Monitoring Stored-Product Pests in Food Processing Plants with Pheromone Trapping, Contour Mapping, and Mark-Recapture

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ABSTRACT Distribution and movement patterns of several species of stored-product pests in a food processing plant were investigated. The objectives of this study were to determine the temporal and spatial variation in abundance of stored-product pests using pheromone traps; assess the effectiveness of trap type, location, and number on monitoring insect populations; and to evaluate the nature of pheromone trap capture hot spots by measuring patterns of insect movement. We determined that the distributions of *Trogoderma variabile* Ballion, *Lasioderma serricorne* (F.), *Tribolium castaneum* (Herbst), and *Plodia interpunctella* (Hübner) within the facility were typically clumped and that foci of high trap captures, based on visual observation of contour maps, varied among species and over time. Trap type and location influenced the number of *T. variabile* captured: traps on the floor and along walls captured more individuals than hanging traps and traps next to support pillars. *T. variabile* was the predominant insect pest at this facility and from mark-recapture studies, we found that individual beetles moved across multiple floors in the facility and from 7 to 216 m though the warehouse.

KEY WORDS *Trogoderma variabile, Lasioderma serricorne, Tribolium castaneum, Plodia interpunctella,* monitoring, integrated pest management

AFTER HARVEST, AGRICULTURAL grain commodities remain vulnerable to damage by insects and the economic costs of this damage increase as raw grain is turned into value-added products while moving through processing and distribution channels. Costs beyond direct damage also can accrue when insects infest processed commodities, including loss of customer good will, health hazards associated with allergens in food, sanitation and chemical treatments, and the consequences of unsatisfactory food safety inspections. Considerable research has gone into stored-product pest behavior, ecology, and the interpretation of pest monitoring programs in bulk stored grain (Sinha 1991, Hagstrum et al. 1990, 1995; Hagstrum and Subramanyam 2000). However, less information is available on pests in spatially and temporally variable ecosystems found in processing plants, warehouses, and retail operations. Stored-product pest species are often found in surveys of these environments (Good 1937, Williams 1961, Evans and Porter 1965, Highland 1978, Zimmerman 1990), but limited information is available on temporal and spatial patterns of their distribution.

The foundation of a successful integrated pest management (IPM) program is an effective monitoring system that supplies information on not only the number and type of pests present but also detects changes in pest populations over time and locates foci of infestation and routes of entry (Burkholder 1990). Pheromones have been isolated and lures are commercially available for many stored-product insects (Chambers 1990, Phillips et al. 2000). Several trap designs specific for stored-product pests also have been developed and are commercially available (Vick et al. 1990, Mullen 1992, Mullen and Dowdy 2001). Pheromone traps have been demonstrated to be effective at capturing stored-product pests, primarily moths in the family Pyralidae, in anthropogenic ecosystems (Vick et al. 1986, Soderstrom et al. 1987, Pierce 1994, Bowditch and Madden 1996, Mankin et al. 1999), and pheromone trap use is increasing in commercial facilities (Phillips et al. 2000). However, many questions remain about the use of these monitoring tools, from the very practical issues such as how many traps are needed and which types work best to the fundamental issues concerning the relationship between pheromone trap captures and actual pest population density, distribution, and level of product infestation (Arbogast and Mankin 1999).

Understanding the spatial distribution of pests is especially important for food production and storage

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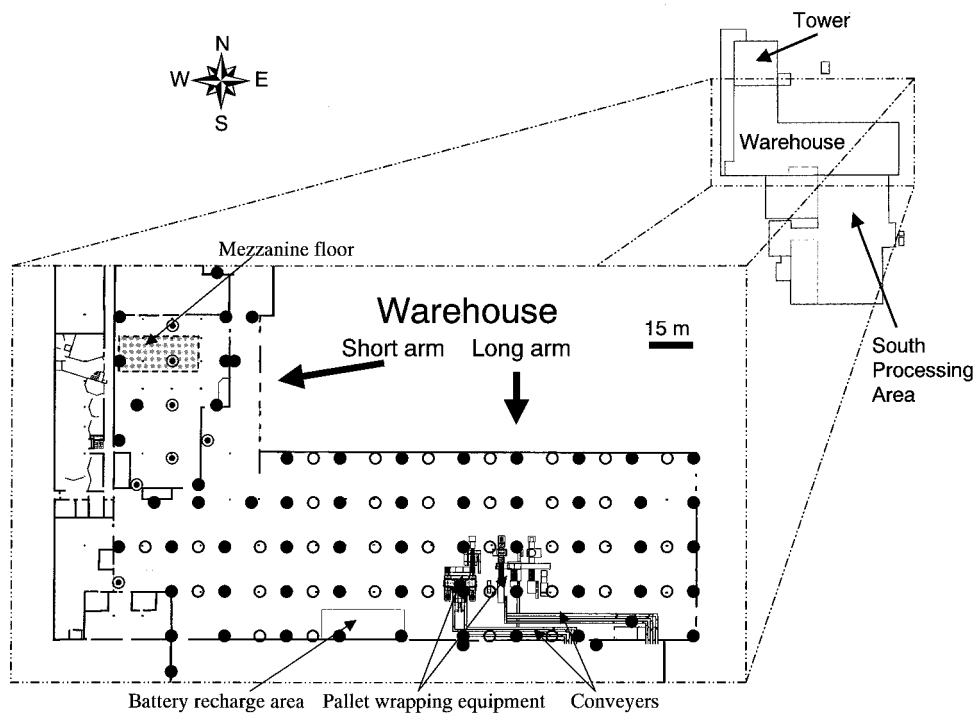

Fig. 1. Floor plan of the facility showing the locations of the warehouse, north processing area (tower), and south processing area. The floor plan of the warehouse is shown in more detail, locations of support pillars are indicated by small dots, and the location of traps are indicated by circles. Pherocon II trap locations are indicated by ●, FLITeTRAK trap locations are indicated by ○, and locations with both trap types are indicated by ⊙.

facilities, because they consist of a mosaic of favorable and unfavorable patches, and insects are unlikely to be uniformly distributed. The probability of suppressing the pest population is increased and the cost of management and risk of negative nontarget effects is decreased when management tactics are both temporally and spatially targeted (Brenner et al. 1998). Geostatistical techniques such as contour mapping facilitate the interpretation of spatial information and are becoming more widely used in entomology (Liebhold et al. 1993, Brenner et al. 1998). Some recent studies have begun addressing the temporal and spatial patterns to stored-product pest abundance in bulk grain storage containers (Arbogast et al. 1998, Brenner et al. 1998), flour mills (Doud and Phillips 2000), food processing plants (Rees 1999), and retail stores (Arbogast et al. 2000), but our understanding of pest ecology and behavior and the effectiveness of using spatial information in IPM for the diverse range of postharvest ecosystems remains limited.

In this study, pheromone trap data from a food processing plant and warehouse was used to assess the spatial distribution and movement patterns of several species of stored-product pests. The following three objectives were addressed: (1) determine the temporal and spatial variation in abundance of stored-product pests using pheromone traps; (2) assess the effectiveness of trap type, location, and number on monitoring insect populations; and (3) evaluate the nature of pheromone trap capture hot spots by measuring patterns of insect movement by using mark-recapture.

Materials and Methods

Study Site. This research was conducted at a food processing plant and was focused on the warehouse (13,832-m^2) portion of the facility where product was stored before shipment (Fig. 1). The warehouse was L-shaped, with the long arm running east to west and the short arm running north to south. To the south of the long arm of the warehouse was an active processing and packaging area (Fig. 1). This south processing area was connected to the warehouse by a series of doorways along the south wall. To the north of the short arm of warehouse was the tower area (Fig. 1). The tower portion of the plant was eight floors tall and it was connected to the short arm of the warehouse through a series of doors along the north end, a hallway running along the east side, and by screw conveyors running from the tower to a mezzanine floor. The long arm of the warehouse was used to store packaged food stacked in pallets, except for the western-most quarter, which was typically used for packaging and equipment storage. In the long arm of the warehouse there were also conveyers and pallet wrapping equipment, packaging materials, forklift battery recharging area, and equipment and supply storage

areas. In the short arm of the warehouse, there was a forklift repair area, supply storage, and overflow packaged food storage. Above the north end of the short arm of the warehouse was a mezzanine level consisting primarily of an open grate floor. This mezzanine contained the terminal ends of screw conveyors that were formerly used to bring in material from the tower processing area to be packaged. There were direct openings from the warehouse to the outside along the east walls of both the long and short arms of the warehouse and in the southeast corner of the warehouse (indicated in Fig. 1 by breaks in the lines indicating these walls).

Monitoring also was conducted in the tower portion (≈282 m^2 per floor) of the facility. Visual inspection of the tower indicated that it harbored populations of *Trogoderma variabile* Ballion (Coleoptera: Dermestidae; warehouse beetle), especially high numbers on the fourth floor, and *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae; red flour beetle), readily apparent on the eighth floor. The tower contained large multifloor bins for storing raw ingredients and each floor contained different machinery for the processing of food. When production in the tower had ceased, cleanup had been inadequate and food material was visible in some of the machinery, particularly on the fourth floor. The tower also was used for the storage of machinery and overflow storage of raw ingredients. There were many potential routes of insect movement among floors in the tower; there were two elevators and a set of stairs, some of the floors had sections where there was grated flooring open to adjacent floors, there were also many holes, chutes, pipes, and duct work running between floors. As previously discussed, there were also potential routes for insects between the tower and the warehouse.

The warehouse environment was very dynamic during the time monitored with product entering and leaving the warehouse and the total levels of product fluctuating. On 31 July 1999 the whole facility was treated with a pyrethrin fogging. Localized interventions such as sanitation and crack and crevice sprays also occurred intermittently during the sampling period.

Pheromone Trapping. A grid of pheromone traps was placed in the warehouse and tower. The pheromone trap grid in the warehouse consisted of 41 FLITeTRAK M^2 and 74 Pherocon II traps (Trécé, Salinas, CA) (Fig. 1) and was in place from 15 July to 1 September 1999. The traps were typically spaced 10–16 m apart in the warehouse. FLITeTRAK traps are pitfall traps with pheromones suspended over the trap and the bottom of the pitfall containing a food oil attractant that are placed on the ground next to walls or pillars and capture walking insects (Mullen 1992). Pherocon II traps are 15 cm long and 15 cm wide with roughly diamond-shaped openings at both ends with the interior of the trap having a sticky surface (280 cm^2). This type of trap is designed to capture flying insects and traps were suspended between 1.5 and 2.1 m off the floor. The trap height used in this study is commonly used in commercial monitoring programs and is based on the balancing of practical factors such as ease of servicing, reduced risk of damage, and location of attachment points.

In most areas of the warehouse, trap placement alternated between the two trap types. From 15 July to 28 July, 12 FLITeTRAK and 12 Pherocon II traps were placed along the walls in an alternating pattern on the fourth and eighth floors. On 28 July, traps in the tower were removed. On 4 August, Pherocon II traps were placed in the four corners of each floor of the tower. In FLITeTRAK traps, pheromone lures for *Trogoderma* spp. (*T. variabile* and *T. granarium* Everts, khapra beetle), *Lasioderma serricorne* (F.) (Coleoptera: Anobiidae; cigarette beetle), and *Tribolium castaneum* and *T. confusum* du Val (red and confused flour beetles, respectively) were used. In the Pherocon II traps, lures for *Trogoderma, L. serricorne,* and *Plodia interpunctella* (Hübner) (Lepidoptera; Pyralidae; Indian meal moth) were used. The pheromone lures were produced by Trécé, different septa were used for each pheromone, and septa were replaced approximately every 2 mo. All pheromones used were sex pheromones, except for the *Tribolium* spp., which is an aggregation pheromone. See Phillips et al. (2000) for further information on the pheromones. Pheromone traps were checked weekly, and all insects were removed, identified and counted.

Mark-Recapture. Self-marking stations were placed in five locations in the facility to assess the movement patterns of stored-product pests. Self-marking stations were in place from 15 July to 1 September 1999. Two types of marking stations were used. The first was based on the design of Wileyto et al. (1994) and consisted of a Pherocon 1C trap (Trécé) with the bottom sticky section replaced with an inverted top piece. Florescent powder (Day-Glo Color, Cleveland, OH) was added to the bottom of the station and pheromone lures were placed in the powder. The same types of lures as in the Pherocon II traps were used. The second type of marking station was based on the FLITeTRAK trap and consisted of the FLITeTRAK sleeve containing pheromone lures with the plastic pitfall portion of the trap replaced with a ring of perforated cardboard with a dusting of florescent powder placed in the center (unpublished data). Both of these marking station designs enabled insects to enter and leave the station while picking up florescent powder during the visit. Laboratory studies indicated that all of the insect species monitored in this study could be marked using the powder, but *T. variabile* and *P. interpunctella* tended to be the most clearly marked.

Marking stations in different locations in the facility contained unique colors of fluorescent powder. Marking stations were placed on the eighth floor (Horizon Blue A pigment, product code A-19), fourth floor (Fire Orange A pigment, product code AX-14-N), and first floor (Aurora Pink A pigment, product code A-11) of the tower, the mezzanine floor in warehouse (Saturn Yellow A pigment, product code A-17-N), and near the pallet wrapping equipment in the warehouse (Signal Green A pigment, product code A-18-N). Four

of each type of marking station were used at each location in the tower, four of the Pherocon 1C traps were used on the mezzanine, and a single Pherocon 1C trap was used in the warehouse.

Captured insects were inspected under long wave (365 nm) ultraviolet light (Black-Ray Lamp model UVL-21; UVP, Upland, CA) to determine whether they had visited a marking station and retained any powder on their cuticle. A magnifying lens was used to determine whether insects had even small amounts of fluorescent powder. The number of marked individuals of each species and the color of the marking powder were recorded.

Analysis. Spatial data were visualized using contour maps created using Surfer (Golden Software 1999). The trap catch data and x-y coordinates of each trap location were used to create a grid with the default parameters of the Kriging method with linear variogram model. This model has been shown to be adequate for precision targeting for IPM in anthropogenic structures (Brenner et al. 1998). To assess dispersion of trap captures, standardized Morisita indexes of dispersion (I_p) were calculated for pheromone trap data of each insect species and trap type combination (Krebs 1999). This index is independent of population density and sample size and in its standardized form ranges from –1.0 to 1.0 (95% confidence intervals of –0.5 and 0.5). With this measure of dispersion, $I_p = 0$ indicates a random pattern, $I_p > 0$ indicates a clumped pattern, and $I_p < 0$ indicates a uniform pattern.

Analyses of variance (ANOVA) and *t*-tests were performed using Systat (SPSS 1998) and general linear models (GLM) procedures and Tukey's multiple range tests were performed using SAS (SAS Institute 1999). Data were square root transformed before analysis to address issues with violations of ANOVA and GLM assumptions of normality of distributions. Data are presented in the text as mean ± SEM.

To assess how different numbers of traps might influence our estimate of pest populations, we used bootstrapping analysis (Manly 1997). We addressed how drawing different numbers of samples (i.e., traps) from the universe (i.e., warehouse) would affect our estimation of the average pheromone trap capture. The actual pheromone trap data were resampled 10,000 times by using Resampling Stats Software (1999) and the number of times the mean trap capture of the resampled data were outside the 95% confidence intervals of the original estimate was determined. These estimates were calculated using sampling sizes of 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100. This approach provides an estimate of the reliability of sampling for insects using different numbers of traps.

Results

Pheromone Trap Monitoring of Temporal and Spatial Variation in Stored-Product Pests. In the warehouse, there was a significant difference among species in the average number of insects captured per trap over the monitoring period (GLM procedure; $F = 172.8$; df = 3, 339; $P < 0.0001$) (Figs. 2–5). Based on Tukey's multiple range test, *T. variabile* mean trap capture (Fig. 5) was greater than the other three species. The average *T. castaneum* capture (Fig. 2) was greater than *L. serricorne* (Fig. 3) but not *P. interpunctella* (Fig. 4), and the capture of *P. interpunctella* and *L. serricorne* did not differ from each other. Nonstored-product pests, including collembolans, staphylinids, carabids, dipterans, homopterans, and arachnids also were captured occasionally but were not included in analyses.

Contour mapping of pheromone trap catch data indicated that the four species also differed in their spatial distribution within the warehouse. A foci of high *T. castaneum* trap catches near the center of the warehouse was present for most of the sampling dates, but the other locations with high trap capture were more variable over time (Fig. 2). The dispersion of individuals among traps was clumped for most sample dates, except for the two sampling dates after the pyrethrin fogging (Table 1). The majority of the *L. serricorne* were captured in the western half of the warehouse in an area where little packaged food material was stored (Fig. 3). The dispersion of *L. serricorne* individuals among traps was frequently different between the two trap types; dispersion was clumped on most sampling dates for FLITeTRAK traps, but varied considerably with Pherocon II traps (Table 1). Contour maps of *P. interpunctella* trap catch indicate that total trap captures were highest around doors to the outside of the facility and near the pallet wrapping equipment (Fig. 4). The dispersion of *P. interpunctella* individuals was variable among sampling dates (Table 1). The spatial mapping of *T. variabile* trap catch indicated two areas of consistently high trap capture (i.e., hot spots) in the warehouse over the sampling period (Fig. 5). The first was located near the south wall, under the conveyer system that carried bagged food, and around the pallet wrapping equipment. The second hot spot contained the highest trap catches in the warehouse and was centered along the north wall at the end of the short arm side area. Because of these consistent hot spots, the dispersion of individuals among the traps was consistently clumped for both trap types and for all sampling dates (Table 1).

In the initial sampling of the fourth and eighth floors, high numbers of *T. variabile* were captured on both floors, with the fourth floor containing the highest trap catches in the facility. On the fourth floor, *T. variabile* captures ranged from 1 to 1,362 insects/trap/wk with a mean capture of 356 ± 83.8 insects/trap/wk on 21 July and 300.3 ± 69.8 insects/trap/wk on 28 July. On the eighth floor, *T. variabile* mean capture was 18.8 ± 5.9 insects/trap/wk on 21 July and 13.8 ± 3.6 insects/trap/wk on 28 July. *T. castaneum* was present on both floors: 2.4 ± 0.8 beetles/trap/wk on 21 July and 5.2 ± 1.4 beetles/trap/wk on 28 July on the eighth floor and 0.75 ± 0.3 beetles/trap/wk on 21 July and 0.7 ± 0.4 beetles/trap/wk on 28 July on the fourth floor. After the pyrethrin fogging of the entire facility on 31 July, Pherocon II trap captures of *T. variabile* were lower than before fogging on floors 4 and 8, but catches on the third to sixth floors increased to an

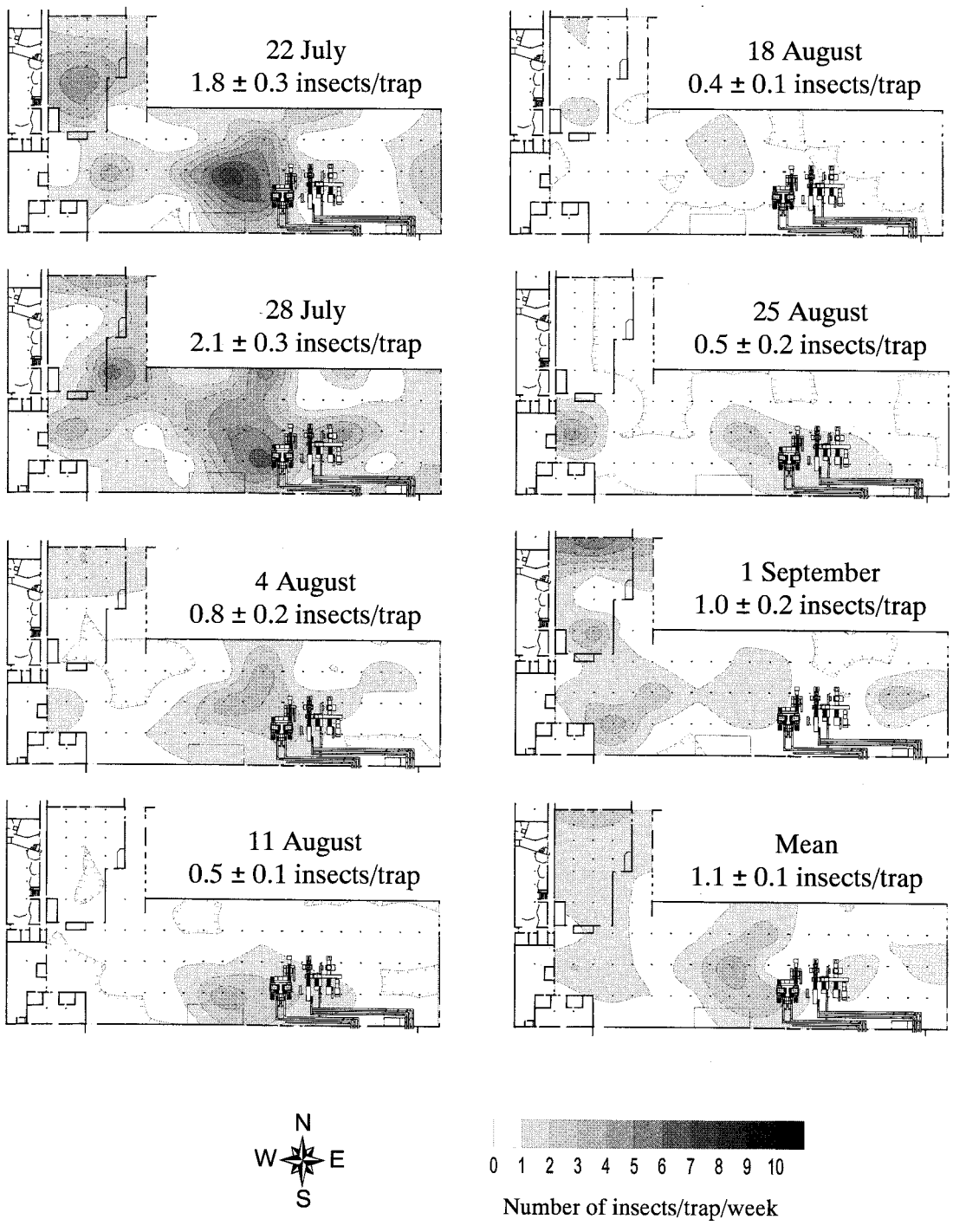

Fig. 2. Contour maps of the number of *Tribolium castaneum* captured in FLITeTRAK traps in the warehouse over 1-wk sampling periods during 1999. Areas with hatch marks pointing inward indicate areas with zero trap captures.

average of >30 individuals per week within 1 mo after treatment. Few *L. serricorne* or *P. interpunctella* were captured in the tower before or after the pyrethrin fogging.

Effectiveness of Trap Type, Location, and Number on Monitoring Insect Populations. The trap type (FLITeTRAK versus Pherocon II) and trap location (wall or pillar) influenced the average number of *T.*

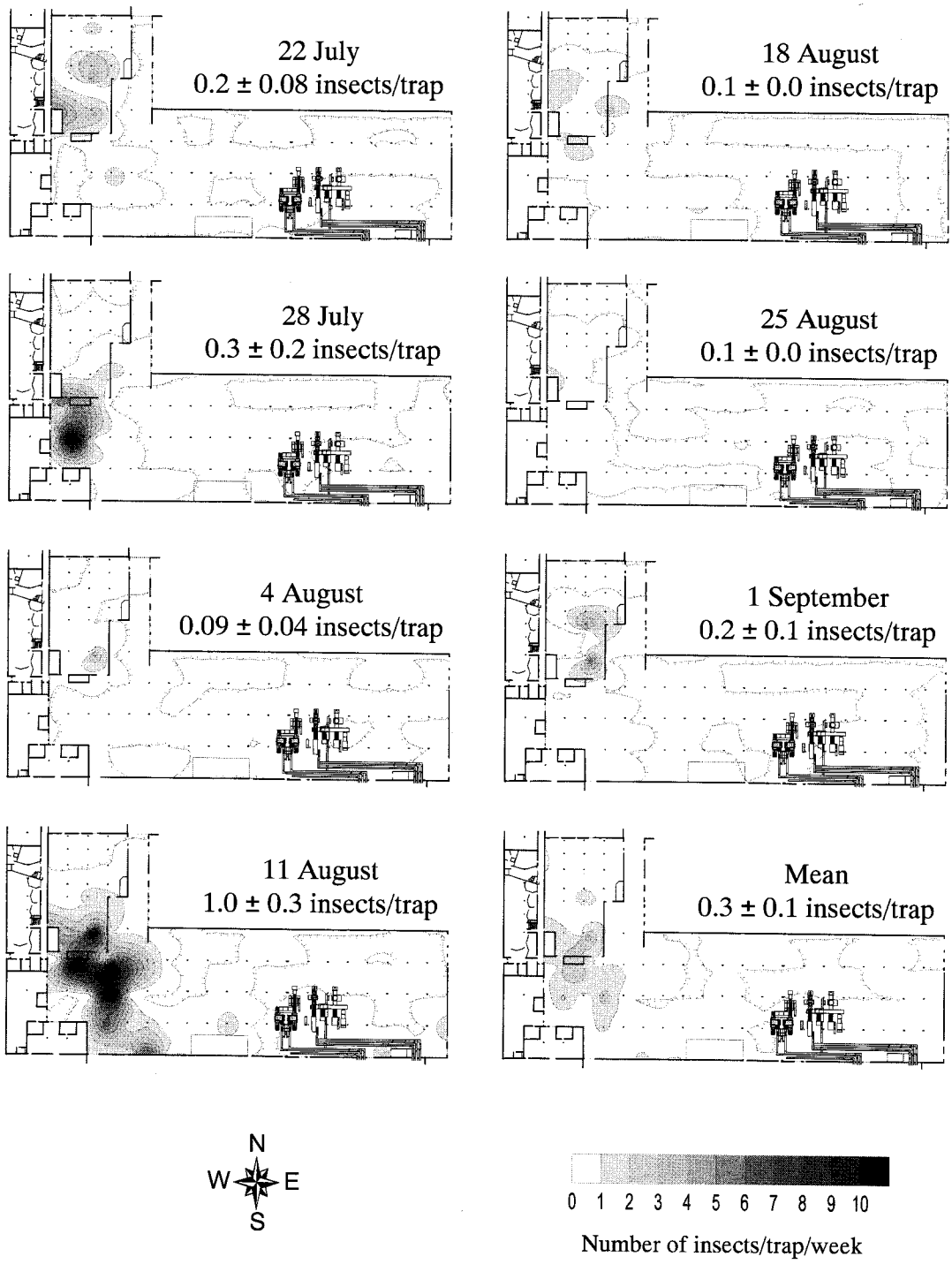

Fig. 3. Contour maps of the number of *Lasioderma serricorne* captured in FLITeTRAK and Pherocon II traps in the warehouse over 1-wk sampling periods during 1999. Areas with hatch marks pointing inward indicate areas with zero trap captures.

variabile that were captured at a trap site based on two-factor ANOVA (trap type: $F = 8.97$; df = 1, 109; $P = 0.003$ and trap location: $F = 4.84$; df = 1, 109; $P = 0.03$). FLITeTRAK traps and traps placed along walls tended to capture more beetles, but there was an interaction between the two factors (trap type/trap

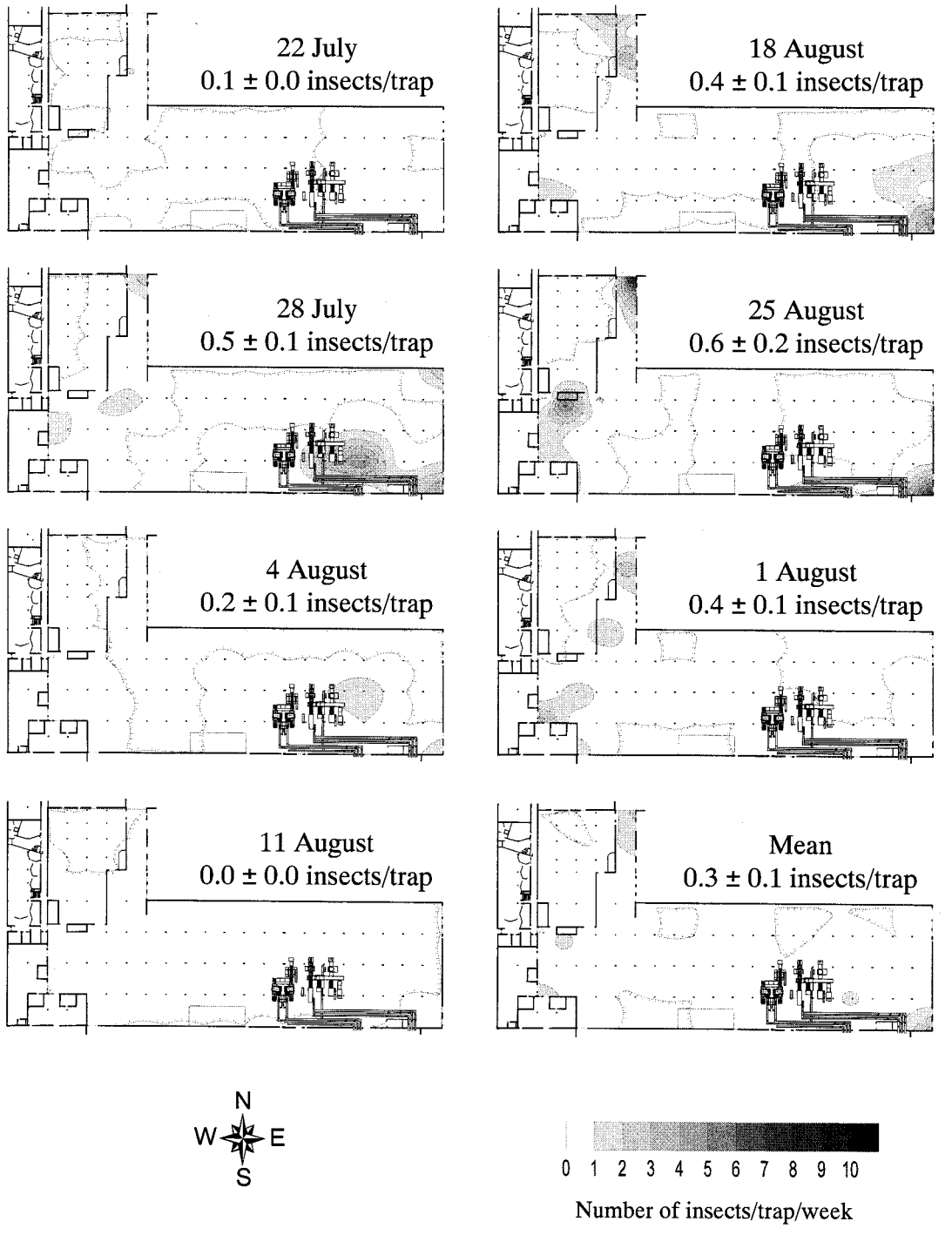

Fig. 4. Contour maps of the number of *Plodia interpunctella* captured in Pherocon II traps in the warehouse over 1-wk sampling periods during 1999. Areas with hatch marks pointing inward indicate areas with zero trap captures.

location interaction: $F = 4.63$; df = 1, 109; $P = 0.034$). The interaction was due to the difference between the two trap types being greater at wall locations than at pillars. The average *T. variabile* trap catch per week over the seven sampling dates was 22.4 ± 5.4 beetles for the FLITeTRAK and 12.6 ± 1.3 beetles for the Pherocon II trap. At pillar locations, the average trap captures were 13.3 ± 2.5 for FLITeTRAK and 9.6 ± 2.1 for Pherocon II traps. At wall locations, the average trap captures were 37.1 ± 13.1 for FLITeTRAK and

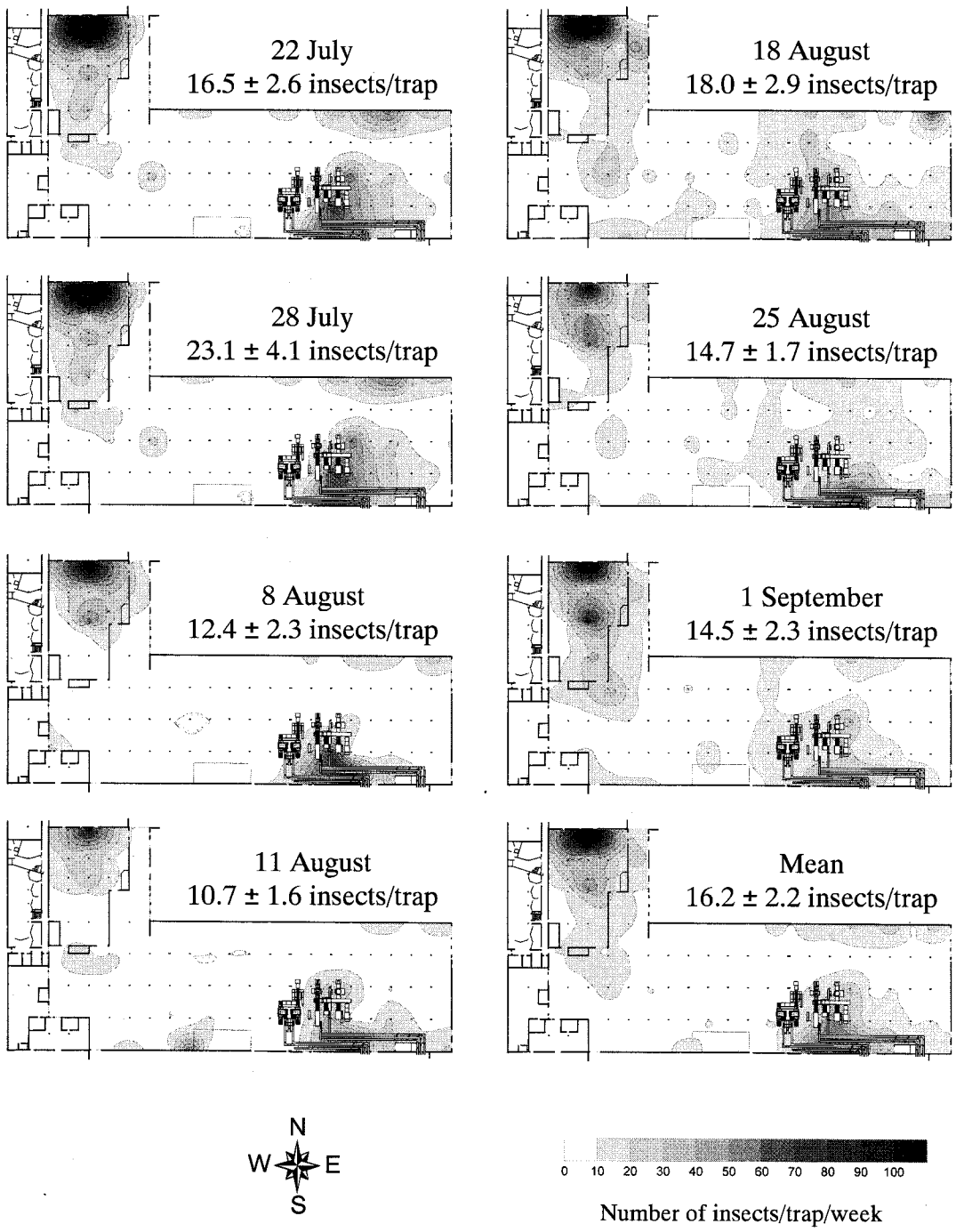

Fig. 5. Contour maps of the number of *Trogoderma variabile* captured in FLITeTRAK and Pherocon II traps in the warehouse over 1-wk sampling periods during 1999. Areas with hatch marks pointing inward indicate areas with zero trap captures.

15.1 ± 2.0 for Pherocon II traps. Due to the generally low numbers captured and the large number of zero values, the other species were not analyzed.

Trap type also influenced the probability that a trap was damaged or lost during a sampling period. There was considerable human and forklift traffic, sanitation, and movement of pallets in the warehouse that all contributed to trap damage and loss. The FLITeTRAK traps (9.0 ± 1.0% of traps lost each sampling period) were more likely to be affected than the Pherocon II

Table 1. Standardized Morisita index of dispersion (I_p) for pheromone trap captures in the warehouse

Sampling date (1999)	*T. castaneum* FLITeTRAK	*L. serricorne* Pherocon II	*L. serricorne* FLITeTRAK	*P. interpunctella* Pherocon II	*T. variabile* Pherocon II	*T. variabile* FLITeTRAK
22 July	0.505	0.660	0.530	−0.188	0.509	0.553
28 July	0.502	0.846	0.606	0.512	0.513	0.547
4 Aug	0.500	−0.071	0.658	−0.157	0.515	0.544
11 Aug[a]	−0.584	0.555	0.561	−0.023	0.509	0.534
18 Aug	−0.123	−0.554	0.520	0.514	0.506	0.538
25 Aug	0.515	−0.439	−0.066	0.544	0.505	0.518
1 Sept	0.506	—	0.567	0.508	0.506	0.540

The index of dispersion ranges from −1.0 to 1.0, where random patterns have an $I_p = 0$, clumped patterns have an $I_p > 0$, and uniform patterns have an $I_p < 0$. The 95% confidence limits for a random pattern of distribution are at −0.5 and 0.5.

[a] Sampling date immediately after a fogging of the warehouse with pyrethrin.

traps (0.9 ± 0.9% of traps lost each sampling period). The number of FLITeTRAK traps lost near pillars (15 traps) or near walls (13 traps) was similar. Location near pallet wrapping equipment appeared to have the greatest influence on whether a trap was lost, probably due to higher levels of sanitation activity in this region.

The relationship between number of traps sampled and the probability of generating a mean outside of the 95% CI of the original data mean decreased as trap number increased (Fig. 6). The relationship was consistent with an exponential decay model: $y = 0.682e^{-0.043x}$ for Pherocon II traps and $y = 0.640e^{-0.071x}$ for FLITeTRAK traps. The curves were similar among insect species within trap type even though the data means varied. For all species and trap types, our analysis indicates that trap number could not be greatly reduced without having a significant impact on the estimation of mean.

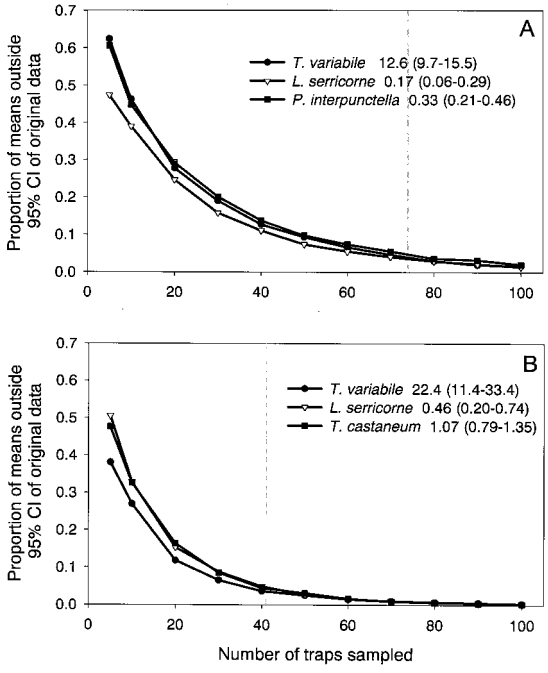

Fig. 6. Relationship between number of traps sampled and the probability of generating a mean outside of the 95% CI of the original data mean for Pherocon II (A) and FLITeTRAK (B) traps was generated using bootstrapping. Numbers following the species names represent the mean and range of the original trap capture data. The vertical dashed lines indicate the number of original traps.

Patterns of Insect Movement Measured by Mark-Recapture. *T. variabile* was the primary species marked and recaptured at this facility. *T. variabile* males were captured on the same floor of the tower in which they were marked, moved between floors in the tower and moved from the tower into the warehouse (Table 2). The largest number of marked individuals recovered in the warehouse were marked on the mezzanine floor (64 of 71 beetles) (Fig. 7). The mezzanine floor itself contained few potential breeding habitats but did contain the terminal ends of screw conveyors that originated in the tower that may have facilitated insect movement into the warehouse. Visual inspection revealed that food material and cast *Trogoderma* larval cuticles were present in the conveyors.

Calculating distance traveled is difficult in this study because multiple marking stations were used at a location and routes traveled to move between floors of the tower are unknown. Because most of the marked insects originated from the mezzanine floor and this location is the easiest marking source from which to estimate dispersal distances, average dispersal distances were calculated for this site. The average distance between where *T. variabile* was marked and where it was recaptured was 26.1 ± 5.0 m (range, 7–216.4 m) and the distance was greater for insects recaptured in Pherocon II traps (37.5 ± 8.2 m, 7–216.4 m, $n = 37$) than those recaptured in FLITeTRAK traps (10.4 ± 1.6 m, 7–41.2 m, $n = 27$). One *P. interpunctella* marked on the mezzanine floor was recaptured 137.8 m away in the warehouse (Fig. 7). One *T. variabile* was marked at the marking station in the warehouse near the pallet wrapping equipment and moved 27 m to where it was captured. Marked insects were recaptured in the warehouse consistently over the sampling period: 18 on 22 July, 13 on 28 July, 14 on 4 August, two on 11 August (week after pyrethrin fogging), four on 18 August, four on 25 August, and nine on 1 September.

Table 2. Number of marked *T. variabile* captured at different locations in a food processing plant

Marking station location	Warehouse	1st floor tower	2nd floor tower	3rd floor tower	4th floor tower	5th floor tower	6th floor tower	7th floor tower	8th floor tower
Warehouse	1	0	0	0	0	0	0	0	0
Mezzanine	64	0	0	0	0	0	0	0	0
1st floor tower	4	12	1	0	0	0	0	0	0
4th floor tower	2	5	0	0	472	1	0	0	1
8th floor tower	0	0	0	0	0	0	0	0	25

Discussion

Anthropogenic structures such as warehouses are temporally and spatially patchy environments for stored-product insects. Plant operations such as control tactics, movement or removal of infested product, generation and accumulation of spillage; population dynamics within infested product; and patterns of dispersal from infested patches may all influence population structure in a facility and ultimately trap capture. The spatial distribution and movement patterns of stored product insects in food processing and storage facilities remain poorly understood, but this information is critical for the development of effective integrated pest management programs. Although pheromone traps are widely used commercially, recommendations on trap number, type, and placement, and how to interpret trap capture data are not based on an understanding of insect behavior and ecology. In this study, we have documented that the spatial distribution of the predominant stored-product insects varied within a facility, changes in spatial distribution occurred over time, trap type and location influenced the number of insects captured, and insect dispersal from foci of infestation influenced pheromone trap captures, and potentially product infestation, in distant parts of a facility. These general observations are potentially applicable to other food processing and warehouse facilities and illustrate the types of information needed to develop and interpret monitoring programs.

Trogoderma variabile was the major insect pest at this facility and was the only species that had relatively stable pheromone capture hot spots. These areas of high trap capture were located at two regions of the warehouse and around the fourth floor of the tower. The first hot spot in the warehouse was located near the south wall, under the conveyer system that carried bagged food, and around the pallet wrapping equipment. There was considerable spillage from damaged packages in this area that could provide an odor source, as well as equipment that could allow spilled food to accumulate and offer a harborage to insects. The second hot spot contained the highest trap catches in the warehouse and was centered along the north wall at the end of the short arm side area. There were few structural or spillage factors present on the main floor that would explain the high numbers captured, but this area of the warehouse had doorways leading to the tower section and was under a mezzanine floor which had outlets from the tower. The hot spot on the fourth floor of the tower contained nonoperational machinery with considerable amounts of infested residue. It is possible that these three hot spots of pheromone trap capture were generated pri-

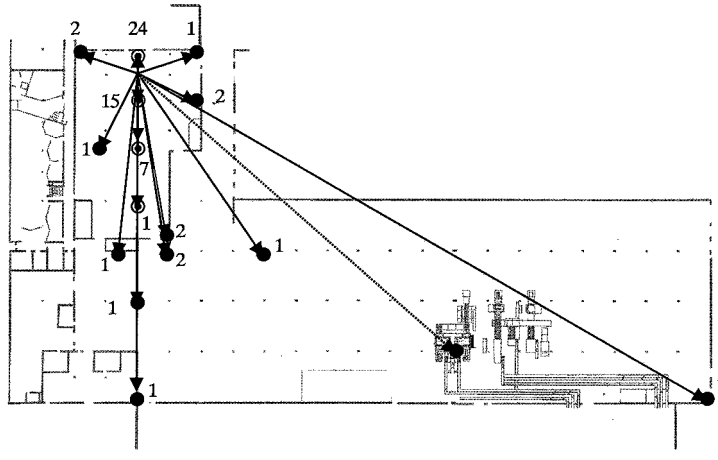

Fig. 7. Movement patterns of insects marked with florescent powder on the mezzanine floor of the warehouse. Solid and dashed arrows indicate the net linear distance between mark and recapture points for *Trogoderma variabile* and *Plodia interpunctella*, respectively. Numbers indicate the number of marked individuals recaptured at that location. Pherocon II trap locations are indicated by ● and locations with Pherocon II and FLITeTRAK traps are indicated by ⊙.

marily by three fundamentally different processes: proximity of a large infestation (fourth floor of tower), proximity of a major route of movement (north wall of warehouse), and proximity to a major source of attractive odor (south wall of warehouse).

It is difficult to determine the relationship between pheromone trap capture and the absolute number of insects present in a structure, i.e., "representative" trap interpretation (Arbogast and Mankin 1999). Research in this area has focused on developing relationships between released insects or insects present in the air and trap capture (Hagstrum and Stanley 1979, Mankin et al. 1983, Sinclair and Haddrell 1985, Leos-Martinez et al. 1986, Wileyto et al. 1994, Rees 1999), but the relationship between trap capture and infestation or between density of insects inside and outside commodities is poorly understood. An alternative approach to trap interpretation is to use the relative numbers captured and their spatial distribution to make targeted management interventions, i.e., "indicative" trap interpretation (Arbogast and Mankin 1999).

The results of this study highlight some of the difficulties of interpreting the spatial distribution of pest infestation based on trap captures. Trap capture in an enclosed environment such as a warehouse can be influenced by multiple physical and biological factors other than the proximity of an infestation source. For example, we captured more *T. variabile* in FLITeTRAK than in Pherocon traps, but this could result from differences in trap type (e.g., FLITeTRAK traps can attract both flying and walking insects), attractants (e.g., FLITeTRAK traps contain food oil in addition to pheromone), or the vertical location of the trap (e.g., Burkholder and Faustini [1991] mentioned that the same type of modified cardboard trap placed on the floor in warehouses captured more *Trogoderma* than those placed 1–2 m above the floor). Trap location also influences the number of insects captured. In this study traps along walls captured more *T. variabile* than those along poles, which could result from differences in the ability of insects to orientate to a trap due to physical factors such as air movement and surface characteristics (Mankin et al. 1980), differences in probability of trap encounter due to a tendency to use walls as movement corridors (Campbell and Hagstrum 2002), or the presence of more sources of insects along walls.

The number of traps needed to effectively monitor a facility is a complex question and many biological, environmental, and economic factors impact on the decision. In this study, we used a higher number of traps than is typically used in a warehouse of this size. Our analysis suggests that due to the high degree of variation among sampling locations, reducing the number of samples quickly begins to have an impact on the estimation of the mean. A more systematic reduction in traps that takes into account spatial variation in capture based on prior experience could moderate some of the impact of reducing the number of traps. However, reducing the number of traps may change the ability to quickly locate developing hot spots and impact the ability to accurately perform spatial analysis (Brenner et al. 1998). Rees (1999) took a similar approach to estimating the number of traps needed by removing subsets of the full data set of *Ephestia cautella* (Walker) (Lepidoptera: Pyralididae; almond moth) pheromone trap capture data from a breakfast cereal factory. Periodic removal of half of the traps or the top or bottom 10% of traps reduced the ability to detect hot spots, but the number of traps could be reduced by 75% before impacting the estimate of average moths/trap/d. Loss of traps is also a significant issue, especially when using floor traps, and has both economic costs and costs in terms of loss of information. Barak et al. (1990) reported that traps placed on the floor were more than twice as likely to be lost or damaged compared with those placed up off the floor. Ultimately, the cost of using additional traps needs to be balanced against the gains in information obtained and the potential economic benefits of reducing the number of chemical interventions.

Movement is a key factor in determining the spatial distribution of insect populations. However, actual measurements of stored-product insect dispersal ability outside of bulk grain are limited. There is considerable indirect evidence that stored-product insects can be highly mobile. Stored-product pests are readily trapped around grain storage and processing structures (Throne and Cline 1989, Throne and Cline 1991, Fields et al. 1993, Dowdy and McGaughey 1994, Doud and Phillips 2000). Stored-product insects also can be trapped far away from anthropogenic structures (e.g., Strong 1970, Cogburn and Vick 1981, Sinclair and Haddrell 1985, Vick et al. 1987), which suggests that they have the capability for long-distance flight, but these captures also may indicate feral populations in proximity of the traps (Khare and Agrawal 1964, Howe 1965, Stein 1990, Wright et al. 1990). Actual measurements of stored-product pest dispersal have involved releasing and tracking or recapturing individuals; Chesnut (1972) demonstrated that *Sitophilus zeamais* Motschulsky (Coleoptera: Curculionidae; maize weevil) flew up to 400 m and Hagstrum and Davis (1980) found that *E. cautella* flew 300 m during a 10-min flight. This is the first study we are aware of that uses self-mark recapture to measure stored-product insect movement in a commercial facility.

The high degree of mobility of males observed in this study for *T. variabile* and to a lesser extent for *P. interpunctella* suggests that there is considerable potential for these species to colonize and exploit patchy resources throughout a facility, independent of movement by people through the transportation of infested material. The high mobility of adult male *T. variabile* also indicates that dispersal from resource patches is influencing pheromone trap capture in relatively distant portions of a facility. We documented that individual beetles were able to move across multiple floors in the tower and from 7 to 216 m through the warehouse. Outside of structures, we have observed that this species can be recaptured up to 508 m from a marking location (J.F.C. and M.A.M., unpublished data). High trap captures along the north wall, espe-

cially in the FLITeTRAK traps, probably results from beetles flying from the mezzanine flour and encountering the wall and dropping down to be captured along the floor. The effectiveness of using the spatial distribution of trap captures to target management tactics is reduced as the dispersal distances from natal sources increase. Decreasing the density of pheromone traps also influences the spatial information generated by a monitoring program because as the number of traps is reduced beetles are less likely to be intercepted and the spatial autocorrelation among traps is reduced. Differences in the capture of marked beetles between the two trap types suggests that the distance from source for beetles captured in Pherocon traps may be greater than for FLITeTRAK traps. We currently do not know whether both sexes have the same dispersal abilities. If females do not disperse as far as males then detecting male immigration into an area may be of less of a concern from a product infestation standpoint, but would still have impact from sanitation, food quality, and inspection perspectives. More information on the factors that influence dispersal and interactions with pheromone traps is needed.

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