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Temporal dynamics and response to fogging or fumigation of stored-product Coleoptera in a grain processing facility

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Abstract

Stored-product Coleoptera were monitored continuously over 22 months using pitfall traps at an operating food mill and adjacent warehouse in Kansas. Mill management practiced conventional pest management, including monthly crack and crevice applications of a residual insecticide and semi-annual fumigation with methyl bromide in the mill, and application of dichlorvos + pyrethrin (commonly called fogging) in the warehouse. The dynamic temporal changes in insect captures and effect of the global interventions on insect captures were analyzed. Data show that more *Trogoderma variabile* individuals were captured in the warehouse than any other species, but *Tribolium castaneum* was captured with greater frequency. *Trogoderma variabile* captures inside the warehouse tended to mirror outside captures suggesting immigration from the outside. The food mill was infested year round with *T. castaneum* but developed substantial populations of *Typhaea stercorea* during the warm months from May through October. Stored-product insects were nearly always captured during the first trapping interval following methyl bromide or dichlorvos + pyrethrin applications, but it was not clear if the insects were surviving inside the structure or if they were rapidly recolonizing after treatment. Population increases immediately following fumigation or fogging occurred only in fungus-feeding species in late spring or summer. The most successful fumigation was conducted late in the autumn when environmental conditions prevented insect activity outside. Information contained in this study provides data that could be used to improve insect management programs for milling and processing facilities.
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Keywords: *Tribolium castaneum*; Traps; Stored products; Methyl bromide; Monitoring; Food mill

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1. Introduction

Successful management of stored-product insects in grain processing facilities requires effective monitoring and a clear understanding of the temporal and spatial changes in the pest population (Burkholder, 1990). Efficacy and economy of pest management interventions can be improved when decisions are based on monitoring data rather than calendar scheduled interventions. Unfortunately, cost and practicality limit direct sampling methods for insect population estimation or classification relative to a threshold and managers are forced to rely on indirect methods such as pheromone-baited insect traps. Aggregation and sex pheromones of the most commonly occurring stored-product insects have been synthesized and are commercially available (Chambers, 1990; Phillips et al., 2000). Additionally, stored-product insect traps have evolved to be more useful in dusty environments commonly found in food processing facilities (Vick et al., 1990; Mullen, 1992, 1994; Mullen and Dowdy, 2001). Industrialized countries have made significant progress toward alternative insect control strategies, monitoring, and management techniques (Phillips et al., 2000), but additional studies are needed to gain widespread acceptance of traps by industry. Previous scientific studies have characterized insect populations in flour mills, feed mills, warehousing, and retail environments (Platt et al., 1998; Arbogast et al., 2000, 2002, 2005; Campbell et al., 2002, 2003; Roesli et al., 2003a).

Insect population dynamics in food processing facilities are regulated by a complex suite of biotic and abiotic factors. Stored-product insects typically have a high growth rate per month under optimal conditions, therefore facility managers are interested in manipulating conditions to prohibit rapid growth. Temperature, relative humidity, commodity moisture, and diet directly affect insect development time (Hagstrum and Milliken, 1988), fecundity, mobility, and survival. Pests such as *Tribolium castaneum* (Herbst) can complete development in 19–20 d at optimum conditions (Howe, 1956). Food in the form of dust and product spillage is inherent to all grain and feed processing operations and insects are able to exploit these patchy environments (Campbell and Hagstrum, 2002; Campbell and Runnion, 2003). Food quality can be a limiting factor for species such as *Rhyzopertha dominica* (F.) and *Sitophilus oryzae* (L.) that develop in whole kernels and for species that require fungi for nutrition. Intraspecific and interspecific competition probably play important roles in pest population dynamics, but it is difficult to isolate and measure the defining factors in the field (Price, 1997).

In the event the pest population is deemed excessively large, global or whole plant intervention strategies are often used in the food processing industries. Mills in the United States are typically fumigated with methyl bromide, but this practice is likely to end in the near future because this compound has been classified as an ozone depleting substance and its use is being phased out (UNEP, 1996; Anonymous, 1998). Another global intervention, commonly used in large warehouses, is the use of aerosols applied as a mist or fog (Arthur and Phillips, 2003; Campbell et al., 2004).

There are limited published data addressing long-term insect population dynamics in grain processing facilities and how to effectively manage these populations. Therefore, the objectives of this study were to: (1) identify and quantify the species of Coleoptera inhabiting the food processing mill and accompanying warehouse; (2) monitor temporal population changes in the facilities; and (3) evaluate the impact of commercial intervention strategies on stored-product insect populations.

2. Materials and methods

2.1. Study site

Monitoring was conducted at a commercial grain processing facility located in Kansas. The modern facility (<10 years old) operated 24 h a day, 7 d a week throughout the study and produced a grain-based product for human consumption. Raw grain, primarily wheat contracted through local growers, was delivered by semi-truck daily because there was little bin storage available. The facility was situated in a rural industrial complex bordered by an animal feed processing facility and agricultural production fields. The five-story mill (10 m × 24 m per floor) was adjacent to a large building containing separate rooms for product drying (22 m × 22 m), and packaging and storage (18 m × 42 m). The mill was constructed of concrete while the warehouse and drying room were corrugated steel buildings with a concrete floor.

In addition to routine sanitation, insect management tactics consistent with commercial grain processing plants were practiced. A contracted pest management professional conducted a residual spray program, while a second company conducted fumigation/fogging in the spring and fall of each year. The residual spray program consisted of monthly crack and crevice (interior perimeter) applications of cyfluthrin (Tempo® SC Ultra, Bayer Corp, Kansas City, MO, USA) at a concentration of 0.05% to every floor in the mill, but not the warehouse and drying room. These applications began 6 months before and continued during the study. The pest management professional stated that he did not directly spray the traps. Cracks in the pavement around the warehouse were cleaned with compressed air and sealed with caulk in July 2003.

During 2003 and 2004, the professional fumigation company simultaneously fumigated the mill with methyl bromide and fogged the warehouse with dichlorvos + pyrethrins in mid-May and again in late September. Both the mill and the warehouse were fogged with dichlorvos + pyrethrins in mid-September 2003. Additional dichlorvos + pyrethrins applications were conducted in 2004 during the summer months in the warehouse only. All fumigation and fogging applications were conducted in accordance with pesticide label concentrations and durations. Detailed data regarding methyl bromide concentration readings during the fumigation are difficult to obtain because commercial fumigators monitor concentrations at very few locations in the mill. Aerosol applications are calibrated solely based on space to be treated and no measure of residue accumulation is conducted. The goal of this research is not to critically evaluate each individual global intervention, but rather to generalize how these commonly applied commercial scale treatments affect insect populations and how much variation in response could be expected.

2.2. Insect traps

Insect monitoring was accomplished using a variety of commercial insect traps and pheromone lures (Mullen, 1994). Pitfall traps (Storgard® Dome™ trap design, Trécé Inc., Adair, OK, USA), baited with a *Tribolium* spp. pheromone lure (Storegard® lures, Trécé Inc., Adair, OK, USA), and attractant oil (Storegard® oil, Trécé Inc., Adair, OK, USA) were placed on the floor immediately adjacent to walls and in corners. The oil attracts a wide range of grain-feeding Coleopteran species (Barak and Burkholder, 1984; Mullen, 1994; Arbogast et al., 2000). Green sticky traps (Pherocon® Delta IIID, Trécé Inc., Adair, OK, USA) baited with a *Trogoderma* spp. pheromone lure (Storegard® lures, Trécé Inc., Adair, OK, USA) were hung on a chain link fence approximately 100 m from the mill. All flight traps were hung at a height of 1.5 m above the ground. In May 2004, *Trogoderma* spp. lures were added to the pitfall traps in the warehouse/drying building and *Tribolium* spp. lures to the outside sticky traps. Traps were generally serviced every 2 weeks but this interval was changed to 1 week immediately before and after fumigations. Captured insects were removed from the traps and placed in vials filled with ethyl alcohol for subsequent identification and enumeration. Pitfall traps were washed in soapy water and pheromone lures replaced every 6–8 weeks.

2.3. Trap placement and duration

Pitfall traps were present throughout the facility commencing 14 February 2003 and ending 4 November 2004. Five to six pitfall traps were positioned on each floor around the perimeter of the mill and under large milling equipment. Traps were generally equally spaced around the periphery of each floor, but traps were not placed in areas of heavy product accumulation or daily cleaning. The warehouse contained seven pitfall traps, the drying room five. When outside temperatures were above 10 °C, 10 sticky traps were deployed outdoors around the perimeter of the facility; these traps were approximately 100–150 m from any buildings.

2.4. Temperature monitoring

Temperature was monitored throughout the study. One data logger (Hobo® H8 family, Onset Computer Corp., Bourne, MA, USA) was situated on the middle floor of the mill and a second was placed in the middle of the warehouse. A Hobo® H8 pro series outdoor data logger placed inside a solar radiation shield (part # M-RSA, Onset Computer Corp., Pocasset, MA, USA) was positioned 50 m away from the mill. All loggers were situated 1.5 m above the floor or ground and recorded temperatures every 2 h during the study.

2.5. Data presentation

Insect captures in traps were quantified for presentation in two ways. First, line plots depicted the mean and standard error of insect captures per week per trap for that trapping interval. These data points were calculated using PROC MEANS (SAS Institute, 1999) where the response variable (adult beetles captured) was divided by the number of calendar days in that trapping interval and then multiplied by seven to give the adjusted weekly average. Mean and standard errors shown on the figures reflect only those traps containing insects. Secondly, a vertical bar graph inserted behind the corresponding mean shows the proportion of traps containing at least one insect.

2.6. Statistical analyses

Statistical comparisons of insect captures (all traps) were conducted separately for the warehouse/dry room complex and the mill since there were differences in building construction and insect management methods. Comparisons of insect captures one week before and one week after interventions were calculated using ANOVA (PROC GLM, SAS Institute, 1999). Comparisons were not conducted for intervals when the intervention occurred while traps were still in place as indicated by the lack of a break between data points on the figures. Comparisons of insect populations on the first floor vs. all other floors in the mill were conducted with single degree of freedom contrasts. A square root transformation (Zar, 1984) was employed prior to statistical tests to normalize variances. Untransformed means and standard errors are presented in the text. Pitfall traps that were found damaged, filled with dust, upside down, missing the pheromone lure, or extremely dirty were considered lost data. Significant differences were based on an alpha value of 0.1 due to large expected variation in insect captures.

3. Results

3.1. Insect species and abundance

In the warehouse, 13 times more *Trogoderma variabile* Ballion were captured than the next most common insect species, *T. castaneum. Anthicus* sp., Lathridiidae, and *Typhaea stercorea* (L.) were also captured in large numbers relative to the rest of the taxa. *Tribolium castaneum* was captured in more trapping intervals (82.9%) than any other insect species or family while *T. variabile*, *T. stercorea*, and members of the Carabidae were captured in >60% of the trapping intervals. *Anthicus* sp., Lathridiidae, *Ahasverus advena* (Waltl), and *Oryzaephilus surinamensis* (L.) were captured in more than 50% of the trapping intervals while the remaining taxa were captured infrequently (Table 1).

Species captured in the greatest numbers by pitfall traps in the mill were *T. castaneum, T. stercorea, Anthicus* sp., and *Cryptolestes* spp. *Tribolium castaneum* was captured in 96% of trapping intervals while *T. stercorea*, *Anthicus* sp., Carabidae, and *Cryptolestes* spp. were captured in at least 60%, and *A. advena* was captured in 50%. Most of the remaining species were captured in small numbers and in less than half of the intervals (Table 2). The longheaded flour beetle, *Latheticus oryzae* Waterhouse, was found in low numbers during 44% of the trapping intervals.

3.2. Temporal changes in insect captures

In both the mill and warehouse, trap catch was maximum during the summer and early fall months. Generally, most captures occurred between May and October with population peaks in September (Figs. 1 and 2). Fungivores such as Lathridiidae, *T. stercorea*, and *A. advena* were absent or scarce during the winter months. *Trogoderma variabile* was a significant pest in the warehouse (61% of trapping intervals) but was captured in only 31% of trapping intervals in the mill. Conversely, *O. surinamensis* was captured in the warehouse during more than half the trapping intervals but was detected in only 9.5% of the trapping intervals in the mill.

Insect captures in the outside traps varied widely by species. Only two *T. castaneum* individuals were captured in the outside traps during the summer of 2004, strongly contrasting with frequent

Table 1
Insect species, number collected, and frequency of capture (% of 41 intervals) for all insects captured in pitfall traps located in the warehouse

Family and species	Total number collected	Frequency of capture (%)
Anthicidae		
Anthicus sp.	135	56.1
Bostrichidae		
Rhyzopertha dominica (F.)	1	2.4
Carabidae	92	61.0
Chrysomelidae		
Alticinae	2	4.9
Cryptophagidae		
Cryptophagus spp.	5	12.2
Curculionidae		
Sitophilus oryzae (L.)	2	4.9
Dermestidae		
Trogoderma variabile Ballion	2828	61.0
Elateridae	33	22.0
Laemophloeidae		
Cryptolestes spp.	35	36.6
Lathridiidae	118	51.2
Mycetophagidae		
Typhaea stercorea (L.)	105	65.9
Litargus balteatus LeConte	57	31.7
Nitidulidae	11	17.1
Phalacridae	3	2.4
Rhizophagidae	9	14.6
Scarabaeidae	3	7.3
Silvanidae		
Ahasverus advena (Waltl)	62	53.7
Oryzaephilus surinamensis (L.)	82	51.2
Staphylinidae	37	46.3
Tenebrionidae		
Tribolium castaneum (Herbst)	211	82.9
Latheticus oryzae Waterhouse	10	14.6
Blapstinus sp.	46	29.3
Cynaeus angustus (Leconte)	1	2.4

T. variabile captures (Fig. 3). No insects were captured in outdoor traps until May, and insects were captured in all 10 traps from July through September in 2003 and from June through October in 2004. No insects were captured outdoors after mid-November.

Table 2
Insect species, number collected, and frequency of capture (% out of 42 intervals) for all insects captured in pitfall traps located in the mill

Family and species	Total number collected	Frequency of capture (%)
Anthicidae		
Anthicus sp.	458	66.7
Bostrichidae		
Rhyzopertha dominca (F.)	2	4.7
Carabidae	183	61.9
Chrysomelidae		
Alticinae	4	4.7
Coccinellidae	8	9.5
Cryptophagidae		
Cryptophagus spp.	4	7.1
Curculionidae		
Sitophilus oryzae (L.)	7	14.3
Dermestidae		
Trogoderma variabile Ballion	47	31.0
Elateridae	91	40.5
Histeridae	1	2.4
Laemophloeidae		
Cryptolestes spp.	321	59.5
Lathridiidae	66	47.6
Mycetophagidae		
Typhaea stercorea (L.)	975	69.0
Litargus balteatus LeConte	22	21.4
Nitidulidae	5	9.5
Phalacridae	24	11.9
Rhizophagidae	12	16.7
Scarabaeidae	4	9.5
Silvanidae		
Ahasverus advena (Waltl)	151	50.0
Oryzaephilus surinamensis (L.)	4	9.5
Staphylinidae	42	28.6
Tenebrionidae		
Tribolium castaneum (Herbst)	1123	97.6
Latheticus oryzae Waterhouse	282	45.2
Blapstinus sp.	25	26.2
Cynaeus angustus (LeConte)	1	2.4

The warmest indoor and outdoor temperatures (Fig. 4) occurred during the month of August. *Trogoderma variabile* indoor captures decreased after the minimum outside temperature fell below freezing. Furthermore, the proportion of indoor traps with insects of this species remained low or absent until May of each year.

3.3. Effectiveness of management interventions

Application of dichlorvos + pyrethrin in the warehouse/drying room or methyl bromide in the mill was generally conducted before insect captures became numerous. As a result, there were few

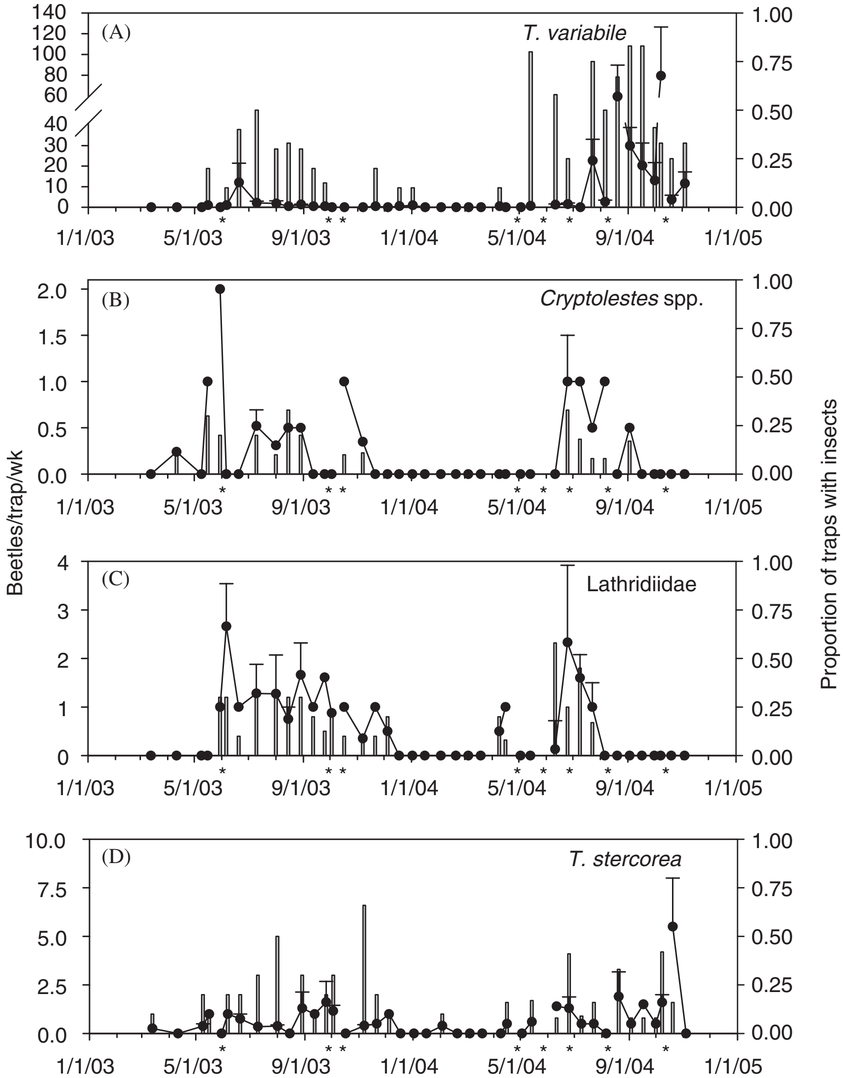

Fig. 1. Mean ± SEM captures per trap per week of insects in pitfall traps containing at least one insect located in the warehouse and drying room. Vertical bars indicate proportion of traps containing at least one insect, and asterisks (*) applications of dichlorvos + pyrethrin. Note that the *y*-axis is different on each figure.

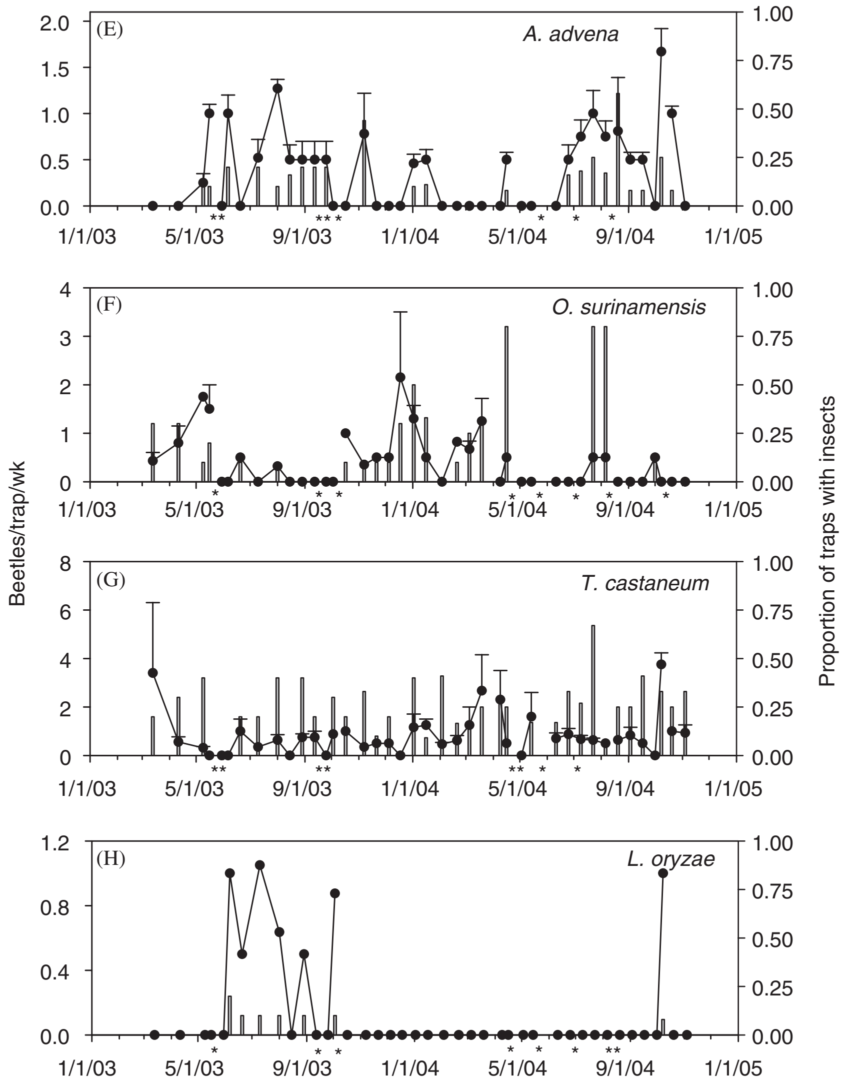

Fig. 1. (*Continued*)

statistical differences in numbers of any species captured before and after the intervention (Tables 3 and 4). Pest management professionals stated that the target of control interventions was *T. castaneum*; however, *T. castaneum* captures in the warehouse only significantly decreased after one of the five dichlorvos + pyrethrin applications. *Tribolium castaneum* individuals were always captured immediately following fogging except in May 2003, when there were no captures before the fogging, and in April 2004 (Table 3). Similarly, *T. castaneum* populations in the mill decreased following each of the four fumigations but this decrease was only significant following the October 2004 fumigation (Table 4). *Tribolium castaneum* was detected immediately following fumigation in three of the four fumigations. Immediately following the October 2004 fumigation, large numbers of live *T. castaneum* were observed on the fifth floor underneath equipment adjacent to an outside wall. Closer inspection revealed substantial quantities (>2 kg) of product in the equipment.

Captures of all species were expected to decrease following fumigation or fogging but they did not. The effect of intervention on numbers captured varied with time of year, population density, and species. Aside from *T. castaneum*, the only other statistically significant decrease attributed to dichlorvos + pyrethrins occurred following the October 2003 fogging in the warehouse when

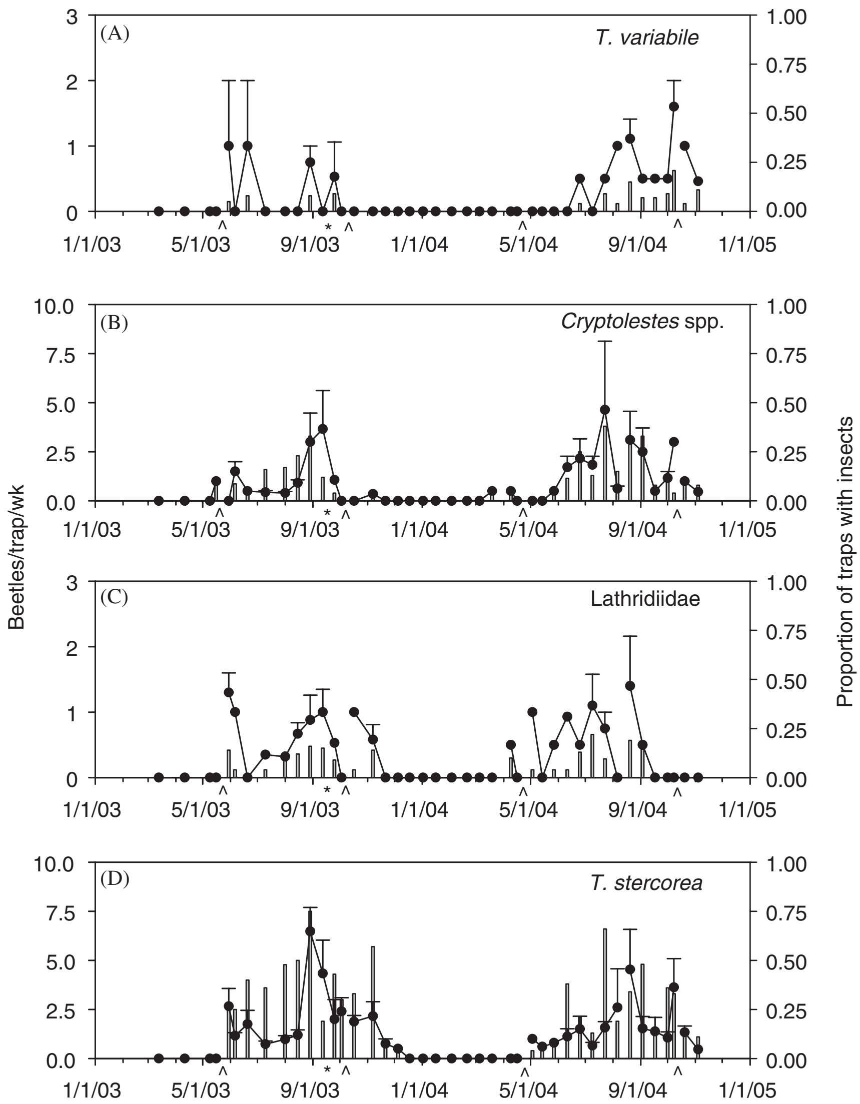

Fig. 2. Mean ± SEM captures per trap per week of insects in pitfall traps containing at least one insect located in the mill. Vertical bars indicate the proportion of traps containing at least one insect. Asterisks (*) indicate the timing of dichlorvos + pyrethrin applications while the circumflex (∧) indicates methyl bromide applications. Note that the *y*-axis is different on each figure.

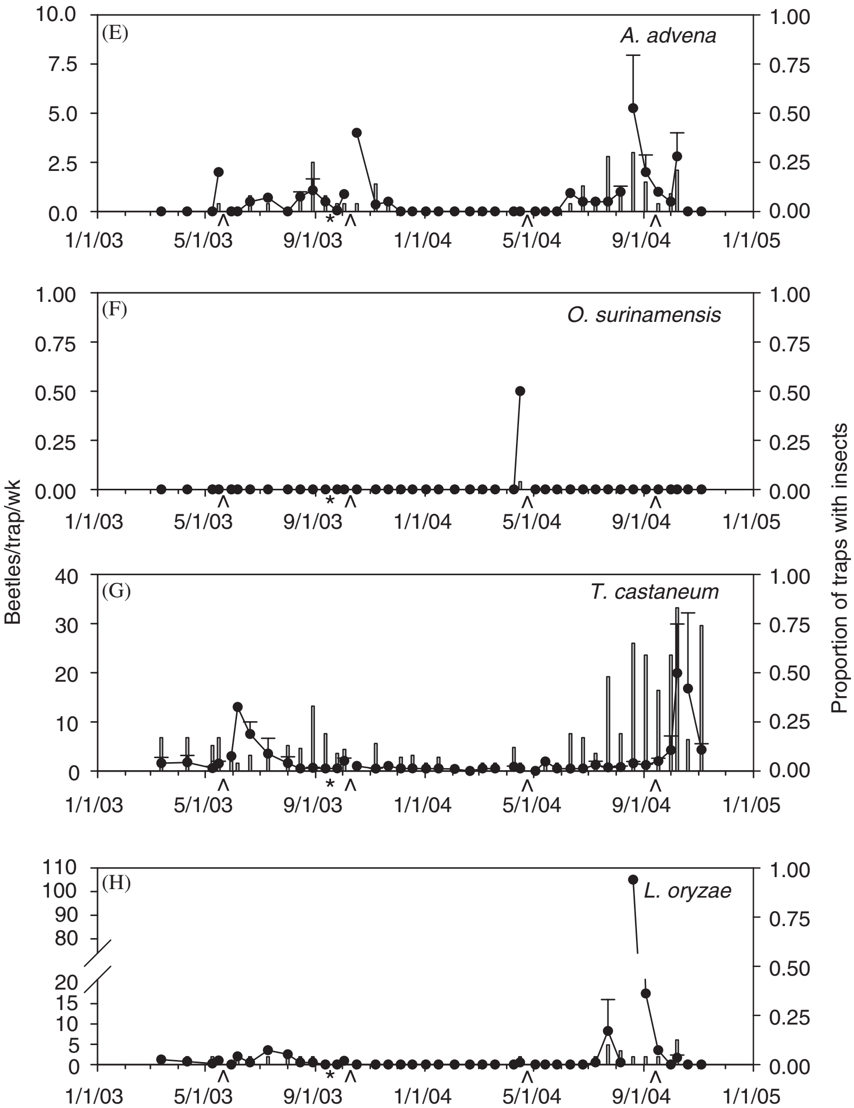

Fig. 2. (*Continued*)

T. stercorea populations fell from 0.4 to 0.0 insects/trap/week (Table 3). Conversely, insect captures sometimes increased immediately following dichlorvos + pyrethrin applications, but these increases were only significant for *T. variabile* and *A. advena* following the August 2004 fogging. In the mill, significant decreases were noted for *T. variabile, T. stercorea*, *A. advena*, and *T. castaneum* following the October 2004 methyl bromide fumigation. The only significant increase following methyl bromide fumigation in the mill occurred in May 2003 when *T. stercorea* captures increased from 0.0 to 0.8 insects/trap/week.

Comparison between insect captures on the first floor (ground level) of the mill and the rest of the mill were based on captures during the first trapping interval after fumigation. The hypothesis

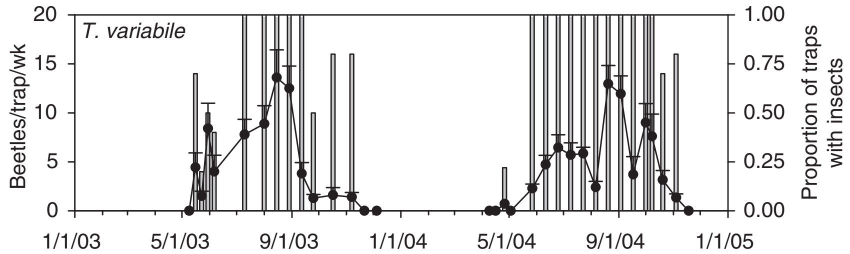

Fig. 3. Mean ± SEM captures per trap per week of *Trogoderma variable* in pheromone-baited sticky traps containing at least one insect. Vertical bars indicate the proportion of traps containing at least one insect. Traps were located on a fence around the perimeter of the facility property.

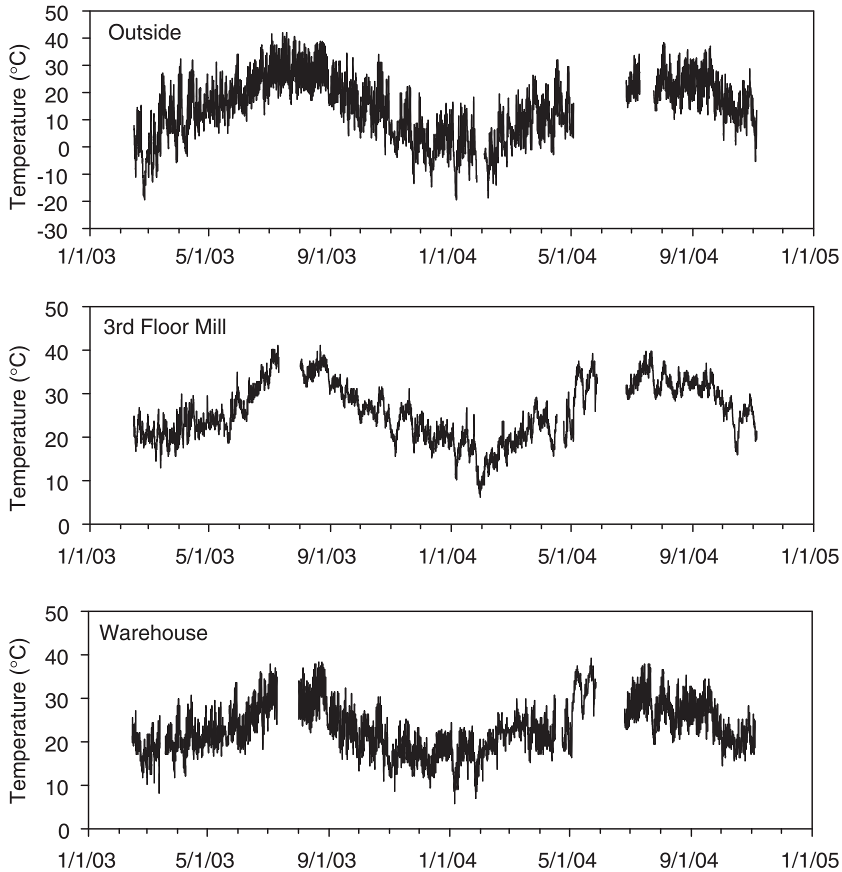

Fig. 4. Temperature in the warehouse, mill, and outside during the study.

was that insects are most likely to colonize the ground floor first. In no case were statistically more insects captured on floors 2 through 5 than on the first floor; however, *T. castaneum* was captured in greater numbers ($F = 4.47$; df = 1, 22; $P = 0.05$) on the first floor than the remaining floors

Table 3
Mean ± SEM insect captures before and immediately after application of dichlorvos + pyrethrins in the warehouse/drying room[a]

Family or species	Intervention date	Mean ± SEM before intervention	Mean ± SEM after intervention	*F*	*P*
T. variabile	5/21/2003	0.2 ± 0.1	0.0 ± 0.0	2.56	0.13
	10/7/2003	0.0 ± 0.0	0.0 ± 0.0	—	—
	4/20/2004	0.0 ± 0.0	0.0 ± 0.0	—	—
	8/7/2004	1.3 ± 0.6	39.7 ± 21.4	3.73	0.07*
	10/11/2004	26.5 ± 18.4	0.9 ± 0.7	1.91	0.18
Cryptolestes spp.	5/21/2003	0.3 ± 0.2	0.2 ± 0.2	0.51	0.49
	10/7/2003	0.0 ± 0.0	0.1 ± 0.1	1.00	0.33
	4/20/2004	0.0 ± 0.0	0.0 ± 0.0	—	—
	8/7/2004	0.1 ± 0.1	0.0 ± 0.0	1.00	0.33
	10/11/2004	0.0 ± 0.0	0.0 ± 0.0	—	—
Lathridiidae	5/21/2003	0.0 ± 0.0	0.1 ± 0.1	0.89	0.36
	10/7/2003	0.2 ± 0.1	0.1 ± 0.1	0.26	0.61
	4/20/2004	0.2 ± 0.2	0.0 ± 0.0	1.00	0.33
	8/7/2004	0.04 ± 0.04	0.0 ± 0.0	1.00	0.33
	10/11/2004	0.0 ± 0.0	0.0 ± 0.0	—	—
T. stercorea	5/21/2003	0.1 ± 0.1	0.0 ± 0.0	1.12	0.31
	10/7/2003	0.4 ± 0.2	0.0 ± 0.0	3.52	0.08*
	4/20/2004	0.2 ± 0.2	0.0 ± 0.0	2.20	0.15
	8/7/2004	0.0 ± 0.0	0.6 ± 0.5	2.69	0.12
	10/11/2004	0.6 ± 0.3	0.3 ± 0.3	1.11	0.30
A. advena	5/21/2003	0.1 ± 0.1	0.0 ± 0.0	1.12	0.31
	10/7/2003	0.0 ± 0.0	0.0 ± 0.0	—	—
	4/20/2004	0.1 ± 0.1	0.0 ± 0.0	1.00	0.33
	8/7/2004	0.1 ± 0.1	0.5 ± 0.2	4.29	0.05*
	10/11/2004	0.3 ± 0.3	0.1 ± 0.1	1.42	0.25
O. surinamensis	5/21/2003	0.3 ± 0.3	0.0 ± 0.0	2.37	0.14
	10/7/2003	0.0 ± 0.0	0.1 ± 0.1	1.00	0.33
	4/20/2004	0.1 ± 0.1	0.0 ± 0.0	1.00	0.33
	8/7/2004	0.04 ± 0.04	0.0 ± 0.0	1.00	0.33
	10/11/2004	0.0 ± 0.0	0.0 ± 0.0	—	—
T. castaneum	5/21/2003	0.0 ± 0.0	0.0 ± 0.0	—	—
	10/7/2003	0.3 ± 0.1	0.2 ± 0.1	0.14	0.72
	4/20/2004	0.8 ± 0.5	0.0 ± 0.0	3.36	0.08*
	8/7/2004	0.04 ± 0.04	0.2 ± 0.1	1.52	0.23
	10/11/2004	1.3 ± 0.6	0.3 ± 0.1	2.33	0.14
L. oryzae	5/21/2003	0.0 ± 0.0	0.0 ± 0.0	—	—
	10/7/2003	0.1 ± 0.1	0.0 ± 0.0	1.00	0.33
	4/20/2004	0.0 ± 0.0	0.0 ± 0.0	—	—
	8/7/2004	0.0 ± 0.0	0.0 ± 0.0	—	—
	10/11/2004	0.1 ± 0.1	0.0 ± 0.0	1.00	0.33

[a]ANOVA comparing insect captures 1 week before and 1 week after interventions by species. Degrees of freedom for each comparison were 1, 22. Asterisks (*) indicate statistically significant differences in insect captures between dates.

Table 4
Mean ± SEM insect captures before and immediately after application of methyl bromide in the mill[a]

Family or species	Intervention date	Mean ± SEM before intervention	Mean ± SEM after intervention	*F*	*P*
T. variabile	5/21/2003	0.0 ± 0.0	0.1 ± 0.1	1.15	0.29
	10/7/2003	0.0 ± 0.0	0.0 ± 0.0	—	—
	4/20/2004	0.0 ± 0.0	0.0 ± 0.0	—	—
	10/11/2004	0.3 ± 0.2	0.04 ± 0.04	3.63	0.06*
Cryptolestes spp.	5/21/2003	0.1 ± 0.1	0.0 ± 0.0	1.82	0.19
	10/7/2003	0.0 ± 0.0	0.0 ± 0.0	—	—
	4/20/2004	0.0 ± 0.0	0.0 ± 0.0	—	—
	10/11/2004	0.1 ± 0.1	0.1 ± 0.1	0.01	0.92
Lathridiidae	5/21/2003	0.0 ± 0.0	0.2 ± 0.1	2.28	0.14
	10/7/2003	0.0 ± 0.0	0.04 ± 0.04	1.00	0.32
	4/20/2004	0.0 ± 0.0	0.04 ± 0.04	0.96	0.33
	10/11/2004	0.0 ± 0.0	0.0 ± 0.0	—	—
T. stercorea	5/21/2003	0.0 ± 0.0	0.8 ± 0.4	6.61	0.01*
	10/7/2003	0.7 ± 0.3	0.6 ± 0.2	0.00	0.97
	4/20/2004	0.0 ± 0.0	0.04 ± 0.04	0.96	0.33
	10/11/2004	1.2 ± 0.6	0.2 ± 0.1	3.92	0.05*
A. advena	5/21/2003	0.1 ± 0.1	0.0 ± 0.0	0.87	0.36
	10/7/2003	0.03 ± 0.03	0.1 ± 0.1	0.39	0.54
	4/20/2004	0.0 ± 0.0	0.0 ± 0.0	—	—
	10/11/2004	0.6 ± 0.3	0.0 ± 0.0	4.33	0.04*
O. surinamensis	5/21/2003	0.0 ± 0.0	0.1 ± 0.1	1.15	0.29
	10/7/2003	0.0 ± 0.0	0.0 ± 0.0	—	—
	4/20/2004	0.04 ± 0.04	0.0 ± 0.0	1.04	0.31
	10/11/2004	0.0 ± 0.0	0.0 ± 0.0	—	—
T. castaneum	5/21/2003	0.3 ± 0.1	0.2 ± 0.2	0.53	0.47
	10/7/2003	0.2 ± 0.1	0.04 ± 0.04	1.65	0.21
	4/20/2004	0.04 ± 0.04	0.0 ± 0.0	1.04	0.31
	10/11/2004	16.6 ± 8.5	2.7 ± 2.5	7.71	0.01*
L. oryzae	5/21/2003	0.04 ± 0.04	0.0 ± 0.0	0.87	0.36
	10/7/2003	0.03 ± 0.03	0.0 ± 0.0	1.00	0.32
	4/20/2004	0.04 ± 0.04	0.0 ± 0.0	1.04	0.31
	10/11/2004	0.2 ± 0.1	0.0 ± 0.0	1.89	0.18

[a]ANOVA comparing insect captures 1 week before and 1 week after interventions by species. Degrees of freedom for each comparison were 1, 22. Asterisks (*) indicate statistically significant differences in insect captures between dates.

following the May 2003 fumigation. Similar results were observed for fungus feeders and other non-stored-product insects. Following the May 2003 fumigation, *Cryptophagus* spp. ($F = 6.33$; df = 1, 15; $P = 0.03$) and Elateridae ($F = 6.33$; df = 1, 15; $P = 0.02$) were captured in greater quantity on the first floor. The same was true for *T. stercorea* ($F = 3.50$; df = 1, 22; $P = 0.08$) and

Carabidae ($F = 5.65$; df $= 1$, 22; $P = 0.03$) following the October 2003 fumigation, and *T. stercorea*, *Blapstinus* sp. and Staphylinidae ($F = 4.47$; df $= 1$, 22; $P = 0.05$ for each species) following the May 2004 fumigation. The few insects captured following the October 2004 fumigation were equally distributed between the first floor and the remainder of the mill.

4. Discussion

Integrated pest management requires that both the location and size of insect populations be understood before prescribing an intervention technique. The novel data presentation method described here provides easy comprehension of population changes for pest management under a variety of commonly encountered situations. Campbell et al. (2003) also recognized the need for more informative data illustrations when they utilized boxplots with whiskers to indicate percentiles, points indicating outliers, thin bars for the median, and thick bars for mean values. However, their method would be less valuable if only one or a few traps captured insects. In theory, concentration of captures in a few areas of a facility indicates local problems calling for a targeted response (closing an open door, repairing a screen, improving sanitation, application of residual insecticides, etc.) (Arthur, 1994). Captures over an entire facility indicate a broader problem perhaps requiring global intervention (fumigation or fogging). For example, *T. variabile* captures on 1 May 2004 were very low (Fig. 1A), and the mean number of captures in the next trapping interval did not increase, but the proportion of traps with insects increased markedly. Thus, the infestation level increased little, but the infestation became more widespread. One can also ascertain by the absence of the error bar that all traps with insects contained the same number of insects; in contrast, a disproportionately large error bar would indicate that only one or two of the traps contained large numbers of insects. A second example of the utility of the method can be observed (Fig. 2(H)) when >100, *L. oryzae* were observed in a single trap located on the fourth floor of the mill. This observation would have increased the mean captures for the mill from virtually zero to >4 insects/trap/week using the conventional method. However, the figure clearly shows that infestation was confined to a single trap and the infestation did not spread over time.

Tribolium castaneum was present in both the warehouse/drying room and mill throughout the year, an observation similar to those of Campbell et al. (2003) and Doud (1999). Because the traps contained only the aggregation pheromone of *Tribolium* spp., there may have been some bias for capture of *T. castaneum*, but the food oil provided an attractant for other species as well. Other insect species were actually more numerous than *T. castaneum* at certain times of the year, yet received no mention from the contracted pest management professional. US federal regulations regarding infestations in food processing plants apply to all insect species and the food can be deemed adulterated even if insects are not found in the edible product (Anonymous, 1985). Fungivores such as *T. stercorea*, *A. advena*, and the Lathridiidae comprised a majority of the captures during the warmer months strongly suggesting that more emphasis should be placed on these insects. Previous authors have also reported capture of several fungivores including *T. stercorea* in commercial mills (Doud, 1999; Campbell and Arbogast, 2004). Stored-product insect activity has previously been reported outdoors (Throne and Cline, 1991; Dowdy and McGaughey, 1998; Doud and Phillips, 2000; Campbell and Arbogast, 2004; Campbell and Mullen, 2004), but outside activity of fungivores is less well known and managers have no commercial pheromones or other attractants to monitor outside the mill and make predictions on the potential for immigration.

The increased number of *T. variabile* trapped in the warehouse/drying room compared to the mill was unexpected. Campbell et al. (2002) also detected a large number of *T. variabile* both inside and outside a food processing plant. This species is of importance because the larval setae are known to cause allergic reactions (Olsen et al., 2001). Sampling in the warehouse/drying room during 2004 was biased due to the *Trogoderma* spp. pheromone in the traps, but the trend for more captures in the warehouse than the mill was evident in 2003 before *Trogoderma* spp. pheromones were used in the pitfall traps. The outside traps indicated an abundance of insects outside the facility and the investigators hypothesize that immigration rates into corrugated steel buildings are much higher than into the concrete mill. In fact, *T. variabile* captures inside the warehouse followed the same trends observed in traps outside the facility. Steel buildings are not as gas tight as the concrete mill which accounts for the decision to utilize dichlorvos + pyrethrin applications instead of methyl bromide. Steel buildings may also permit rapid insect immigration. Campbell and Mullen (2004) demonstrated that *T. variabile* could fly considerable distances (average of 75 m with a range from 21 to 508 m) and that individual beetles immigrated into the structure. Immigration into structures by *Plodia interpunctella* has also been reported (Campbell and Arbogast, 2004). Further studies should focus on routes of insect immigration to warehouses and processing plants.

Although it was difficult to assess the effectiveness of fogging with dichlorvos + pyrethrin because insect populations were already low before fogging, it was clear that this treatment did not consistently eliminate *T. castaneum* and other beetles. One hypothesis is that this lack of efficacy occurred because fogging does not penetrate; however, none of the packaged products and equipment were removed, thereby allowing beetles to escape exposure by hiding under pallets and in non-exposed cracks. Combinations of dichlorvos + pyrethrins are intended to kill exposed insects only, suggesting these treatments would be most successful in empty warehouses.

Fumigation of the mill with methyl bromide did not consistently eliminate *T. castaneum* infestations, yet methyl bromide is considered a standard for mill disinfestations. From the brief record obtained from the fumigator following the October 2004 fumigation, three of four indoor monitoring sites showed sufficient gas concentration and time to meet the label requirements. Several plausible explanations follow to explain why methyl bromide fumigation did not consistently reduce pest populations to zero. First, fumigation may not have killed all insects present in the facility. The data clearly shows that some *T. castaneum* survived inside machinery following the October 2004 fumigation. Methyl bromide applications are dependent upon tight sealing and the absence of bulk product. From a practical standpoint, it is extremely difficult to locate and seal all cracks in a structure. Furthermore, methyl bromide does not penetrate well into bulks of finely ground products, and these may serve as insect refugia. Also, the eggs and pupae of insects are more tolerant of fumigants than the active adult and larval stages (White and Leesch, 1996; Adler et al., 2000). It is possible that insects exposed as pupae did not succumb to the fumigant and then emerged as adults during the week long trapping interval following the fumigation.

Alternatively, fumigation may have succeeded in disinfesting the mill, only to have insects re-enter during the ventilation to remove the fumigant. If the insect population is more widespread than the mill itself, then fumigating only a small portion of the population (i.e., those in the structure) will have little effect on the population. At this study site and at many others, it is customary to position fans in front of open doors, windows, and vents for several hours after fumigation. Based on the significant numbers of both stored-product and other insects captured on the first floor immediately following fumigation, it seems likely that the infestation originated from outside. Roesli et al. (2003b) observed that the ground floor of a Kansas feed mill was a source of increased trap captures. Stored-product insects marked outside have been recaptured inside food facilities (Campbell and Arbogast, 2004; Campbell and Mullen, 2004). Furthermore, the importance of preventing immigration after treatment has been suggested by data from other locations (Campbell et al., 2002; Campbell and Arbogast, 2004; Campbell and Mullen, 2004). An appropriate solution may be to seal the first floor by screening all open doors and windows when venting the fumigant. Interestingly, capture of insects on the first floor was not greater for any species following the October 2004 fumigation when cooler conditions prevented insect activity, as observed with *T. variabile* outside captures. Postponing fumigation until cool weather arrives in the autumn should be investigated as an effective way to reduce insect immigration.

The disturbance created by extra cleaning immediately before or after the fumigation may make insects more active and likely to encounter traps. Effective fumigation of a food processing plant requires proper sealing of the building and thorough cleaning of both the building and equipment. Cleaning removes patches of material that would provide refuge for insects, and the disturbance created makes the insects more active. Roesli et al. (2003a) showed that sanitation alone actually increased insect captures in retail stores because food removal made the insects more active and likely to encounter the traps. Toews et al. (2005) presented data showing increased trap efficiency when monitoring *T. castaneum* in pilot-scale warehouses under treatments without food patches compared to treatments with food patches.

These data strongly suggest much remains to be learned about the science of fumigation and its effects on insect communities inhabiting food-processing plants. Global interventions such as application of dichlorvos + pyrethrins or methyl bromide are expensive because they require a complete shut down of the facility resulting in lost production in addition to the cost of methyl bromide. Clearly, some of the global interventions were not needed based on the insect monitoring data. The timing of global interventions may have a profound effect on their effectiveness as a pest management tool. Finally, these results indicate that there are many opportunities to improve the system by fine-tuning the methods or experimenting with alternative suppression methods. Future studies should focus on the impact of eliminating routes of insect immigration, quantifying actual gas concentrations throughout the facility, assessing spatial variation in locations of pest rebound, and evaluating the dispersal of insects after immigration.

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