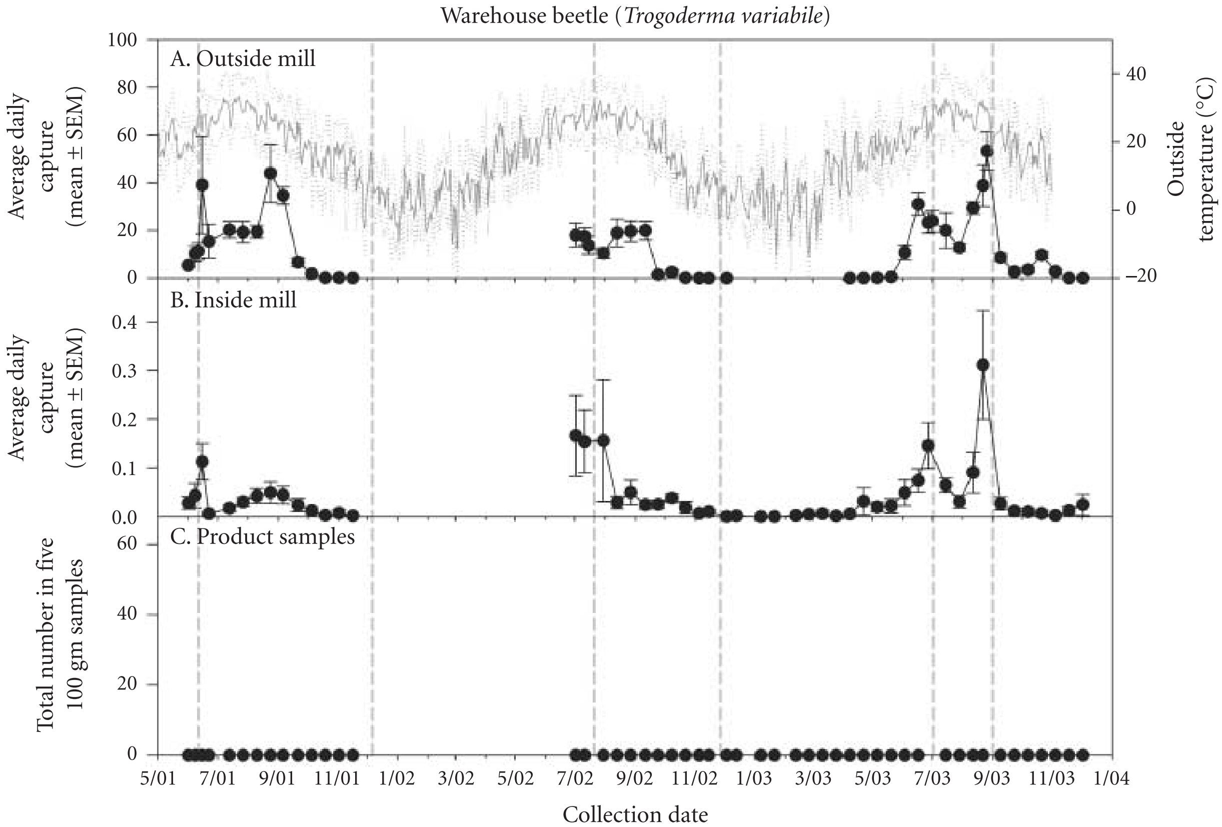

Figure 4 Changes in the number of *Trogoderma variabile*, the warehouse beetle, associated with a flour mill from June 2001 until December 2003. (A) Average daily capture of beetles in pitfall traps baited with pheromone placed outside the flour mill. Dark gray lines indicate the daily outside air temperature over the monitoring period: solid line indicates daily mean temperature and dotted lines indicate the daily maximum and minimum temperatures. (B) Average daily capture of beetles per trap per floor baited with pheromone and food attractant placed within the flour mill. (C) Total number of live adults recovered per 500 g product: combined product samples collected at four locations in the product stream (3rd, 4th, and 5th mids, and purifiers) and a trash bucket. Gray vertical dashed lines indicate the dates on which fumigations of the mill were performed.

first (n = 5), and fourth (n = 3) floors. An additional eight marked moths were captured in the warehouse adjacent to the mill.

Discussion

Since pheromone traps in this type of landscape primarily capture insects that are moving between resource patches, it can be difficult to relate pheromone trap capture with the spatial distribution of the pest and to make management decisions based on the data (Campbell et al., 2004). There is limited information available on what spatial scale pest subpopulations interact, but this has important implications for interpreting pheromone trap capture data. Our results, based on pheromone/food trap captures, suggest that at this facility pest species followed one of two general patterns.

The first pattern was that source patches for the insects lay over a spatial scale that was greater than the mill itself and there was considerable movement of individuals across this larger spatial scale, effectively linking activity inside and outside the mill. This pattern applied to both *P. interpunctella* and *T. variabile* at this location. Pheromone trap captures outside were higher than those inside the mill. Inside and outside trap captures were correlated, and both indoor and outdoor trap captures tended to cycle according to a seasonal pattern. Fumigations did not consistently influence pheromone trap captures. These species were rarely found in product samples. The capture of other stored-product associated species in the Dome traps followed a similar pattern to *P. interpunctella* and *T. variabile.* Mark–recapture data demonstrated that *P. interpunctella* was capable of entering the building from the outside, and indicated that this movement is primarily at the basement/

first and top floor levels. The result of this pattern is that pheromone/food trap captures within the mill for these species indicated the potential for infestation and the capacity for insects to immigrate, but did not accurately reflect the current level of infestation within the mill.

The second pattern suggests that source patches for the insects lay over a spatial scale contained within the mill itself, with pheromone/food traps capturing primarily insects moving among these internal patches. This pattern was seen with the major pest of this mill, *T. castaneum*. For this species, trap captures, in contrast to the other two species, tended to be lower outside compared to inside. Trap captures showed a sharp decline after fumigation treatment and then steady increase in numbers until the next fumigation. Resurgence, other than the potential rate of increase, was not impacted by season and outside trap capture levels. *Tribolium castaneum* was the most prevalent species in the product samples. Rebound after fumigation may result from a persistence of individuals within some of the patches within the mill and, probably to a lesser extent, the movement of new individuals into the mill either actively or in infested products. Our data is consistent with *T. castaneum* being considered a more important pest to the milling industry than *P. interpunctella* and *T. variabile*.

The utility of pheromone traps for monitoring *T. castaneum* in flour mills has also been questioned, but our findings demonstrate that patterns in pheromone trap capture were correlated with product infestation. Pheromone monitoring provided a more consistent measure of population trends than our product samples, but a visual inspection of larger amounts of product sample from more locations, or monitoring of the tailings samples might have provided a better estimate. Some potential advantages of a thorough pheromone trapping program over product sampling are that it can be better at detecting immigrating individuals, providing an earlier warning of a potential problem, and may be better at detecting insect levels in inaccessible areas within the structure of the building.

The source(s) of the high numbers of *P. interpunctella* and *T. variabile* captured outside is not known. Other studies have reported that stored-product insects can be captured in high numbers outside, and that many stored-product pest species are highly mobile (Chestnut, 1972; Hagstrum & Davis, 1980; Fadamiro, 1997; Campbell et al., 2002; Campbell & Mullen, 2004). Potential sources for these outside trap captures could be onsite or offsite. Doud & Phillips (2000) speculated that an adjacent grain elevator was an important source of *P. interpunctella* captured within a mill. Campbell & Mullen (2004) found that *P. interpunctella* trap capture next to a food processing facility was the same as that along the perimeter of the property, and that *T. variable* trap captures were lower away from the building, but, based on mark-recapture data, the beetles tended to be moving toward the building. *Plodia interpunctella* and *T. variabile* can also be prevalent in residential areas away from grain storage and processing facilities (J.F. Campbell, unpubl.). At this location, the presence of bulk grain storage, the accumulation of grain based spillage outside, and the surrounding residential areas could all contribute to the presence of insects outside the mill.

There is limited published information on methyl bromide fumigation efficacy and the mechanism and rate of pest rebound after this treatment. Although the fumigation rebound dataset reported here is still very limited, it does suggest some interesting hypotheses. First, because the timing of the fumigations is typically constrained by factors other than insect density, due to the necessity of shutting down the facility for several days, the insect density at the time of fumigation was variable. On average, the daily trap capture of *T. castaneum* was reduced by 88% after fumigation and in most cases populations rebounded, based on pheromone trapping, at a linear rate for at least 100 days. This linear rate appeared to be lower in the winter, perhaps due to cooler temperatures within the mill or less recolonization from outside sources.

In two cases, there was a sharp upturn in the trap capture rate, possibly indicating a shift in an exponential population increase. This was probably not observed in the other fumigations because either an additional fumigation was performed before this happened, or the monitoring was terminated. In June 2003, this rebound occurred shortly after the fumigation, indicating some kind of treatment failure, although the reason for this is not known. The reasons for the difference in rebound between June 2001 and June 2003 are not clear, but the two fumigations differed in the initial population density and the type of fumigant used. From the perspective of using monitoring data to make decisions about the timing of fumigations or other whole structure treatments, some type of intervention is likely to be needed prior to the start of this rapid growth in the population. In practice, a second fumigation was typically performed before the average trap capture exceeded the level prior to the first fumigation, except in cases where exponential growth had started. Pheromone trapping has also been found to be a valuable tool for monitoring suppression and rebound after heat treatments (Roesli et al., 2003).

Our understanding of pest ecology and behavior in flour mills is limited. Although the results presented here are limited to a single mill, they are the most complete data available on stored-product pest ecology in and around flour mills. This data set is also limited to some extent by the constraints of working in an operating mill and the need to use different types of traps for different insect species and locations. Using more of a landscape ecology perspective is a valuable framework for addressing questions about pest management in food processing facilities. The type of information generated in this case study is important in the development of methyl bromide alternatives because it provides baseline information for evaluating the efficacy of new alternative management tools, and because it suggests which management approaches may be best for a particular species. Further research on pest population structure and dynamics at additional mills is needed in order to determine more general information and to develop improved integrated pest management programs.

Acknowledgements

R. Hammel provided excellent technical support, with assistance from B. Barnett and J. Vardeman. We thank the management and personnel of the flour mill for their cooperation, M. Mullen, B. Schneider, and S. Prabhakaran for assistance in setting up the project and reviewing the manuscript prior to submission. The research was supported in part by USDA CSREES RAMP Agreement no. 00-51101-9674. 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 US Department of Agriculture.

References

Arbogast RT, Kendra PE, Mankin RW & McGovern JE (2000) Monitoring insect pests in retail stores by trapping and spatial analysis. Journal of Economic Entomology 93: 1531–1542.

Arbogast RT, Weaver DK, Kendra PE & Brenner RJ (1998) Implications of spatial distribution of insect populations in storage ecosystems. Environmental Entomology 27: 202–216.

Brenner RJ, Focks DA, Arbogast RT, Weaver DK & Shuman D (1998) Practical use of spatial analysis in precision targeting for integrated pest management. American Entomologist 44: 79–101.

Campbell JF, Arthur FH & Mullen MA (2004) Insect management in food processing facilities. Advances in Food and Nutrition Research, in press.

Campbell JF & Hagstrum DW (2002) Patch exploitation by *Tribolium castaneum*: Movement patterns, distribution, and oviposition. Journal of Stored Products Research 38: 55–68.

Campbell JF & Mullen MA (2004) Distribution and dispersal behavior of *Trogoderma variabile* Ballion and *Plodia interpunctella* (Hübner) outside a food processing plant. Journal of Economic Entomology, in press.

Campbell JF, Mullen MA & Dowdy AK (2002) Monitoring stored-product pests in food processing plants: a case study using pheromone trapping, contour mapping, and mark-recapture. Journal of Economic Entomology 95: 1089–1101.

Campbell JF & Runnion C (2003) Patch exploitation by female red flour beetles, *Tribolium castaneum*. Journal of Insect Science 3(20). Available online: http://insectscience.org/3.20.

Chestnut TL (1972) Flight habits of the maize weevil as related to field infestation of corn. Journal of Economic Entomology 65: 434–435.

Doud CW & Phillips TW (2000) Activity of *Plodia interpunctella* (Lepidoptera: Pyralidae) in and around flour mills. Journal of Economic Entomology 93: 1842–1847.

Dowdy AK & McGaughey WH (1994) Seasonal activity of stored-product insects in and around farm-stored wheat. Journal of Economic Entomology 87: 1351–1358.

Evans BR & Porter JE (1965) The incidence, importance, and control of insects found in stored food and food-handling areas of ships. Journal of Economic Entomology 19: 173–180.

Fadamiro HY (1997) Free flight capacity determination in a sustained flight tunnel: Effects of age and sexual state on the flight duration of *Prostephanus truncatus*. Physiological Entomology 22: 29–36.

Fields PG, Van Loon J, Dolinski MG, Harris JL & Burkholder WE (1993) The distribution of *Rhyzopertha dominica* (F.) in western Canada. Canadian Entomologist 125: 317–328.

Good NE (1937) Insects found in the milling streams of flour mills in the southwestern milling area. Journal of the Kansas Entomological Society 10: 135–148.

Gorham JR (1987) Insect and Mite Pests in Food: An Illustrated Key. Agriculture Handbook Number 655. US Department of Agriculture.

Hagstrum DW & Davis LR Jr (1980) Mate-seeking behavior of *Ephestia cautella*. Environmental Entomology 9: 589–592.

Mullen MA (1992) Development of a pheromone trap for monitoring *Tribolium castaneum*. Journal of Stored Product Research 28: 245–249.

Roesli R, Subramanyam B, Campbell JF & Kemp K (2003) Stored-product insects in Kansas retail pet stores. Journal of Economic Entomology 96: 1958–1966.

Roesli R, Subramanyam B, Fairchild FJ & Behnke KC (2003) Trap catches of stored-product insects before and after heat treatment in a pilot feed mill. Journal of Stored Product Research 39: 521–540.

Scott JH (1951) Flour Milling Process. Chapman & Hall, London.

Taylor RWD (1994) Methyl bromide – is there any future for this noteworthy fumigant? Journal of Stored Product Research 30: 253–260.

Throne JE & Cline LD (1989) Seasonal flight activity of the maize weevil, *Sitophilus zeamais* Motschulsky (Coleoptera: Curculionidae), and the rice weevil, *S. oryzae* (L.), in South Carolina. Journal of Agricultural Entomology 6: 183–192.

Throne JE & Cline LD (1991) Seasonal abundance of maize and rice weevils (Coleoptera: Curculionidae) in South Carolina. Journal of Agricultural Entomology 8: 93–100.

Wileyto EP, Ewens WJ & Mullen MA (1994) Mark-recapture population estimates: a tool for improving interpretation of trapping experiments. Ecology 75: 1109–1117.

Zimmerman ML (1990) Coleoptera found in imported stored-food products entering southern California and Arizona between December 1984 and December 1987. Coleopterists Bulletin 44: 235–240.