Journal of Stored Products Research 53 (2013) 7–14

Contents lists available at SciVerse ScienceDirect

Journal of Stored Products Research

journal homepage: www.elsevier.com/locate/jspr

Distribution, abundance, and seasonal patterns of *Plodia interpunctella* (Hübner) in a commercial food storage facility

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ARTICLE INFO

Article history:
Accepted 28 December 2012

Keywords:
Plodia interpunctella
Indianmeal moth
Monitoring
Warehouse
Infestation
Costs

ABSTRACT

Populations of *Plodia interpunctella* (Hübner), the Indianmeal moth, were monitored inside a 105,000 m^3 food warehouse in the central United States for a 3-year period, using pheromone-baited traps for males. A total of 52 traps were placed in the warehouse, which was roughly divided into four main areas. Ten traps were placed in the grounds outside the warehouse. Total inside moth catch was nearly 50,000 for the three-year study, suggesting a large population was present within the warehouse. Moth captures both inside and outside the warehouse generally peaked during the summer months, and few adult males were caught during the cooler months of the year. Within a year, trap locations where greater numbers of moths were captured varied over time within the warehouse. Trap locations in an area where food was not stored consistently captured adults, but this area was connected to the main part of the warehouse that contained the stored food. Inside temperatures were above 15 °C for most of the year, while outside temperatures were consistently above 15 °C from mid-May to mid-October. Economic analyses of conducting a monitoring program were done using estimates for fixed costs of traps and variable costs for labor provided by private industry, calculating labor costs for in-house monitoring versus outside contractor costs, and comparing those estimates with the research costs of conducting the program (three different scenarios). A threshold trap catch level of two males per day was used to describe methodologies for reducing total trap numbers and associated economic costs, with minimal loss of data resolution.

1. Introduction

Plodia interpunctella (Hübner), the Indianmeal moth, is a cosmopolitan pest of food storage facilities, and can infest a variety of nuts, spices, and food products (Mohandass et al., 2007). Recent field studies have shown abundant populations of this species and other stored product insects in and around milling and processing facilities, food storage warehouses, and feed mills in the United States (US) (Arbogast et al., 2000; Doud and Phillips, 2000; Campbell and Mullen, 2004; Larson et al., 2008). Mobile adults can easily disperse from sources of infestation outside or within a facility, and focal points of infestations often shift within a storage site in the same season (Campbell et al., 2002). Immigration from outside populations, resident infestations within a site and the introduction of infested product into the facility can all contribute to infestation pressure (Campbell and Arbogast, 2004).

Pheromone trapping using the commercially available (*Z*,*E*)-9,12-tetradecadienyl acetate (ZETA) lure to attract male *P. interpunctella* can be employed to monitor population trends, identify sources of infestation, examine distribution patterns, and document the spread of an infestation within a facility (Zhu et al., 1999; Campbell et al., 2002; Nansen et al., 2008; Trematerra et al., 2011). However, it is sometimes difficult to interpret moth capture data because of various factors that affect trap performance (Arbogast et al., 2005; Nansen et al., 2008). Interpretation of trapping data is especially difficult in food warehouses because of the constant movement of commercial food products into and out of the building and among different locations within facility. Therefore, it may be more difficult to pinpoint the sources of infestation in warehouses compared to more static facilities such as mills or processing plants. Recent research has also focused on improving the efficiency of pheromone traps, through additional attractants (Nansen and Phillips, 2004), better placement of traps (Nansen et al., 2004), and new approaches to data interpretation (Nansen et al., 2008).

Although pheromone traps are widely used for monitoring *P. interpunctella* populations inside facilities, many questions

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0022-474X/$ – see front matter © 2013 Published by Elsevier Ltd.
http://dx.doi.org/10.1016/j.jspr.2012.12.008

remain about the optimal number of traps needed, where best to place traps, and how to interpret the data in regards to management decisions. Guidelines for trap placement supplied by manufacturers have not been scientifically evaluated in the literature, nor have the economics of monitoring programs and methods of processing traps. The cost of sampling for stored-product insects in bulk grains has been addressed on a limited basis (Adam et al., 2010; Yigezu et al., 2010), but there are no comparable studies evaluating pheromone trapping programs. Campbell et al. (2002) evaluated data from a monitoring study using re-sampling to assess how changing the number of traps impacted the estimated mean capture level; however; impact of trap density on labor and material costs of a sampling program have not previously been evaluated in the literature. Hence, the objectives of this study were to: 1) use pheromone baited traps to determine temporal and spatial patterns of male *P. interpunctella* captures inside and outside a food facility warehouse, 2) estimate the costs of the components of the program, including fixed and variable costs, and 3) evaluate the trapping data and economic analysis to describe how a targeted *P. interpunctella* monitoring program could be developed for a food storage facility that would minimize sampling costs while providing data necessary for management decisions.

2. Materials and methods

2.1. Monitoring study

This study was conducted in a large food warehouse responsible for storage and distribution of packaged and canned food products. This was a new site that became operational in early June of 2005, and products were moved from the former location to this new site. The warehouse was heated during the winter but not cooled by air conditioning during the summer. We began monitoring for *P. interpunctella* on 22 June 2005 and concluded the program on 4 April 2008. Traps were set out at the approximate locations shown in Fig. 1. The traps were diamond traps baited with the ZETA pheromone, both manufactured by Trécé, Inc. (Adair, OK, USA). The pheromone lures in the traps were changed approximately every 6 weeks from late spring to early autumn, and every 8 weeks during the rest of the year.

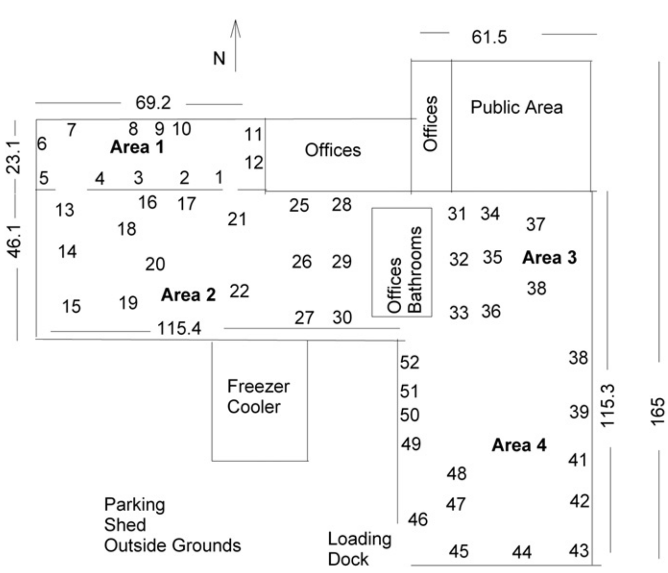

Fig. 1. Diagram showing approximate placement of pheromone traps inside each main area 1, 2, 3, and 4 within the food warehouse. All dimensions are in meters.

For analysis the food warehouse was divided into four main areas (Fig. 1). Length and width dimensions of each area are given in Fig. 1. The ceiling heights in Areas 1, 2, 3, and 4 were 10.8, 10.8, 4.9, and 3.4 m, respectively. This gave calculated volumes for Areas 1, 2, 3, and 4, of 17,264; 57,406; 22,059; and 8300 m^3, respectively. Area 1 had walls with no openings along the west and north sides, and an interior door on the east end. There were overhead doors at the southeast and southwest ends, open to the interior of the warehouse (Area 2). Area 1 contained canned goods and various non-food items such as furniture, office supplies and equipment, and shelving units. Twelve traps were hung approximately 1.5 m above the floor on beams, support cables, electrical boxes, etc. along or near walls. Traps #1–8 were evenly placed along the side walls, while the remaining traps were more clustered due to the location of stacked palleted goods. Area 2 was the primary storage area for packaged and processed food items, and had fifteen units that were about 6 m in height and 28 m long. Each unit had three levels of shelving where food goods were stored. Eighteen traps were hung underneath first level shelves, about 1.5 m from the floor, and traps #16 and #17 (Fig. 1) were hung from the electrical conduit at the same approximate height from the floor. These traps were evenly placed underneath areas where there were packaged goods on the shelves, as opposed to an evenly spaced grid placement. Area 3 was also a site for food storage with twelve shelf units smaller in height than those in Area 2 (about 3 m high), six on each side. Eight traps were evenly placed and tied to the first level shelf as described above for Area 2. The amount of packaged food goods stored in Areas 2 and 3 varied but overall it declined during the study. Thus, while all traps in Areas 2 and 3 were on shelves that contained packaged or processed food at the start of the study, some of the shelves were empty by the end of the study. Adjoining Area 3 but separated by a fixed wall on the north side was a separate room 46.1 by 36.9 m in width and length and 4.9 m in height where the general public brought donated goods and volunteers sorted those goods. There was an interior door from Area 3 into this room, which was usually closed. Areas 3 and 4 were separated by an open fence with multiple aisle openings to accommodate transfer of pallets by forklifts, but no wall. Area 4 contained no shelf units, and served as a transfer point from the loading dock to Areas 1–3. Nine traps were hung from electrical conduits, randomly spaced but in an even pattern, as described for Area 1. Four additional traps (#49–#52) were added in the second and third years of the study and placed along a back wall on the southeast side of Area 3 that separated a storage closet from the larger area.

During the summer months, traps were checked every one or two weeks, during autumn the traps were typically checked every 3 weeks, and during the winter traps were checked every five or six weeks because of limited moth activity during that time (Table 1). When traps were sampled, a new trap was substituted for the existing trap, and pheromone lures were replaced about every 6 weeks as recommended by the manufacturer. In the laboratory, male *P. interpunctella* were counted and recorded, moths were

Table 1
Total number of *P. interpunctella* trapped inside each of the four areas of the food warehouse (see Fig. 1) by year from 6/29/05 to 12/19/07[a], with the percentage of the total in each area in each year in parentheses. Number of traps in Areas 1, 2, 3, and 4 in 2005 were 12, 18, 8, 10, respectively, in 2006 and 2007 the number for each Area was 12, 18, 8, and 14, respectively.

Area	2005[a]	2006	2007	Total
1	1954[a] (16.0)	2736 (12.3)	2800 (18.5)	7490
2	6153 (50.3)	8405 (37.7)	5241 (34.6)	19,799
3	2667 (21.8)	5025 (22.6)	3782 (25.0)	11,474
4	1451 (11.9)	6562 (29.4)	3320 (21.9)	11,333
Total	12,225	22,278	15,143	49,646

[a] The first sampling date in 2005 was 6/29.

scraped from the traps, and traps reconditioned by replacing the sticky material as needed.

Data for capture of male *P. interpunctella* were first analyzed using the Means Procedure (PROC MEANS) in the Statistical Analysis System (SAS, Version 9.2, Cary NC, USA) to determine overall numbers within areas. Differences in captures among the 48 traps for the first year, and the 52 traps for the second and third year, were determined using the Bonferroni option at $P < 0.05$ in the General Linear Models Procedure (PROC GLM) of SAS, to account for experiment-wise error rate. Sample dates during the winter and early spring months of a particular year which had very low moth activity, with total captures of <10 moth across all traps in the facility, were eliminated from the analysis to avoid unduly biasing mean captures in traps. Also, traps #1–12 were removed from Area 1 from 7 June through 7 September in 2005 because of a facility renovation, and data for those times were recorded as missing data. Similarly, data for traps #49–52 in 2005 were also coded as missing data. The Bonferroni analysis was used to differentiate those traps that were in the upper end of the range for trap catch from those at the lower end.

The temperature inside the warehouse was recorded hourly using a Hobo temperature/relative humidity data logger (Onset Computers, Bourne, MA, USA). These data were summarized into daily values. Daily data for maximum and minimum outside temperatures for the area where the facility was located were obtained from recorded weather data available on the National Climatic Data Center website, part of the US National Oceanic and Atmospheric Administration (www.ncdc.noaa.gov).

2.2. Economic analysis

Because costs for materials and labor vary considerably and to facilitate comparisons among methods, values used in the economic analysis were consistent with typical estimates obtained from the pest management industry rather than our actual costs to conduct this study. Costs of pheromone lures and traps were obtained from the manufacturer (www.trece.com) and from national pest management firms which also utilized those traps. These cost estimates provided by the manufacturer and the pest management firms ranged from $3.00 to $4.50 USD for each trap and lure combination, depending on the volume purchased from an individual supplier. Hence, for economic analysis we used a cost of $4.00 per trap ($2.00 for each component separately). Pest management professionals (PMPs) in five states of the USA (CA, GA, IN, MI, and MO) were also contacted to determine general industry practices on servicing traps and frequency of replacing traps and lures. Normal procedures were for a technician to count the number of adults in a trap whenever it was sampled, but not to remove them. Traps and lures for *P. interpunctella* tended to be replaced every 6–8 weeks (8 weeks was used in subsequent analysis). The PMPs estimated that the time to sample a trap would be 1–1.5 min per trap, and when traps and lures were replaced this time would be doubled. Hence, 1.5 h for counting adults in the 52 traps used in our study, and 3 h for trap removal and replacement, assuming traps and lures were assembled beforehand, was used as a cost value. For simplicity, we made the further assumption that all 52 traps would be present during an entire 8-week period, even though traps were occasionally lost between sample periods in our study.

Labor costs required to pay a technician for sampling the traps was estimated by contacted PMPs to be anywhere from $20 to $40 per h (salary plus benefits), depending on the area of the USA where they were located and their level of expertise. We used labor costs of $30.00 per h for our economic analysis. Also, traps would have to be assembled beforehand whenever traps and lures were changed, so the technician could record numbers in the current trap, change over to the new one, and record the date. Assembly of the 52 traps was estimated to take 1 h, which would add to the labor costs. The range a customer could be charged for the monitoring program ranged from $70 to $100 per h, and the cost of traps and lures would be an additional charge. We used a labor cost of $90.00 per h for economic analysis of contracting monitoring to an outside source.

Three monitoring scenarios were examined; estimated costs for conducting the monitoring program as described in this manuscript, the cost to conduct the monitoring program using industry standard methods, and cost of contracting the program out to a pest management firm. Adam et al. (2010) also estimated labor costs in this way, regardless of whether the work was performed by facility staff or contracted out.

The first scenario evaluated estimated costs for the monitoring program as described for the research study (ARS research costs). We used a duplicate set of traps, so that each time the warehouse was sampled the traps were replaced, and the deployed traps were returned to the ARS lab for counting. All male *P. interpunctella* were individually counted, the adults scraped off of the trap, and the traps were re-conditioned by adding glue when necessary. Counting in the laboratory, particularly when dealing with multiple species and greater capture levels, is more accurate and reconditioning traps is desirable in situations where labor is available but funding for supplies is limited. On sample dates with low trap catch, little time was spent re-conditioning traps, but when trap catch was high additional time was required. Even using this approach it is necessary to replace traps occasionally since some traps were lost during a monitoring period and traps with many captures did eventually need to be replaced. For comparison purposes, we calculated our costs on a yearly basis, assuming all traps were replaced each year. We used a base figure of 52 traps, which would result in 104 traps needing to be replaced each year to account for the two sets of traps. Pheromone lures were replaced every 8 weeks at the same cost for all scenarios evaluated. For labor costs, we used a rate of $20.00 per h with salary and benefits which is approximately a General Schedule-5 level federal employee and comparable with private industry salary estimations. The physical process of trap replacement, plus the walking distance required to collect and replace all 52 traps in the facility, was estimated to be about 2 h.

The second scenario considered the cost of the monitoring program using $30.00 per h for labor, the cost of replacing the traps and lures every eight weeks, and assumes all counts were done on-site. These costs are only for labor associated with the traps, and does not include additional costs such as data entry and interpretation, overhead, training and equipment, etc. The third scenario considered the cost of the monitoring program if it was contracted out to an outside entity. Time estimates for the contracted work are based on the time estimates for the second scenario.

3. Results

3.1. Monitoring study

Inside temperatures during most of the calendar year were above 15 °C, the general lower limit of development for most stored product insects, including *P. interpunctella* (Howe, 1965; Fields, 1992) (Fig. 2). The temperature was above 15 °C for 755 of the total of 938 days of temperature recordings for the inside of the warehouse (a gap in 2007 due to data logger malfunction), and ranged from 22 to 32 °C for 6–7 months of the year. The recorded daily averages for the outside climatic zone where the food warehouse was located varied with season, and there was more daily

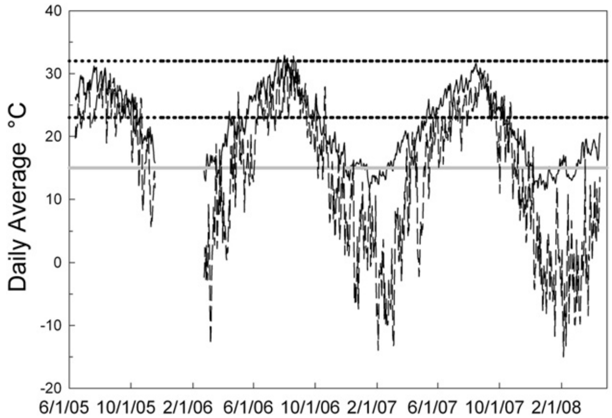

Fig. 2. Temperatures in relation to development of *P. interpunctella*; the solid line is inside temperature (recorded data on HOBO data loggers), the long-dash line is outside temperature (data obtained from NOAA weather station). The solid gray line at 15 °C represents the approximate lower limit of development for *P. interpunctella*. The two dotted lines at 22 °C and 32 °C represent the optimal developmental range.

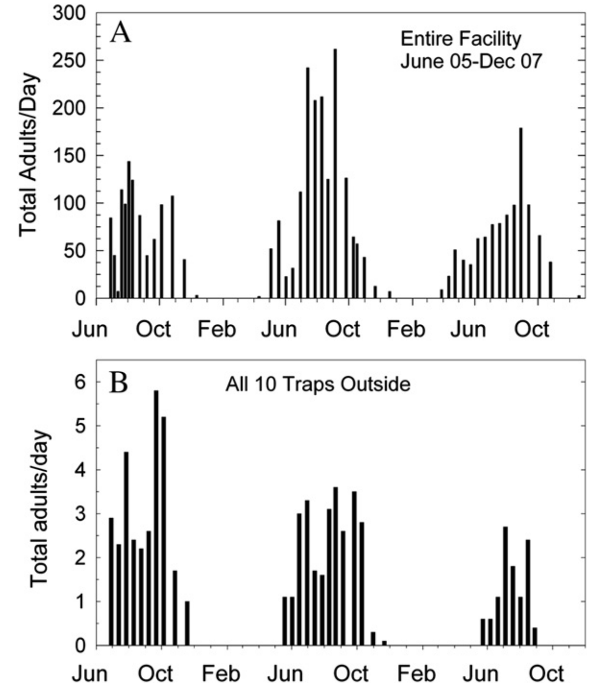

Fig. 3. Capture of male *P. interpunctella* in traps placed inside the facility, adjusted for males caught per trap per day in all traps (A, inside captures in 52 traps, and B, outside captures in 10 traps).

fluctuation compared to the inside temperatures (Fig. 2). Hence, the temperature in the outside environment of the warehouse was in the optimum range for population development of *P. interpunctella* on 510 out of the 938 days total, which were mostly between June and September during each of the three years.

A total of 49,646 male *P. interpunctella* were captured inside the warehouse during the study (Table 1). Each year the total trap catch was greatest in Area 2, the site within the warehouse where most food products were stored, but *P. interpunctella* were found in all four areas, including Area 1, which did not contain food. There was an increase in captures in 2006, with a full year of trapping, compared to 2005 which had only a partial year, but total captures declined from more than 22,000 in 2006 to about 15,000 in 2007, the last full year of data. It was also evident visually that the amount of stored food in Areas 2 and 3 declined over the same time period and the amount of food visually estimated at the end of the study as about 60–70% of the amount present in early 2006. Many of the pheromone traps that had been placed underneath full shelves at the start of the study were hanging underneath under empty shelves in April 2008.

Capture of male *P. interpunctella* inside the warehouse was immediate. On the first sample date of 29 June 2005, trap catch for the entire site was 84.3 male *P. interpunctella* per day, which increased to a maximum of 124 males per day in August, and then began declining in late autumn (Fig. 3A). Few males were caught during the winter months of 2005–2006, when temperatures were cool enough to limit development and flight, but as temperatures inside the warehouse began to warm in April–May trap catch increased to follow the same patterns as shown for the previous year, and on four occasions total trap catch exceeded 200 per day for the entire site (Fig. 3A). This seasonal pattern was also evident in 2006–2007 (Fig. 3A), but at a lower level that seemed to be related to the reduced amount of processed food stored at the site, as there were no management changes that could account for the sharp decline in total numbers of male *P. interpunctella* trapped at the site.

Male *P. interpunctella* were also trapped outside the food warehouse, with trap catch generally following the same seasonal pattern as the inside captures; increasing in late spring and summer and then declining in autumn (Fig. 3B). Data are presented as trap catch in all ten traps/day. These captures may suggest that a moth population was readily available to immigrate into the facility, but moths could have emigrated outdoors from the inside population. The numbers captured per trap outside tended to be less than inside the warehouse, but direct comparisons between these locations may not be valid because of the large distances between traps and the small number of traps outside compared to inside the warehouse. Furthermore, the environmental conditions at these two locations were often different. Additional data analysis was done only on the data from inside the food storage warehouse.

Data were analyzed to determine differences among trap locations, by averaging data over sample periods for the entire year. In 2005 (Fig. 4A), there were significant differences among traps ($F = 4.1$, df = 57, 533, $P < 0.001$, Bonferroni analysis). Traps 4, 5, 46, 47, and 48 were at the lower end of the range, with average catches of 0.1 ± 0.1, 0.3 ± 0.3, 0.7 ± 0.2, 0.9 ± 0.3, and 0.9 ± 0.2 moths, respectively (all averages on a per day basis), while average catch in 13 and 14 were at the upper end of the range, 6.4 ± 1 and 5.7 ± 1.0, respectively. Two of the traps with fewest captures and two with the greatest captures were located quite close to each other (Fig. 1), and although they were separated by a wall, the two traps were near a doorway connecting two different areas. In 2006 (Fig. 4B), the overall model was significant ($F = 2.0$, df = 51, 825, $P < 0.001$), but no differences were detected among traps using Bonferroni analysis ($P \geq 0.05$). In particular, captures in traps 13 and 14 were reduced and not different than other traps. The model was again significant for captures in 2007 (Fig. 4C) ($F = 3.7$, df = 51, 777, $P < 0.001$), with trap 5 at the low end of the range with 0.2 ± 0.0 males per day, and trap 37 at the high end of the range with 3.2 ± 0.7 males per day. The fluctuation in trap catch between sample periods in any given year, along with the change in average values between years, suggests the spatial pattern of infestation inside the warehouse changed with time. Although captures of moths varied significantly among trap locations, in practical terms the average number of *P. interpunctella* captured was relatively similar among trap locations and areas within the facility.

Given the potential for change in captures at a specific trap location as food products were moved within the facility, coupled with the constant influx and outflow of products, mean captures in

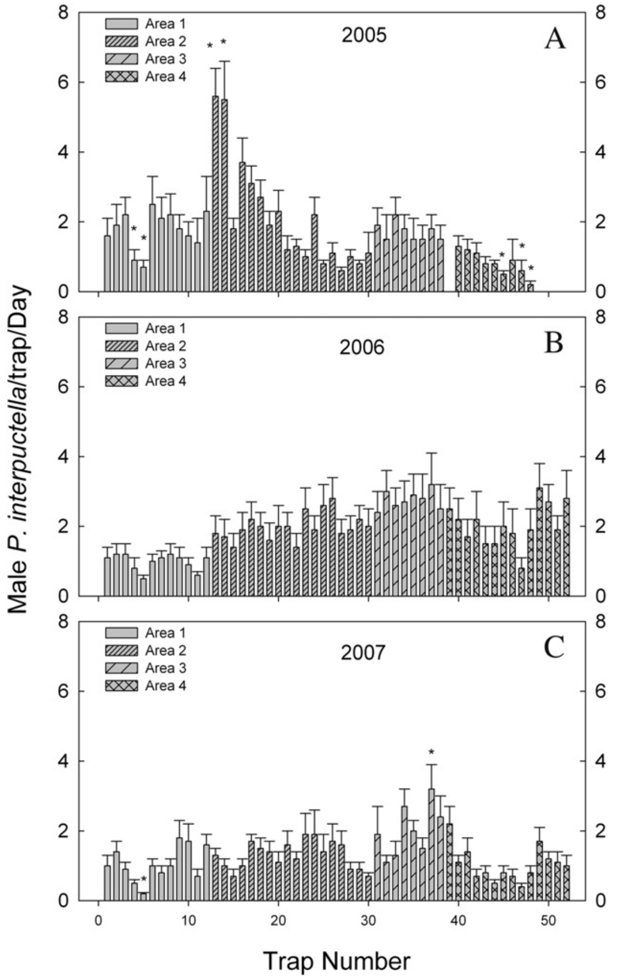

Fig. 4. Capture of male *P. interpunctella* inside the facility at each trap location, adjusted for males caught per trap per day in all traps (mean ± SE), for 2005 (A), 2006 (B), and 2007(C). The traps placed in the four different areas are indicated by different hatch patterns in the bars. Means marked with an asterisk are at the upper and lower end of the ranges for trap catch as determined by Bonferroni analysis and are significantly different ($P < 0.05$).

traps may be less informative than how frequently moth are captured at a specific location. To identify these locations, we used the number of observations above a threshold value of moth catch rather than average trap capture. Threshold levels of 1, 2, or 3 *P. interpunctella* per day were selected and how many times captures exceeded these values for a given trap location and year was calculated (Table 2). The number of times moth captures exceeded thresholds decreased with increasing threshold level and this metric revealed greater variation among trap locations than was apparent in the mean moth capture data. All areas of the mill had individual trap locations that exceeded thresholds frequently, even though traps in some areas like Area 1 did not have food storage nearby (e.g., traps 9, 10, and 12), and often trap locations physically near each other had very different levels of capture. For example, in Area 1 traps 4 and 5 rarely exceeded any of the threshold levels on any sample date in any year, yet these traps were located close to the access door to the main storage area (Area 2) and trap 13 which frequently exceeded threshold levels (Fig. 1, Table 2).

3.2. Economic analysis

The research cost estimates (ARS) were done by estimating an approximate processing time of 2 h for the 52 traps, based on the average trap catch for each sample period for each year (Table 3). Fixed costs were pheromone lure replacement every 8 weeks at \$2.00 per lure (4, 7 and 7 replacement times for each year in succession) and new traps purchased each year (at \$2.00 per trap). Labor costs associated with servicing and reconditioning traps are shown in Table 3. Total costs of operating the monitoring program for each year were estimated to be \$1622 in 2005, \$2256 in 2006,

Table 2
Number of times during a year that the number of *P. interpunctella* captured at a trap location exceeded thresholds of 1, 2, or 3 males/day. There were 13 sample dates in 2005[a], 17 sample dates in 2006, and 15 sample dates in 2007. The threshold values refer to the three horizontal values for each year.

Area	Trap	Threshold value								
		2005			2006			2007		
		1	2	3	1	2	3	1	2	3
1	1	5	2	1	9	3	1	6	3	0
	2	5	3	2	8	4	2	6	5	1
	3	5	5	2	6	2	1	7	1	0
	4	3	1	0	3	2	1	1	0	0
	5	2	0	0	2	0	0	0	0	0
	6	5	5	2	6	2	1	7	2	0
	7	6	4	2	7	3	1	4	2	0
	8	4	4	3	8	4	1	5	1	1
	9	5	3	2	7	3	2	8	5	3
	10	5	4	0	5	2	0	8	6	2
	11	3	1	1	3	0	0	5	1	0
	12	3	2	1	6	3	1	9	6	1
2	13	12	12	11	8	5	4	1	4	0
	14	12	12	9	9	3	2	7	1	0
	15	11	6	4	6	4	3	3	0	0
	16	12	11	10	9	4	2	8	1	0
	17	13	10	7	10	6	4	12	7	0
	18	13	8	6	14	6	4	10	3	1
	19	9	5	3	8	4	2	10	1	1
	20	8	4	4	8	4	4	7	1	1
	21	5	2	2	10	6	5	6	4	3
	22	5	1	0	9	4	2	10	2	0
	23	8	3	3	11	6	6	7	5	3
	24	8	5	4	10	5	4	9	3	1
	25	6	3	0	10	8	6	8	3	1
	26	8	2	0	12	7	6	8	5	1
	27	3	2	0	11	7	3	9	4	1
	28	6	3	2	10	6	4	4	1	0
	29	6	2	2	12	8	6	3	1	0
	30	7	4	2	9	6	5	6	0	0
3	31	9	7	4	11	7	7	7	3	1
	32	8	5	4	13	10	6	6	3	1
	33	12	7	4	12	9	4	5	3	2
	34	9	6	3	11	6	6	12	6	5
	35	7	5	3	13	8	6	10	7	3
	36	7	2	1	11	6	5	9	5	1
	37	11	7	4	11	6	4	12	9	7
	38	9	6	5	12	6	5	10	6	4
4	39	.	.	.	11	8	6	10	7	3
	40	8	4	1	10	8	6	8	2	0
	41	8	3	1	7	6	5	7	2	1
	42	8	4	0	7	5	4	3	1	0
	43	7	3	2	7	5	5	5	2	0
	44	4	2	0	7	5	5	3	0	0
	45	4	2	2	7	5	5	5	1	0
	46	6	4	0	6	5	5	3	1	0
	47	1	1	0	5	2	0	2	0	0
	48	0	0	0	8	6	5	3	1	1
	49	.	.	.	12	9	7	8	4	1
	50	.	.	.	11	10	7	8	1	0
	51	.	.	.	10	6	3	5	1	1
	52	.	.	.	12	7	5	3	1	1

[a] Area 1 was not available for monitoring in 2005 from 7/27 to 9/7 (5 sample dates), monitoring was renewed on 9/21 with two additional traps in positions 11 and 12, trap 39 was repeatedly damaged or missing in 2005, hence data were not used in analysis, and Traps 49–52 first placed in warehouse in 2006. Values denoted with a "." represent a missing trap.

Table 3
Economic costs (USD) of the monitoring program for *P. interpunctella* inside the food warehouse, using the methods described in the text to conduct the monitoring study. Fixed costs of traps and lures assume 52 traps per year and lures changed every 8 weeks. Sampling costs were for 2 h per site visit and processing times of 4, 5, and 3 h for the average trap catches in 2005, 2006, and 2007. Labor was calculated at $20.00 per h.

Year	Traps	Lures	Number of samples	Site visits	Trap catch	Processing costs[a]	Total cost[b]
2005	$208	$416	13	$520	20.8 ± 0.9	$480	$1622
2006	$208	$728	17	$680	27.6 ± 1.9	$640	$2256
2007	$208	$728	15	$600	18.1 ± 0.7	$560	$2096
Total	$624	$1872	27	$1800		$1680	$5974

[a] Processing time was estimated as 2 h per sampling period.
[b] Includes a one-time cost estimate of $20 (1 h × $20.00 per h) for trap assembly.

and $2096 in 2007, respectively, for a total of $5974 for the whole project. This cost does not include costs associated with reconditioning traps or replacing lost traps, labor and fixed costs associated with data processing and analysis, or labor costs associated with interpretation and making recommendations.

The fixed cost of traps and lures are assumed to be the same if the monitoring program was conducted by the food warehouse personnel or if contracted with an outside company. For 2005, a partial year of monitoring, the food warehouse was sampled on 13 occasions and using an 8-week schedule for trap and lure replacement, this would require four replacements of traps and lures (about 32 weeks/8 for a fixed materials cost of $832) (Table 4). The labor costs, 4 trips with trap replacement and 9 visits without replacing the traps, was estimated as $1050 for actual cost and $3015 for contracted cost. In 2006 there were 17 sampling dates, which would result in 7 trips with replacement of traps and lures. Fixed cost for traps would be $1456 and variable costs for in-house versus outside contractor were $1500 and $4500, respectively (Table 4). In 2007, using 15 sampling dates and 7 times having to replace traps and lures, the fixed costs of traps was $1456 and variable costs for in-house versus outside contractor were $1410 and $4230, respectively (Table 4).

To illustrate how trap density affected the cost of a monitoring program, general recommendations for the number of traps to use in a monitoring program for *P. interpunctella* is to place 1 trap every 7.6 or 15.2 m apart in a grid pattern (Toews and Nansen, 2012), which is approximately 1 per 58 m^2 or 1 per 231 m^2, respectively. The floor dimensions of Areas 1, 2, 3, and 4 in the food storage facility were 1453, 5315, 4502, and 2835 m^2, respectively. The costs of a monitoring program using these estimated trap densities was compared to the density and placement pattern used in the current study. Using the higher density trapping (7.7 m apart), the number of traps was estimated to be 25, 90, 76, and 48 for each area in the warehouse, respectively, for a total of 239 traps (compared to 52 traps used in the current study). Using the lower density trapping (15.4 m apart), the number of traps was estimated to be 6, 23, 19, and 12 for each area in the warehouse, respectively, for a total of 60 traps (which is similar to the 52 traps used in the current study). Using the higher density trapping and the scenarios of trap and lure replacement described in Table 4 for commercial operations, the fixed costs for materials were $17,208 (239 traps × 18 trap/lure changes × $4 per trap/lure). The recommended number of traps is roughly 5 times what was used in this study, and simply multiplying the labor costs ration of 239 traps/52 traps (Table 4) yields estimated labor costs of $17,933 and $60,186, respectively. However, using the lower density trapping grid, resulted in labor costs based on the ratio of 60–52 traps for in-house and outside contractor labor are $4517 and $15,109, respectively.

Table 4
Economic costs (USD) of the monitoring program for *P. interpunctella*, fixed costs of traps and lures and also trap assembly, are compared for in-house personnel (an internal cost for a facility) versus the cost of using an outside contractor (what they would have to pay a pest management professional to provide this service).

Year	Trap + lure replacements	Cost	Number of samples[a]	In-house	Outside contractor
2005	4	$832	13	$1005	$4365
2006	7	$1456	17	$1500	$4500
2007	7	$1456	15	$1410	$4230
Total	18	$3744	27	$3915	$13,095

[a] Hourly sample time was 1.5 h on the 9 dates when traps would not have been replaced, and 5 h (double the sample time plus the 1 h trap assembly time) when traps were replaced.

Based on our findings of limited variation among trap locations in terms of mean capture and the identification of specific trap locations that tend to have greater probability of high moth capture, it may be possible to develop effective monitoring programs using even fewer traps. Reducing trap numbers reduces the spatial resolution of the data, although this may be less of an issue given the mobility of this moth species, and reducing the time and effort spent on servicing traps could free up time for additional inspection methods and/or interpretation of trapping programs (Toews and Nansen, 2012). If the objective was to detect an overall level of activity in a food storage facility, then selecting trap locations which are likely to exceed one of the threshold values reported earlier might be a method to reduce trap numbers in a systematic manner. For illustrative purposes, if we use the two-moth capture threshold shown in Table 2 and calculate the traps that met or exceeded this threshold value 30% of the time during a given year (≥4 for 2005, ≥6 for 2006, ≥5 for 2007), specific trap locations might be selected that yield the most informative data. This percentage of time exceeding the threshold is used as a starting point because it seems like a reasonably stringent level; however, higher and lower threshold levels could be used as well. Using this 30% level, 25, 26, and 13 trap locations met the criteria in 2005, 2006, and 2007, respectively (data in Table 2). Evaluating across years, 43 trap locations exceeded the level in one of the three years, 16 trap locations exceeded the level in 2 of the 3 years, and only 5 trap locations exceed the level in all three years, illustrating again how spatially variable captures of *P. interpunctella* were over time within the warehouse.

If just these trap locations were used to calculate the average number of moth captured per trap per day for the whole monitoring period the mean captures would have been 2.1 ± 0.1, 2.3 ± 0.1, and 2.4 ± 0.1, for the 43, 16, and 5 traps, respectively. If we then compare this to the average determined using all the traps (1.9 ± 0.1 moth per trap per day) and determine the difference between the two averages, then we get an average difference of 0.2, 0.4, and 0.5 moth per trap per day for 43, 16, and 5 traps, respectively. Thus, all three trap densities are providing mean moth captures that are similar to the mean generated with the greater density of traps. We can then calculate an estimated cost of the trapping program using these reduced numbers, for both in-house and outside contractor costs, as was done in Table 3. The fixed and variable costs are reduced considerably as the number of traps is decreased (Table 5). Therefore, a more targeted trapping program with reduced numbers of traps with substantial cost savings could be generated based on analysis of the results of a more intensive monitoring program.

4. Discussion

Vick et al. (1986) used pheromone traps to detect *P. interpunctella* infestations in food distribution warehouses ranging from 60,000 to 120,000 m^3, but that study was done from July to January. Similarly, several authors have examined *P. interpunctella* populations inside retail stores within the US (Platt et al., 1998; Arbogast et al., 2000;

Table 5
Economic costs (USD) of the monitoring program for *P. interpunctella* inside the food warehouse, using cost estimates for 43, 16, and 5 traps. These trap numbers were based on how many times during the monitoring period that trap catch exceeded a threshold of two moths per trap 30% of the monitoring periods within any one year, two of three years, or all three years, respectively. Fixed and variable costs for in-house versus outside contractor were set as described for Tables 3 and 4.

Number of traps	Cost[a]	Number of samples	In-house	Outside contractor
52	$3744		$3915	$13,095
43	$3096	13	$1005	$4365
16	$1162	17	$1500	$4500
5	$360	15	$1410	$4230

[a] 18 total changes for traps and lures and 27 sample periods for all three years.

Roesli et al., 2003), but most of these studies were conducted during a single year as well. Campbell et al. (2002) monitored populations of several stored product insects, including *P. interpunctella*, inside a food processing plant warehouse during a one-year period, and found extensive spatial and temporal variation in pest populations. A multi-year study in a flour mill also showed spatial and temporal variation in *P. interpunctella*, with strong correlations between outside populations and inside populations (Campbell and Arbogast, 2004). In some instances, specific focal points of infestation and/infested products were detected inside these facilities (Vick et al., 1986; Arbogast et al., 2000; Roesli et al., 2003). In the current study, consistent focal points of infestations were not common within the warehouse. For example, only five trap locations exceeded the 2 moth per trap per day level 30% of the time every year. This likely is a result of the physical movement of infested food products into, out of and within the facility, and the mobility of the adult male moth. Retail stores would also have movement of products, but the same products are generally shelved in the same location within the store. Even though temperatures inside the food warehouse were above the minimum threshold of 15 °C for most of the year, trap catch was generally low from November through April during the 3-year study. A laboratory study by Cox et al. (2007) showed that the minimum temperature range for flight initiation in *P. interpunctella* was about 12.5–15 °C, which corresponds to the minimum developmental temperature of 15 °C. The increased trap catch from May through October could reflect more favorable temperature conditions for population development and moth flight, increased immigration from outside populations, or greater probability of infested goods being brought into the facility. Abrupt population increases in specific traps during the summer months could have resulted from importation of infested goods or movement from less favorable food sources. Roesli et al. (2003) also discussed the potential of infested food products being brought into retail stores, but tracking an infestation is difficult in a retail environment, and the problems are compounded in a commercial food storage and distribution site with constant high-volume movement of food products. Outside populations of *P. interpunctella* have been correlated with inside trap catch (Campbell and Arbogast, 2004), as they were in this study, suggesting an important role for active immigration. However, the greater levels of capture inside, a trend for captures near doors not to be greater than in the warehouse interior, and observation of infested product suggests that at this location a resident population within the warehouse was of primary importance.

Interpretation of pheromone trap catch data of stored product insects in relation to actual population density is confounded for a number of reasons including trap density, internal air movement, height of traps, age of pheromone lures, temperature and insect movement patterns (Campbell et al., 2002; Nansen et al., 2004, 2008; Trematerra and Gentile, 2010; Semeao et al., 2012), which ultimately affects adoption of monitoring programs and management strategies. Arbogast et al. (2000) described two approaches for interpretation of trap catch data: representative, which assumes trap catch is a proportion of the total population, and indicative, which assumes trap catch as an indication of risk or a necessary management action. The indicative interpretation for our study demonstrated how *P. interpunctella* populations in a commercial food storage facility fluctuate within a season and among years, but more importantly, patterns in moth capture with warehouse were not necessarily associated with areas likely to contain infested product. Most trap locations were highly variable in terms of the number of moth captured over time, with the result that it was difficult to identify specific locations where monitoring should be focused. This could be the result of movement of infested material into and out of the warehouse, although a similar pattern was observed for *Tribolium castaneum* (Herbst), the red flour beetle, in flour mills (Semeao et al., 2012). In both cases, it may be that the high mobility of the adult insects is covering up the actual dispersion of the infestations. Hence, the spatial pattern information from a monitoring program may be less useful, and emphasis should be on using the average captures to indicate trends in insect activity over time (Toews and Nansen, 2012). These observations strongly suggest that it is possible to reduce the number of traps used while still maintaining the ability to estimate the level of insect activity, whether it is a representative or an indicative interpretation.

Developing threshold values for moth captures can be considered as an example of an indicative interpretation to evaluate risk. This approach was used by Campbell et al. (2010a,b) to establish a trap threshold value for *T. castaneum* of 2.5 beetles per trap per 2-week trapping period, which was then used to calculate population rebound rates after fumigations. This threshold value was shown to be associated with an increased risk of subsequent large increases in beetle captures if it was exceeded. Here, we used three threshold values as a relatively simple method to evaluate variation among traps, although the relationship between these levels of moth capture and risk to the product is unknown. This approach was useful in evaluating the likelihood of moth activity in different locations within the warehouse and was used to show how the number of traps could be reduced in a more systematic way from that typically used in implementing pheromone trapping programs in food facilities. Campbell et al. (2002) stated that monitoring programs should start with a high density grid of traps and then use the information generated to determine how few traps could be used to provide equivalent information about pest trends. Here, we provide a method that could be used to determine which specific locations should be used to provide information on pest activity. This approach needs further evaluation in other locations and systems, but holds promise as a practical method that could relatively easily be adopted by pest management practitioners in a wide variety of commercial facilities.

This study is the first to assign an economic cost to a sampling program for *P. interpunctella* by estimating the costs of a monitoring study conducted using different processing methods or different numbers of traps and if done directly or if contracted with a pest management firm. The cost of sampling programs for stored product insects have been quantified in only a few recent studies on insect pests in stored grain (Adam et al., 2010; Yigezu et al., 2010). In food facilities, treatments such as fumigation and aerosol application are much more expensive and disruptive, thus the primary focus should be on prevention and containment. Monitoring programs using pheromone traps are useful for detection and tracking of pest activity and inclusion in pest management programs is often required in food facilities. The question of how many traps and where to place them within a facility has been difficult to address and these results are germane to solving that problem.

The economic costs associated with monitoring programs of different scales needs to be taken into account so that the costs and benefits can be determined. There may be alternatives to using a grid-based approach for placement of pheromone traps for mobile insects such as *P. interpunctella*. One method would be to use fewer traps but place them in areas that are vulnerable to pest activity and the analysis of this dataset has shown how that might be approached as well as the economic benefits in terms of the cost of the monitoring program. Costs associated with a monitoring program for *P. interpunctella* could be greatly reduced through more specific targeting of where pest populations would be most likely to occur in a site. The economic information provided here is a useful first step in this process, although further evaluation of the economic benefits of monitoring programs needs to be conducted.

Acknowledgments

We thank B. Barnett, C. Doll, R. Hammell, J. Rowan, M. Kennedy, and J. Staats for technical assistance with this project. Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture or the University of Georgia. The USDA is an equal opportunity provider and employer. We would like to thank Dominic Reisig for reviewing a draft of this manuscript prior to submission. This study was supported by the USDA/CSREES Risk Avoidance and Mitigation Program Award No. 00-511-01-9674.

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