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Trap catches of stored-product insects before and after heat treatment in a pilot feed mill ☆

Rennie Roesli, Bhadriraju Subramanyam*, Fred J. Fairchild, Keith C. Behnke

Department of Grain Science and Industry, Kansas State University, Manhattan, KS 66506-2201, USA

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Abstract

The pilot feed mill at Kansas State University was heated to temperatures of ⩾50°C for 28–35 h during August 4–6, 1999 using natural gas heaters to kill stored-product insects. A three-parameter nonlinear regression model satisfactorily described temperature profiles on each of the four mill floors and was useful in showing differences among floors in the number of hours taken to reach 50°C and hours above 50°C. Pitfall traps with food and pheromone lures and sticky traps with pheromone lures were used to sample adults of beetles and moths, respectively, between July 8 and December 1, 1999 to evaluate heat treatment effectiveness. A total of 32 insect species representing 26 families in seven orders were captured in traps. Immediately after heat treatment, there was 95% reduction in total beetle captures in pitfall traps and 99% reduction in moth captures in sticky traps. Trap captures of the almond moth, *Cadra cautella* (Walker) and cigarette beetle, *Lasioderma serricorne* (L.) were significantly reduced and remained low after heat treatment. However, trap captures of the flat grain beetle, *Cryptolestes pusillus* (Schöenherr), Indianmeal moth, *Plodia interpunctella* (Hübner), and red flour beetle, *Tribolium castaneum* (Herbst) increased gradually after heat treatment, especially on the 1st and 4th floors. Our results indicated that traps are valuable tools for gauging the degree and duration of insect suppression obtained by heat treatment. In addition to trapping, visual inspection of the mill areas and absolute sampling of ingredients, products and spillage should be undertaken, so that areas of incipient insect reinfestation can be identified and potential problems rectified or averted.

Keywords: High temperatures; Stored-product insects; Efficacy assessment

1. Introduction

The feed mill ecosystem is conducive for survival, growth, and reproduction of stored-product insects, because of year-round warm conditions in production areas, open production areas, and

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*Corresponding author. Tel.: +1-785-532-4092; fax: +1-785-532-7010.

E-mail address: bhs@wheat.ksu.edu (B. Subramanyam).

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storage and utilization of various feed ingredients of cereal and noncereal origin (Mills, 1992). Insects associated with feed mills have been reported from the United States (Rilett and Weigel, 1956; Triplehorn, 1965; Loschiavo and Okumura, 1979; Pellitteri and Boush, 1983), Canada (Mills and White, 1993), and Japan (Kiritani et al., 1963). These surveys listed insect taxa found in the mills but did not report on insect management issues and methods. Quantitative data are lacking on the impact of chemical and nonchemical intervention on insect populations associated with feed mills.

Typical feed mill pest management recommendations include fumigation, residual sprays for general surface or crack/crevice treatment, space sprays, sanitation, stock rotation, and visual inspection (Pedersen, 1994). Feed mill construction, equipment design, and frequent changes between batches of different feeds during formulation and pelleting make effective pest management or sanitation programs difficult (Mills, 1992; Imholte and Imholte-Tauscher, 1999). Fumigation with phosphine may not be a viable option for feed mills because longer exposure periods are necessary to control all insect life stages, economically important insect pests are resistant to phosphine, and sensitive electronic equipment may be corroded (van S. Graver and Annis, 1994; Subramanyam and Hagstrum, 1995). In the United States and elsewhere, methyl bromide, a popular space fumigant for use in flour and feed mills, has already been or is being phased-out because of its atmospheric ozone-depleting potential (Banks, 1994; Taylor, 1994; Ragsdale and Wheeler, 1995). Therefore, there is renewed interest in evaluating safe and effective alternatives to methyl bromide for disinfesting flour and feed mills.

The use of high temperatures or heat treatment is now gaining popularity as a viable alternative to methyl bromide (Bursiek, 1999). Heat has been used for insect control in flour mills since the early 1900s (Dean, 1911, 1913), but has been largely supplanted by inexpensive mill fumigants such as methyl bromide (Menon et al., 2000). During heat treatment, the temperature within a mill is increased to 50–60°C using gas, electric, or steam heaters. However, it is important for all portions of the facility to reach the target temperature of at least 50°C for effective disinfestation (Dowdy and Fields, 2002; Wright et al., 2002). The duration of a heat treatment, from the time heaters are turned on until they are turned off, is typically, 24–36 h (Imholte and Imholte-Tauscher, 1999). Temperature data measured during heat treatment of flour mills (Dean, 1911, 1913; Heaps and Black, 1994; Dosland, 1995; Norstein, 1996; Dowdy, 2000) have not been quantitatively described. In addition, there is no quantitative information on the impact of heat treatment on mill insects.

In this paper, we evaluate the impact of heat treatment on stored-product insects in a pilot feed mill. Specific objectives of our research were to describe temperature changes during heat treatment using simple nonlinear regressions, determine mortality of insects confined in plastic dishes, and monitor insect numbers before and after heat treatment using food- and pheromone-baited traps.

2. Materials and methods

2.1. Feed mill layout

The pilot feed mill in the Department of Grain Science and Industry at Kansas State University was built during 1951–53. The mill is used for teaching, research, holding short courses/

workshops, and developing feed formulations for private industry. The feed mill has six vertical sections: a basement, 1–4th floors, and a roof. The 1st floor is attached to an extrusion room and a warehouse; dimensions of this floor are approximately $24 \times 21 \times 4$ m. The dimensions of the 2nd, 3rd or 4th floor are $17 \times 12 \times 4$ m. Metal bar grating separates the first three floors, and metal plates separate the 3rd and 4th floors.

The mill produces cattle, swine, poultry, and experimental rat feed in mash and pellet forms. Different types of grain used in the mill in descending order of importance are maize, sorghum, wheat, and barley. Additional ingredients such as soybean meal, meat and bone meal or fishmeal are also used from time to time. All raw ingredients, feed additives, and minerals are stored in bins or a warehouse for several weeks to months.

2.2. Heat treatment

The pilot feed mill was heated during August 4–6, 1999 using natural gas heaters from Temp-Air® (Rupp Industries, Inc., Burnsville, MN, USA). Three THP–550 heaters, each producing 550,000 BTUs (38,598 kcal), and one THP–1400 heater producing 1,400,000 BTUs (352,794 kcal) were used for heating the mill. Heaters were placed outside the mill, and the heat generated by the units was discharged into the mill using 50.8 cm diameter nylon ducts with circular openings (about 10 cm in diameter). Ducts from the THP–550 heaters (one duct per unit) were placed in the basement and 1st floor. Both the ducts from the THP–1400 heater were placed in the 1st floor. To facilitate heat distribution, Bayley® fans (Rupp Industries, Inc., Burnsville, MN, USA), each with a 1.5 horse power motor, fan blade diameter of 0.78 m, and an airflow rate of 391 $cm^3\,min^{-1}$, were placed in the 1st, 2nd, and 3rd floors (two fans per floor).

Two 7.6×7.6 cm metal plates were placed at 1–1.5 m above the floor level in different, and widely separated, locations within each floor. Surface temperatures were measured at hourly intervals throughout the heat treatment by reflecting the light from an infrared ray gun (Model 4TP78, Raytek®, Santa Cruz, CA, USA) off the metal plates. The accuracy of temperature measurements with this instrument is $\pm 0.25\%$ for temperatures $\leqslant 600°C$. Temperature outside the mill and heater discharge temperature throughout the heat treatment were also recorded.

Prior to heat treatment, floors and all accessible equipment were thoroughly cleaned. Bulk or bagged ingredients and finished feed products were loaded into a trailer and fumigated with phosphine by a commercial applicator. No pest control treatments of any kind were made after heat treatment, but sanitation was performed as needed.

2.3. Insect bioassay dishes

In separate $4.5 \times 4.5 \times 1.5$ cm plastic dishes, each containing 10 ml of whole wheat flour plus 5% brewer's yeast (w/w), 10 eggs, younger instars (6-d-old larvae; weighing 0.12 mg), pupae (26-d-old), or adults (2-wk-old) of the red flour beetle, *Tribolium castaneum* (Herbst) and confused flour beetle, *Tribolium confusum* (J. du Val) were introduced. Ten unsexed adults of mixed ages of the sawtoothed grain beetle, *Oryzaephilus surinamensis* (L.); rusty grain beetle, *Cryptolestes ferrugineus* (Stephens); lesser grain borer, *Rhyzopertha dominica* (F.); rice weevil, *Sitophilus oryzae* (L.), and ten 3rd instars of the Indianmeal moth, *Plodia interpunctella* (Hübner) were placed in separate dishes containing 10 ml of whole-wheat flour plus brewer's yeast, or hard red winter wheat kernels of 12% moisture (only for *R. dominica* and *S. oryzae*). All dishes were placed on metal trays in the 1st floor of the mill. These dishes were removed at the beginning of heat treatment, and at 3, 12, and 24 h after turning-on the heaters. For each species and time period, five dishes were removed and taken to the laboratory. Mortality assessments were made 48 h later at room conditions (27°C and 45% r.h.). The dishes removed just before heat treatment served as controls, and none of the insects in these dishes died during the heat treatment period.

2.4. Sampling insect populations

Pitfall traps (Trécé, Salinas, CA, USA) with food attractant oil and pheromone lures (Mullen, 1994) were used for sampling beetles in the feed mill. The oil is attractive to several species of stored-product insects (Barak and Burkholder, 1984; Mullen, 1994; Arbogast et al., 2000). Commercial pheromone lures (from Trécé) for three different insect species were used in conjunction with the food oil to increase trap attractiveness (Phillips et al., 2000). Each trap had an aggregation pheromone lure (4,8-dimethyldecanal) for *T. castaneum* and *T. confusum*, sex pheromone lure (4,6-dimethyl-7-hydroxy-nonan-3-one) for the cigarette beetle, *Lasioderma serricorne* (L.), and sex pheromone lure ((*Z*)-14-methyl-8-hexadecenal) for the warehouse beetle, *Trogoderma variabile* (Ballion) and Khapra beetle, *Trogoderma granarium* (Everts) (which is not established in North America).

Visual inspection in May of 1999 revealed severe infestation of the almond moth, *Cadra cautella* (Walker) in the mill. Therefore, Pherocon II sticky traps from Trécé (Mullen et al., 1991), baited with the sex pheromone ((*Z*,*E*)-9,12-tetradecadien-1-ol acetate) of *C. cautella,* were used. This pheromone is also attractive to *P. interpunctella*, because the major pheromone component is the same for both species (Brady et al., 1971).

Ten pitfall and 10 sticky traps were placed on each floor (1st–4th) in a grid pattern. Pitfall traps were placed on the floor, usually away from areas of regular traffic, whereas sticky traps were hung above the floor at various heights (0.66–1.96 m). These heights were comparable to those used by Vick et al. (1981) for trapping *C. cautella* and *P. interpunctella* in peanut warehouses. Traps were checked periodically (5–19 d), and the insects captured in traps were identified to genus or species. The total trapping period spanned from July 8 to December 1, 1999. During this period, pitfall traps were inspected on 16 and sticky traps on 14 different occasions. On each sampling occasion, beetle adults captured in pitfall traps were removed and the filter paper and oil (10–15 drops) replaced. Male moths captured in sticky traps were counted on-site and removed to minimize effects on trap catch efficiency from moths already caught in traps (Riedl, 1980). New traps and lures were used after heat treatment. Generally, lures in pitfall and sticky traps were replaced with new ones every 4–5 weeks. Insect species captured in both trap types from July 8 to December 1, 1999 were enumerated, and expressed as numbers captured per trap per week for statistical analysis or for showing trends over time.

One HOBO® data logger (Onset Computer Corp., Pocasset, MA, USA) was used on each floor to record temperature and relative humidity throughout the trapping period. HOBO® units recorded temperature and relative humidity at 30–60 min intervals. Daily mean temperature and relative humidity from these data were calculated using the PROC MEANS procedure (SAS Institute, 1989).

2.5. Fitting a model to describe temperature changes during heat treatment

Because temperature in a heated room stratifies both horizontally and vertically (Dowdy and Subramanyam, 1999; Dowdy, 2000), temperature data measured at each location within a floor were fitted to the following three-parameter regression model using TableCurve 2D (Anonymous, 1994).

$$y = a + b(1 - 1/(1 + bcx)), \tag{1}$$

where y is the predicted temperature, x is the time in hours, and a, b, and c are parameters estimated from the time–temperature data. This model was preferred over other models because it satisfactorily described temperature data of gas, steam, and electric heaters, and is independent of the starting ambient temperature during heat treatment (Bh. Subramanyam and R. Roesli, unpublished data; R. Mahroof and Bh. Subramanyam, unpublished data).

Relative humidity was not measured because humidity during heat treatment is generally $<25\%$ (Dowdy and Fields, 2002). Furthermore, mortality of insects at elevated temperatures is independent of humidity if temperatures $\geqslant 50°C$ are maintained for 3 h or more (R. Roesli and Bh. Subramanyam, unpublished data).

2.6. Impact of heat treatment on trap captures

The impact of heat treatment on stored-product insects associated with the mill was assessed by two-way analysis of variance (ANOVA) on insect counts in traps immediately before and immediately after the heat treatment, and by plotting changes in trap captures from July 8 to December 1, 1999. The former provides information on the degree of suppression and the latter provides a measure of duration of effective suppression following heat treatment.

Data on insects captured immediately before and immediately after heat treatment were transformed to $\log(x + 1)$ scale and subjected to two-way ANOVA using the PROC GLM procedure (SAS Institute, 1989) to determine differences (at $\alpha = 0.05$) among the main (date and mill floor) and interactive (date $\times$ floor) effects. Percentage reduction in insect numbers immediately after heat treatment was calculated as: $[(A/B) - 1] \times 100$, where A is mean number of insects/trap/floor/week immediately after heat treatment (on an untransformed scale), and B is the mean number of insect species/trap/floor/week immediately before heat treatment. Mean weekly captures and associated standard errors were calculated using PROC SORT and PROC MEANS procedures (SAS Institute, 1989). Means and standard errors for individual or total stored-product beetle species captured in pitfall traps and moths captured in sticky traps among mill floors were plotted as a function of time using SigmaPlot® software.

3. Results

3.1. Temperature profiles during heat treatment

The gas heater discharge temperatures during heat treatment ranged from 62.8°C to 112.8°C. Temperatures outside the feed mill during heat treatment ranged from 22.2°C to 31.1°C.

Table 1
Temperature profiles within and among feed mill floors during August 4–6, 1999 gas heat treatment[a]

Floor	Sensor[b]	Temperature (°C)			Hours to reach 50°C	Rate of increase (°C/h)[c]	Hours above 50°C
		Start	End	Max.			
1st	1	28.3	63.9	72.2	3.2	6.8	32.8
	2	29.4	61.7	75.0	1.5	13.7	34.5
2nd	1	30.0	63.3	71.7	2.1	9.5	33.9
	2	30.6	63.3	70.6	2.4	8.1	33.6
3rd	1	30.0	61.7	70.0	3.1	6.5	32.9
	2	29.4	62.2	68.9	3.4	6.1	32.6
4th	1	29.4	59.4	64.4	7.2	2.9	28.8
	2	28.9	58.9	58.9	8.0	2.6	28.0

[a] Heat discharge and outside temperatures ranged from 62.8°C to 112.8°C and 22.2°C to 31.1°C, respectively.
[b] At each sensor location temperature readings were taken hourly for 37 h ($n = 37$).
[c] The rate of increase from the ambient to the target temperature of 50°C was calculated as: (50°C—starting temperature in °C)/h to reach 50°C.

Temperatures among the four mill floors at the start of heat treatment were 28.3–30.6°C (Table 1). The target temperature of 50°C was reached quickly (1.5 h) in the 1st floor of the mill and slowly (8 h) in the 4th floor of the mill (Table 1, Fig. 1). The hourly rate of increase from the ambient to the threshold temperature varied among mill floors (2.6–13.7°C/h). Temperatures on all four mill floors were above 50°C for 28–34.5 h. The maximum temperatures recorded were 9–25°C above the target temperature.

Except for the 1st floor temperature data, the three-parameter nonlinear regression model satisfactorily described temperature increases within and among the mill floors (adjusted $r^2 = 0.90 - 0.94$) (Fig. 1). The model explained only 76–79% of the total variation of the 1st floor temperature data. All parameters of the nonlinear regression model fitted to temperature data within and among mill floors were significantly greater than zero (for parameter a, b, or c, df = 34; $P < 0.01$; t-test).

3.2. Mortality of insects confined in dishes

Adults of all species and immature stages of *Tribolium* species and *P. interpunctella* larvae confined in plastic dishes died after 3 h of exposure to heat. All insects exposed for 12 and 24 h also were dead.

3.3. Temperature and relative humidity inside the mill

Daily temperature and relative humidity changes among the four mill floors were essentially similar. From July to August, temperature and humidity ranged from 26.3°C to 35.7°C and 26.4% to 61.9%, respectively. During this period, the mean temperatures were mostly above 30°C, with wide daily fluctuations in humidity. Humidity increased at night because of cooler nighttime temperatures. From September to November, mean temperatures ranged from 14.2°C

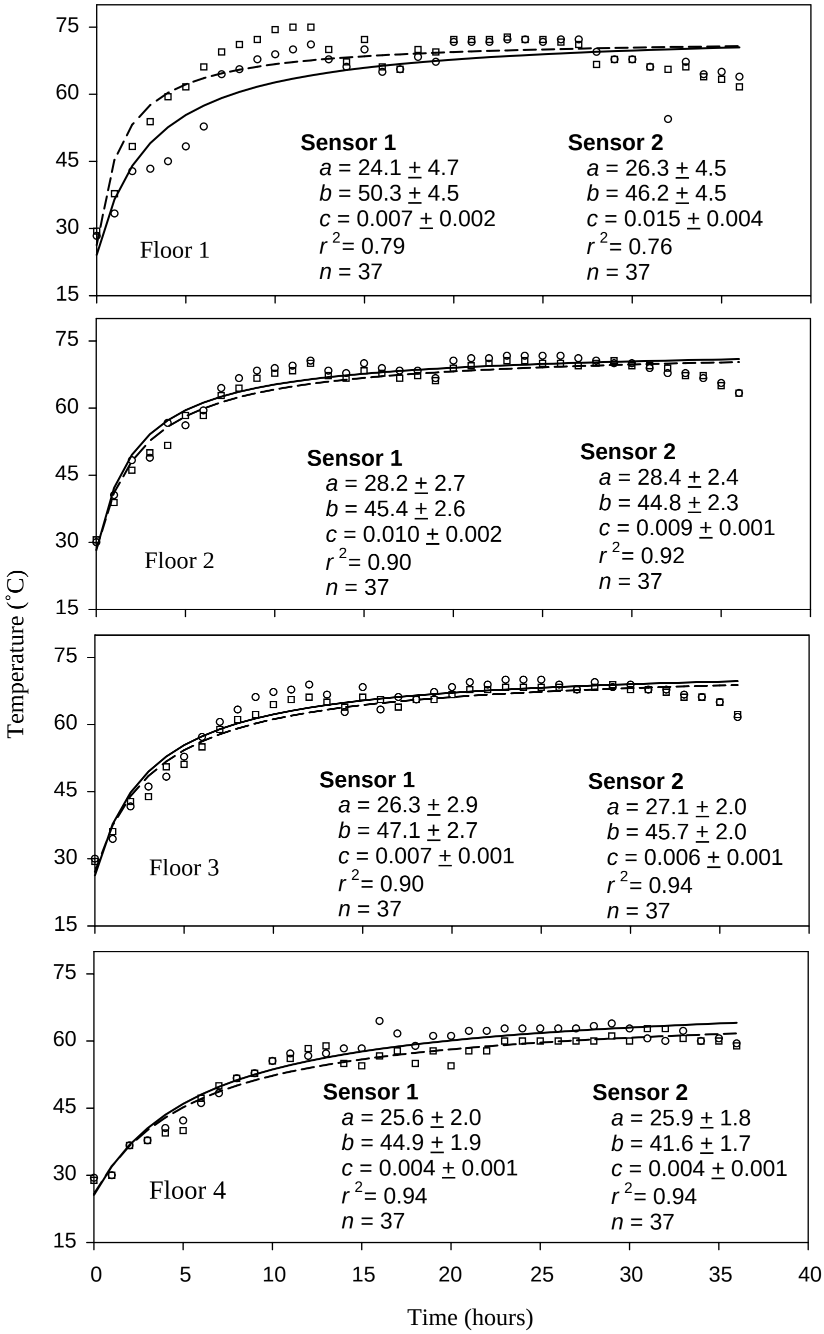

Fig. 1. Observed data (○, sensor 1; □, sensor 2) and fitted lines (solid line, sensor 1; broken line, sensor 2) showing temperature increases in the four feed mill floors during August 4–6, 1999 gas heat treatment. Temperatures were predicted by fitting a three-parameter nonlinear regression model, $y = a + b(1 - 1/(1 + bcx))$, to temperature–time data.

to 31.5°C, but most of the temperature readings were close to 20°C. The humidity ranged from 23.7% to 64.7% during September until the end of November. The environmental conditions observed throughout the study were well within ranges conducive for insect activity.

3.4. Insect species captured in traps

Pitfall traps captured adults of 32 insect species representing 26 families in 7 orders (Table 2). Additionally, there were four unidentified individuals, of which two belonged to two different families (Scydmaenidae and Staphylinidae) of Coleoptera, one individual each belonged to the orders Homoptera and Hymenoptera. Species belonging to Coleoptera (beetles) were more common and captured in large numbers in pitfall traps. Besides stored-product beetles, pitfall traps also captured insect predators, such as the warehouse pirate bug, *Xylocoris flavipes* (Reuter), storage moths, accidental intruders, and scavengers.

The psocid, *Liposcelis entomophila* (Enderlein) was captured in large numbers in pitfall traps followed by *T. castaneum, L. serricorne,* flat grain beetle, *Cryptolestes pusillus* (Schöenherr), and *C. cautella*. Other species were captured in smaller numbers (total over all sampling occasions, 1–132 insects). One *C. cautella* and three *P. interpunctella* adults were found in pitfall traps. The sticky traps caught both *C. cautella* and *P. interpunctella*. However, 86% of the total moths captured were *C. cautella*.

3.5. Impact of heat treatment on trap captures

Trap captures of 7 of the 8 beetle species and *C. cautella* immediately after heat treatment decreased by 68–100% relative to captures immediately before heat treatment (Table 3). *Cryptolestes pusillus* was not captured immediately before heat treatment, but small numbers were captured after heat treatment. There was a significant reduction ($P < 0.05$) in *L. serricorne*, *T. confusum*, total beetles, and *C. cautella* captures after heat treatment relative to those captured before heat treatment. Adults of *Ahasverus advena* (Waltl), *R. dominica*, and the granary weevil, *Sitophilus granarius* (L.), were present in small numbers immediately before heat treatment, but were not captured immediately after heat treatment. However, differences in captures were not significant ($P > 0.05$). Lack of significant differences in captures of these three species before and after heat treatment indicated that the small numbers present before heat treatment were not significantly different from zero ($P > 0.05$). The reduction in trap captures was consistent among mill floors for all species, except *T. castaneum*, because the date and date $\times$ floor interactions were not significant ($P > 0.05$). The significant date $\times$ floor interaction for *T. castaneum* suggested that the reduction in trap capture was significant on some floors and insignificant on others.

Mean captures of beetles were generally higher in the 1st floor than in the other three mill floors (Fig. 2). Heat treatment significantly reduced trap captures of beetles in all floors immediately after heat treatment. However, small numbers of insects were captured in traps within 2–4 weeks after heat treatment, especially in the 1st and 4th floors (Fig. 2). *Lasioderma serricorne*, which was the most abundant insect species before heat treatment, was almost eliminated by heat treatment (Fig. 3). Reduction in *T. castaneum* numbers immediately after heat treatment occurred only in the 1st and 2nd floors, but not in the 3rd and 4th floors (Fig. 4). These differences resulted in the

Table 2
Insect taxa and total numbers of each insect species captured in pitfall and sticky traps during July 8–December 1, 1999 in the pilot feed mill

Order, family, and species	Total no. adults	% of total
Coleoptera		
Anobiidae		
Lasioderma serricorne (F.)	1433	13.46
Anthicidae		
Anthicus sp.	1	0.01
Bostrichidae		
Rhyzopertha dominica (F.)	9	0.08
Cryptophagidae		
Anchicera gilvipennis Casey	1	0.01
Cryptophagus cellaris (Scopoli)	1	0.01
Curculionidae		
Sitophilus granarius (L.)	8	0.08
Sitophilus oryzae (L.)	112	1.05
Sitophilus zeamais Motschulsky	3	0.03
Dermestidae		
Trogoderma sp.	132	1.24
Laemophloeidae		
Cryptolestes pusillus (Schöenherr)	1331	12.50
Lathridiidae		
Cartodere sp.	3	0.03
Corticaria fulva Com.	4	0.04
Lathridius sp.	1	0.01
Lophocateridae		
Lophocateres pusillus (Klug)	1	0.01
Mycetophagidae		
Typhaea stercorea (L.)	21	0.20
Nitidulidae		
Carpophilus sp.	2	0.02
Ptiliidae		
Acrotichis sp.	1	0.01
Ptinidae		
Gibbium psylloides (de Czenpinski)	2	0.02
Rhizophagidae		
Monotoma fulvipes Melsheimer	1	0.01
Rhizophagus sp.	1	0.01
Scydmaenidae	1	0.01
Sphindus trinifer Casey	1	0.01
Silvanidae		
Ahasverus advena (Waltl)	41	0.39
Oryzaephilus surinamensis (L.)	53	0.50
Sphindidae		
Sphindus trinifer Casey	1	0.01
Staphilinidae		
Species not identified	4	0.04
Tenebrionidae		
Tribolium castaneum (Herbst)	2845	26.73

Table 2 (*continued*)

Order, family, and species	Total no. adults	% of total
Tribolium confusum duVal	29	0.27
Hemiptera		
Anthocoridae		
Xylocoris flavipes (Reuter)	49	0.46
Homoptera		
Family and species not identified		
Hymenoptera		
Family and species not identified		
Lepidoptera		
Gelechiidae		
Sitotroga cerealella (Olivier)	3	0.03
Pyralidae		
Cadra cautella (Walker)	1277[a]	12.00
Plodia interpunctella (Hübner)	201[b]	1.89
Psocoptera		
Liposcelididae		
Liposcelis bostrychophila Badonnel	3	0.03
Liposcelis entomophila (Enderlein)	3066	28.80
Thysanura		
Lepismatidae		
Thermobia domestica (Packard)	3	0.03

[a] All individuals were captured in sticky traps, except for one that was captured in a pitfall trap.
[b] All individuals were captured in sticky traps, except for three that were captured in pitfall traps.

Table 3
Analysis of variance results showing differences in trap captures immediately before and immediately after heat treatment, and percentage reduction in trap captures following heat treatment

Species	Date[a]		Floor		Date × floor		Mean ± SE[b]		% Reduction
	F	*P*	*F*	*P*	*F*	*P*	Before	After	
A. advena	2.21	0.141	2.21	0.094	2.21	0.094	0.13 ± 0.09	0.00 ± 0.00	100
C. pusillus	1.00	0.321	1.00	0.398	1.00	0.398	0.00 ± 0.00	0.03 ± 0.03	—[c]
L. serricorne	24.02	< 0.001	0.87	0.460	0.87	0.460	8.96 ± 3.13	0.00 ± 0.00	100
R. dominica	1.00	0.321	1.00	0.398	1.00	0.398	0.03 ± 0.03	0.00 ± 0.00	100
S. granarius	1.00	0.321	1.00	0.398	1.00	0.398	0.08 ± 0.08	0.00 ± 0.00	100
S. oryzae	2.73	0.103	2.47	0.069	1.55	0.210	1.15 ± 0.93	0.03 ± 0.03	98
T. castaneum	1.76	0.189	1.35	0.266	2.84	0.044	1.80 ± 0.69	0.58 ± 0.19	68
T. confusum	4.39	0.040	0.45	0.715	0.45	0.715	0.28 ± 0.15	0.00 ± 0.00	100
Total beetles	15.23	0.001	0.48	0.695	1.07	0.368	12.43 ± 4.24	0.63 ± 0.20	95
C. cautella	29.76	< 0.001	0.53	0.660	0.50	0.680	2.95 ± 0.83	0.04 ± 0.03	99

[a] Comparison of captures during July 22–29, 1999 (before heat treatment) with captures during August 18–25, 1999 (after heat treatment).
[b] Mean number of insects/trap/floor/week.
[c] There was an increase in trap catch immediately after heat treatment.

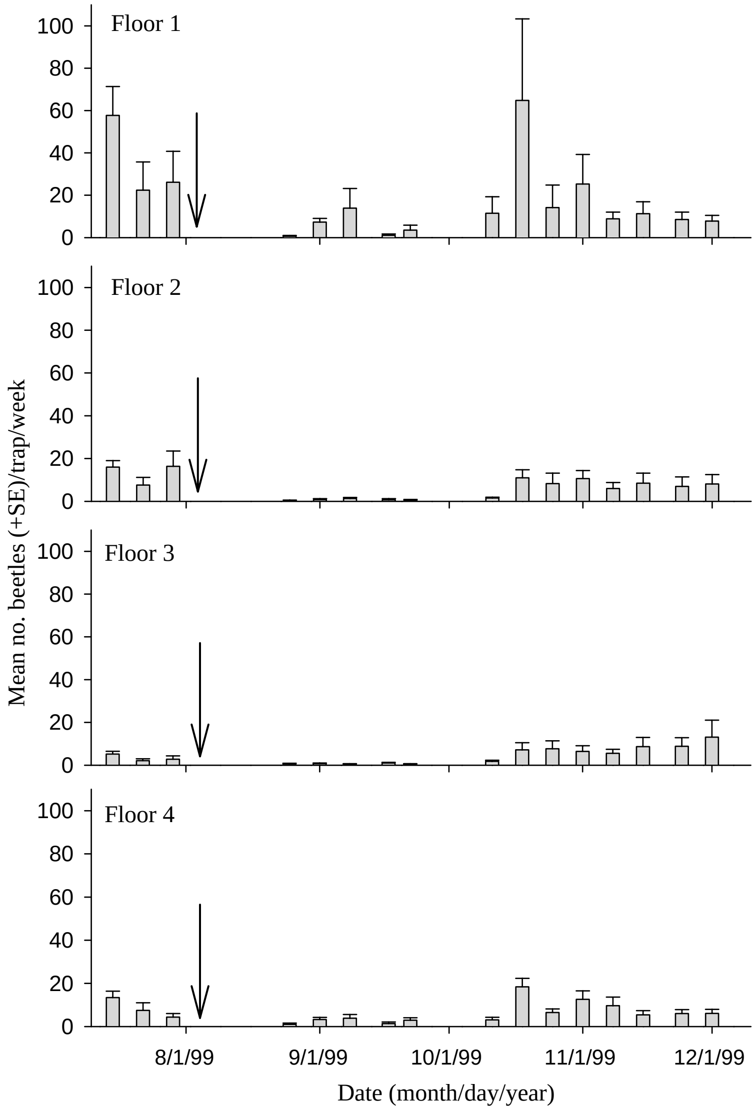

Fig. 2. Mean number of all beetle pests captured in pitfall traps in each of the four floors of the feed mill from July 8 to December 1, 1999. The arrow indicates the date when heat treatment occurred.

significant date × floor interaction noted above (Table 3). Generally, *T. castaneum* was captured in greater numbers after heat treatment, especially from mid-October onwards. *Cryptolestes pusillus* was absent or found in very small numbers in trap samples before heat treatment, but was found in large numbers on several occasions after heat treatment, especially in the 1st floor (Fig. 5).

Cadra cautella was found in greater numbers among mill floors than *P. interpunctella* before heat treatment (Fig. 6). Heat treatment significantly reduced *C. cautella*, as indicated by extremely

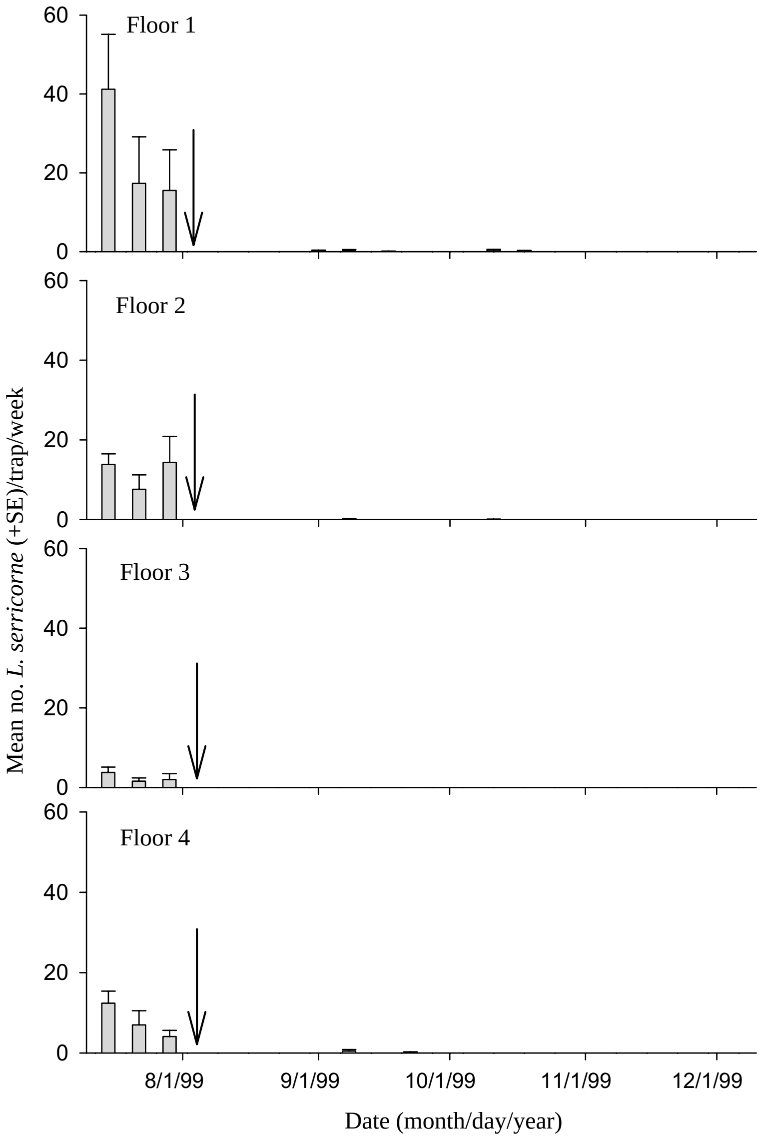

Fig. 3. Mean number of *L. serricorne* captured in pitfall traps in each of the four floors of the feed mill from July 8 to December 1, 1999. The arrow indicates the date when heat treatment occurred.

low or zero captures after heat treatment. On the other hand, *P. interpunctella*, captured in small numbers before heat treatment, became the dominant moth species after heat treatment.

Liposcelis entomophila, which constituted 29% of all insects sampled, was not found before heat treatment (Fig. 7). It was found in traps a month after heat treatment. Generally, numbers in the 1–3rd floors were low, except on one occasion in the 2nd floor. High numbers were found in the 4th floor, especially during mid-October; these numbers dropped again at the end of October and beginning of November 1999.

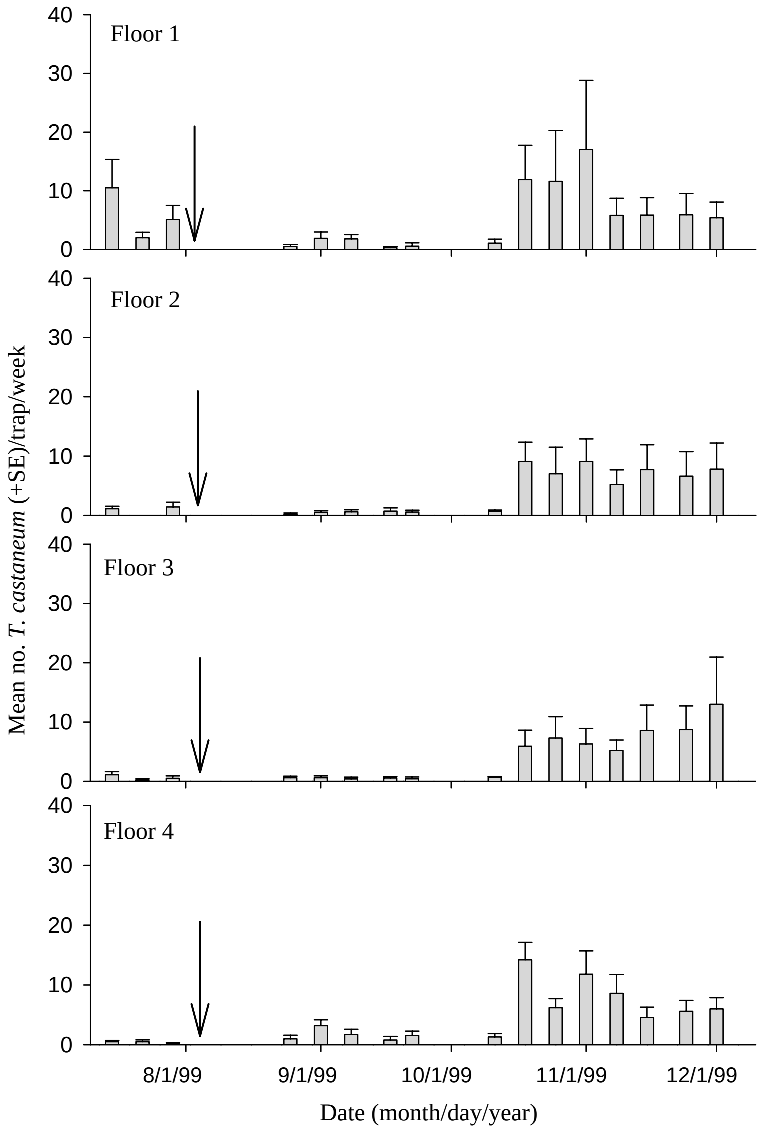

Fig. 4. Mean number of *T. castaneum* captured in pitfall traps in each of the four floors of the feed mill from July 8 to December 1, 1999. The arrow indicates the date when heat treatment occurred.

4. Discussion

Temperature increases among the mill floors during heat treatment were not consistent, although temperatures above 50°C were maintained for 28–35 h. The slow heating of certain areas of the 4th mill floor is perhaps related to loss of heat through the roof opening, which was not sealed during heat treatment. Dosland (1995) reported differences in the rate of heating of five floors of commercial flour mill in Chester, IL, USA. Temperature distribution within and among

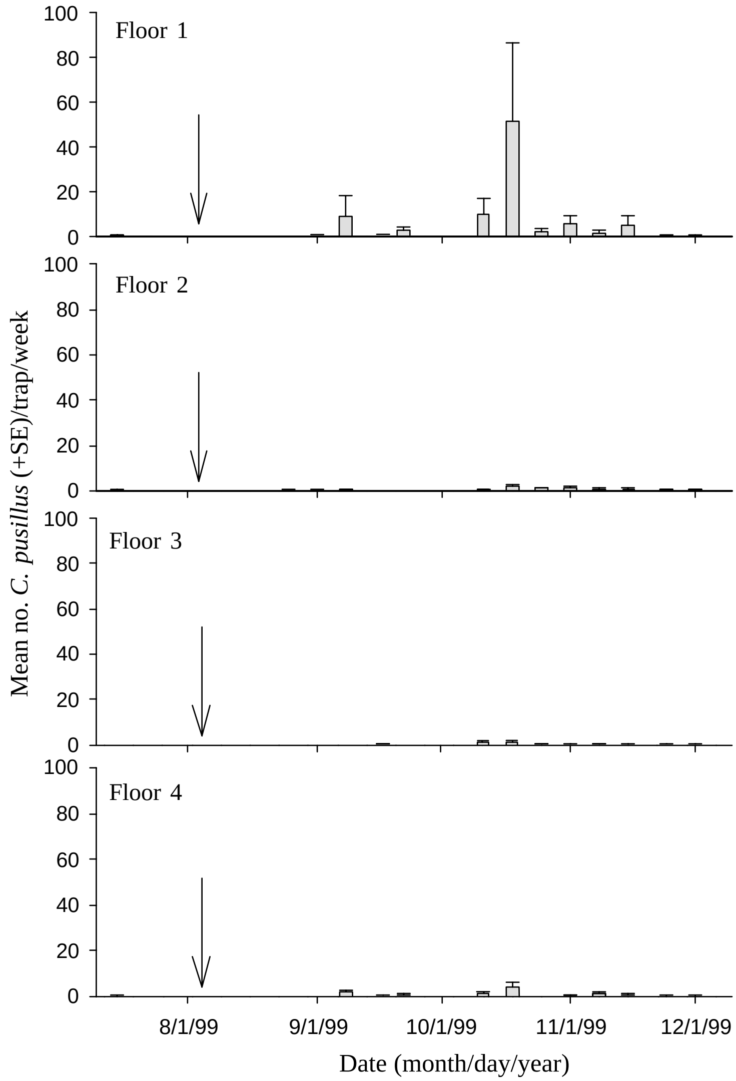

Fig. 5. Mean number of *C. pusillus* captured in pitfall traps in each of the four floors of the feed mill from July 8 to December 1, 1999. The arrow indicates the date when heat treatment occurred.

floors is not uniform during heat treatment. There will always be areas where temperatures do not reach lethal levels (Dean, 1911; Dowdy and Subramanyam, 1999; Dowdy, 2000), and insects in these areas can escape the effect of lethal temperatures. The differential heating and the high temperatures recorded had no adverse effect on the structural integrity of the mill or on the proper functioning of the mill equipment after heat treatment.

Exposures to temperature above 50°C for 1 h are sufficient to kill stored-product insects (Fields, 1992). All insects in dishes exposed for 3 h to high temperatures were killed. The dishes were close to sensor 2, and near this area, the temperature of 50°C was reached within 1.5 h and stayed above

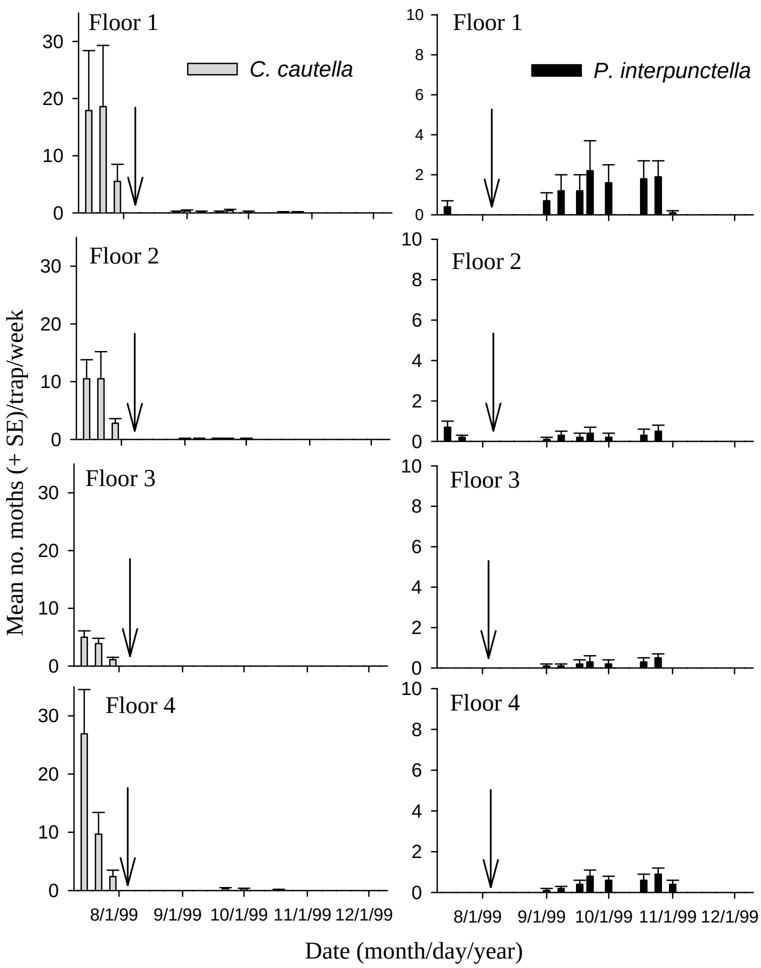

Fig. 6. Mean number of *C. cautella* or *P. interpunctella* captured in sticky traps in each of the four floors of the feed mill from July 8 to December 1, 1999. The arrow indicates the date when heat treatment occurred.

50°C for an additional 1.5 h before the dishes were removed to assess insect mortality. Based on experiments in a flour mill subjected to heat treatment and experiments in a growth chamber in the laboratory, we found that it takes about 55 min to kill all exposed adults of *T. castaneum*, and 90 min to kill all exposed pupae (Menon et al., 2001). Generally, immature stages of stored-product insects are more tolerant to high temperatures than adults (Fields, 1992). Less than 4 h of exposure was sufficient to kill 99.9% of the most tolerant immature stage of *S. oryzae* (2nd instars) in 12% moisture wheat at 48°C (Beckett et al., 1998). About 16 h of exposure at 50–53°C was required to kill 99.9% of the most tolerant stages of *R. dominica* (1–3rd instars) in 9–12% moisture wheat (Beckett et al., 1998). In the case of *P. interpunctella*, 99% mortality of exposed 1–3 day-old eggs occurred after 10.3 h of exposure to 42°C, and 34 min of exposure to 48°C (Lewthwaite et al., 1998). Therefore, during heat treatment, temperatures above 50°C

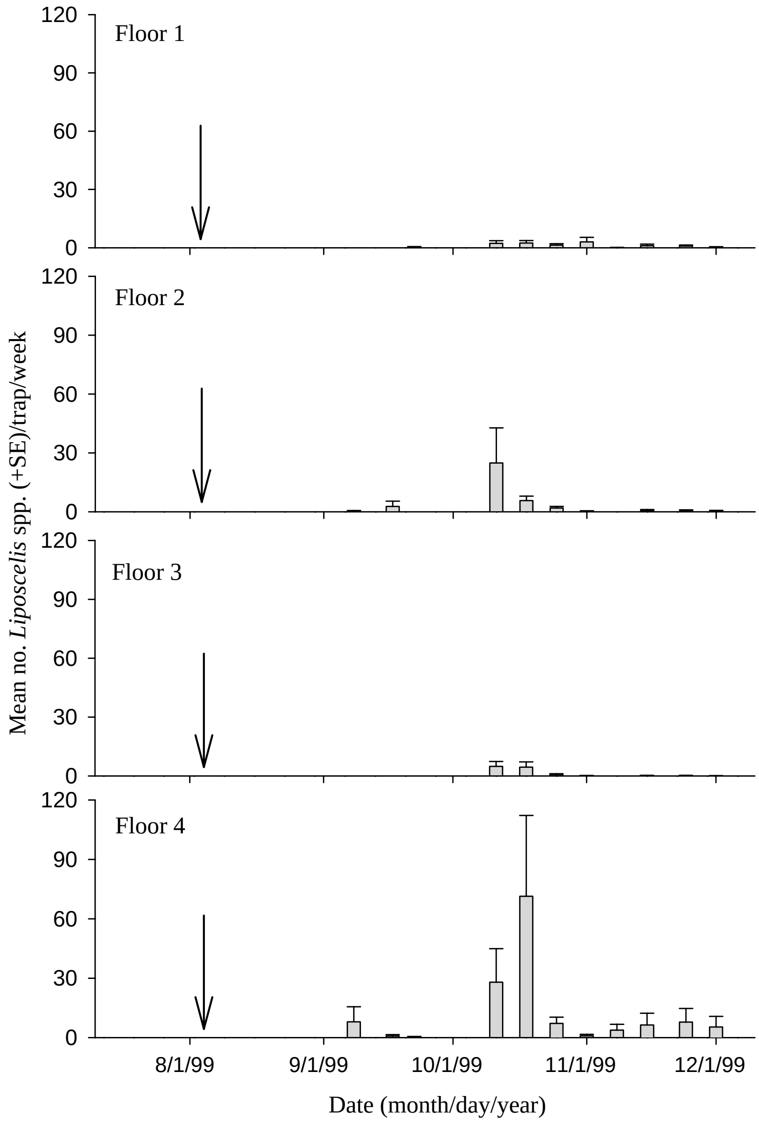

Fig. 7. Mean number of *Liposcelis* species captured in pitfall traps in each of the four floors of the feed mill from July 8 to December 1, 1999. The arrow indicates the date when heat treatment occurred.

that were maintained for 28–35 h should have effectively killed all exposed stages of stored-product insects in the feed mill.

The three-parameter nonlinear regression model satisfactorily described the increase in temperature over time during heat treatment. The 1st floor temperature data were highly variable, as the ducts directly discharged heat into these areas and the heater discharge temperature had to be adjusted periodically to avoid overheating. This irregular heating resulted in the regression model explaining only 76–79% of the variation in the temperature data.

The major stored-product insects, such as *A. advena*, *C. cautella*, *L. serricorne*, *O. surinamensis*, *P. interpunctella*, *R. dominica*, *S. granarius*, *S. oryzae*, *T. variabile*, and *Tribolium* species captured in pitfall and sticky traps have been reported from feed mills in Japan (Kiritani et al., 1963), the United States (Rilett and Weigel, 1956; Triplehorn, 1965; Pellitteri and Boush, 1983), and Canada (Mills and White, 1993). Pitfall traps also captured small numbers of beetles associated with stored products. These individuals belonged to the families Cryptophagidae, Lathridiidae, Mycetophagidae, and Ptinidae, and Order Thysanura. Beetles in the families Ptiliidae, Scydmaenidae, and Sphindidae are not associated with stored products, and very few of these individuals were captured in pitfall traps. Three adults of the Angoumois grain moth, *Sitotroga cerealella* (Olivier) were captured in pitfall traps after heat treatment. We did not notice activity of this species in the feed mill during our entire trapping period. Therefore, the source of these insects cannot be ascertained. Three adult *P. interpunctella* and one adult *C. cautella* captured in the pitfall traps may have been attracted to odors emanating from the food lure (oil) (Barak and Burkholder, 1984).

The presence of large populations of psocids in feed mills is not unusual. Roesli and Jones (1994) found *Liposcelis* species to be abundant in silos of a feed mill in Queensland, Australia. Pellitteri and Boush (1983) reported psocids from over 55% of the southern Wisconsin feed mills they sampled during 1975–76. Mills and White (1993) found psocids in 6 out of the 7 sampling sites within a feed mill in Manitoba, Canada. Before heat treatment, *Liposcelis* may have been present in low numbers, and was either overlooked or was not captured in traps. Through field and laboratory observations, Roesli et al. (2000) inferred that *Liposcelis* populations were regulated by facultative predator species such as *T. castaneum* and *Cryptolestes* species. The low numbers of *Liposcelis* before heat treatment was probably due to the presence of these facultative predators in the mill. *Liposcelis* captures decreased in traps as numbers of *T. castaneum* and *Cryptolestes* increased.

Pitfall and sticky trap captures were generally greater in the 1st and 4th floors, and population rebound following heat treatment also was apparent in these floors. The 1st floor was a constant source of insects, because it includes a warehouse where new ingredients and finished feed products are temporarily stored. In addition, spillage from the grated 2nd and 3rd floors accumulates on the 1st floor. The receiving dock doors that lead into the 1st floor are always open between 8:00 a.m. and 5:00 p.m., Monday through Friday, thus providing an avenue for stored-product and nonstored-product insects present outdoors to enter the mill. Stored-product insect activity outdoors has been reported on farms and at commercial elevators (Throne and Cline, 1991; Dowdy and McGaughey, 1998), around flour mills (Doud and Phillips, 2000), and also outside our pilot feed mill (Menon et al., 2001). The 4th floor was another source of insects, because the tops of vertical metal bins for storing ingredients and bulk-stored feed products were located on the 4th floor and the metal plate floor retained and accumulated large quantities of spilled feed.

Heat treatment was most effective against *C. cautella* and *L. serricorne* as indicated by the absence of these insects in traps following heat treatment. Captures of *P. interpunctella* one month after heat treatment suggested that this species was introduced into the mill on raw ingredients, primarily maize, or it could have entered the mill from sources outdoors. Outdoor activity of *P. interpunctella* has been reported around flour mills (Doud and Phillips, 2000) and feed mills (Menon et al., 2001). High numbers of *T. castaneum* captured in traps 2 months after heat treatment may represent adult progeny produced by the small numbers found after heat treatment in the 4th floor or those produced by adults surviving the phosphine fumigation. Numerous live *T. castaneum* adults were found in fumigated and aerated feed materials brought into the mill after heat treatment.

Effective suppression of insect pest populations in the feed mill after heat treatment can be maintained by following certain simple practices. For example, proper fumigation of infested feed ingredients and finished products prior to heat treatment is important to prevent reintroduction of insects into the mill. Simple practices, such as closing doors, screening windows, using plastic strips, or installing air curtains near doorways (Imholte and Imholte-Tauscher, 1999) may exclude outdoor insects from gaining entry into the mill after heat treatment. Proper sanitation of the mill floors, walls, and equipment, and application of residual pesticide products, such as cyfluthrin or an inert dust to nonfood areas, may result in keeping insect populations below acceptable levels.

In summary, achieving temperatures of $\geqslant 50^{\circ}$C for 28–35 h killed all stored-product insects in dishes, and should be able to eliminate all exposed stages of stored-product insects within the feed mill. Our trapping results suggest that heat is a viable alternative to methyl bromide for disinfesting a feed mill. Traps are useful for gauging the impact of heat treatment on insect populations, but they do not indicate the source of insects. Therefore, it is important to sample all potential sites and sources of infestation such as receiving pits, screw conveyers, spilled feed, accumulations of feed in mill equipment, raw ingredients, finished products, and moving mill stock. Information on insect species and numbers found in these samples with those found in traps will provide additional insights into the impact of heat treatment on insects, especially on the causes of population rebound after intervention.

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