Distribution and Dispersal Behavior of *Trogoderma variabile* and *Plodia interpunctella* Outside a Food Processing Plant

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ABSTRACT The distribution and dispersal distances of insects outside of food processing and storage facilities potentially have an important influence on the population dynamics and spatial distribution of insects inside facilities. In this study, *Trogoderma variabile* Ballion and *Plodia interpunctella* (Hübner) sex pheromone-baited trap captures outside and inside a food processing facility were measured, the relationship between trap captures outside and inside the facility was evaluated, and the dispersal ability of the males of these species was assessed using self-mark–recapture stations. *T. variabile* and *P. interpunctella* males were captured in high numbers outside the food facility. The two species differed in their spatial distribution around the facility, with *T. variabile* being more closely associated with the proximity of the building, but most likely originating from sources outside the building. For marked *T. variabile*, the average recapture distance was 75 m (range 21–508 m) and for marked *P. interpunctella* the average recapture distance was 135.6 m (range 21–276 m). In an immigration/emigration experiment, three *T. variabile* marked outside were recaptured inside, but no *T. variabile* marked inside were recaptured outside and no marked *P. interpunctella* were recaptured in either location. The potential for outside populations to influence inside populations has implications for the effectiveness of different management and monitoring tools.

KEY WORDS *Trogoderma variabile*, *Plodia interpunctella*, pheromone monitoring, dispersal behavior, spatial distribution

Landscapes created or modified by humans tend to be fragmented mosaics of resource patches that are separated from each other by barriers to movement or by patches of less hospitable habitat (Wiens 1976). This is certainly true of landscapes containing anthropogenic structures where grain and grain-based food materials are processed and stored (e.g., grain bins, processing facilities, mills, warehouses, residential, and retail buildings). Landscape structure in turn influences inhabitant behavioral and ecological processes such as dispersal, population dynamics, and spatial distribution (Turner 1989, Wiens et al. 1993, Wiens 1997). For stored-product insects, it is likely that landscapes are fragmented at a range of spatial scales and populations are made up of subpopulations that are interconnected by dispersal behavior (Campbell et al. 2004). At a simplistic level, we can ask what is the degree of interconnection among individuals inside and outside an anthropogenic structure (i.e., subpopulations interacting on a spatial scale greater than the structure). The distribution and dispersal distances of insects outside of food processing and storage facilities potentially have an important influence on the population dynamics and spatial distribution of insects inside facilities. Unfortunately, relatively little is known about the spatial distribution and movement patterns of stored-product insects in anthropogenic landscapes, particularly at spatial scales larger than that of a room in a building.

The foundation of a successful integrated pest management (IPM) program for processed grain-based commodities is an effective monitoring program that supplies information on not only the number and type of pests present but also locates foci of infestation and routes of entry (Burkholder 1990). The probability of suppressing the pest population is increased and the cost of management and risk of negative nontarget affects is decreased when management tactics are targeted both temporally and spatially (Brenner et al. 1998). Within food facilities, some of the major pests of the food industry are highly mobile (Campbell et al. 2002) and temporally and spatially patchy in distribution (Arbogast et al. 1998, 2000; Brenner et al. 1998; Rees 1999, Doud and Phillips 2000, Campbell et al. 2002). It is likely that stored-product pest subpopulations are also patchy and interacting through active dispersal over much larger spatial scales. Therefore, information on pest population ecology and behavior

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in the vicinity of food processing and storage facilities is potentially important.

Many species of stored-product pests are readily trapped outside grain storage and processing structures (Throne and Cline 1989, 1991; Fields et al. 1993; Dowdy and McGaughey 1994; Doud and Phillips 2000). For example, Doud and Phillips (2000) captured higher numbers of Indianmeal moth, *Plodia interpunctella* (Hübner), outside a flour mill and in the gallery above grain silos adjacent to the mill than inside the mill and speculated that moths may be moving from source populations associated with the silos into the mill. Pest species are also sometimes captured far away from anthropogenic structures (e.g., Strong 1970, Cogburn and Vick 1981, Sinclair and Haddrell 1985, Vick et al. 1987), which supports the hypothesis that long distance dispersal is possible; although these captures also may indicate feral populations in the proximity of the traps (Khare and Agrawal 1964, Howe 1965, Stein 1990, Wright et al. 1990). In some cases, trap captures drop off as distance from a grain storage structure increases (Cogburn and Vick 1981, Doud and Phillips 2000).

Measurements of actual dispersal distances by stored-product insects are limited. Chestnut (1972) demonstrated that the maize weevil, *Sitophilus zeamais* Motschulsky, flew up to 400 m. Hagstrum and Davis (1980) found that *Cadra cautella* (Walker) flew 300 m during a 10-min flight. Long-duration flights by *Prostephanus truncatus* (Horn) in wind tunnel experiments have been estimated to lead to dispersal distances of 1,620 m in an hour, but they did not occur frequently and observations suggest shorter flights under field conditions (Fadamiro 1997). Campbell et al. (2002), using a self-mark–recapture technique based on Wileyto et al. (1994), demonstrated a high degree of male warehouse beetle, *Trogoderma variabile* Ballion, mobility, with individual beetles moving vertically through multiple floors and horizontally up to 216 m across a warehouse.

Here, we investigate the population dynamics, spatial distribution, and dispersal behavior of two major pest species outside a food processing facility. In this study, *T. variabile* and *P. interpunctella* sex pheromone-baited trap captures outside and inside a food processing facility were measured, the relationship between trap captures outside and inside the facility and the spatial distribution of outside trap captures was evaluated, and the dispersal ability of the males of these species was assessed using self-mark–recapture.

Materials and Methods

Study Site. This research was conducted at a food processing plant and in its surrounding environment [see Campbell et al. (2002) for additional detail on the site]. The plant consisted of two processing wings (one an eight-story tower) and a central warehouse. Indoor monitoring was focused on the warehouse (13,832 m^2) where product was stored before shipment and the eight floor tower (≈282 m^2 per floor) portions of the facility (Fig. 1A). Normal pest management practices were conducted during this monitoring period, including a methyl bromide fumigation of the structure that was conducted on 5 August 2000. The property around the building (Fig. 1A) was level and consisted of areas of pavement, gravel and grass. The property was surrounded by paved roads on the west and north sides, an agricultural field to the south, and mixed woodland and meadow to the east.

Pheromone Trapping. The pheromone trap grid in the warehouse was in place from 14 May to 15 November 2000 and consisted of 44 Pherocon II traps (Trécé Inc., Salinas, CA) spaced between 10 and 32 m apart. Pherocon II traps are 15 cm by 15 cm with a roughly diamond-shaped opening 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. In the tower section, there were eight traps per floor from the second to the eighth floors (total 56 traps). Each trap contained two septa with pheromone (Trécé Inc.) for *Trogoderma* spp. and *P. interpunctella,* respectively, that were replaced approximately every 2 mo. Pheromones for both species are sex pheromones that attract only males (Phillips et al. 2000). These species were selected for monitoring because previous research had indicated that these two species were prevalent at this location (Campbell et al. 2002).

Outdoor trapping was conducted around the perimeter of the building and the perimeter of the property from 14 May until 15 November 2000. Delta traps (Scentry Biologicals Inc., Billings, MT) contained the same two types of pheromone lures used in the indoor traps and were placed on wood stakes ≈1 m off the ground. This trap type is triangle shaped (10 cm in width per side) at the ends and 18 cm in length with a sticky surface on the three interior walls (540-cm^2 trapping surface). This type of trap was used outdoors, rather than the Pherocon II traps used inside, because it offered better protection from the more extreme weather conditions that occur outdoors. Traps were placed along the perimeter of the building (11 traps), along the perimeter of the property (17 traps), and near the railroad tracks and road to the east of the plant (three traps) (Fig. 1A). Additional traps where hung outside of the tower processing section of the building, on the southern outside wall of the third and fifth floors, and on the eighth floor roof, from 28 June to 15 November 2000.

Traps in the warehouse and outside locations were checked weekly until 30 August 2000 and then at 2-wk intervals, except for the 1 November 2000 sample, which covered a 1-mo period. Tower traps were checked at 2-wk intervals, except for the 1 November 2000 sample that covered a 1-mo period. When traps were checked all insects were removed, identified, counted, and, as described below, checked for the presence of marking powder.

Mark–Recapture. Self-marking stations were placed in five locations outside the facility from 28 June to 15 November 2000. Marking stations were modified from those described in Wileyto et al. (1994) and Campbell et al. (2002) and designed to enable insects to enter and leave but to confine and protect the fluorescent marking powder from exposure to the weather. Marking stations consisted of a plastic bucket (17 cm in diameter and 11 cm in height) with a snap on lid (Airlite Plastics, Omaha, NE). Three 2.5 by 2.5-cm flaps were cut equidistant from each other on the sides of the buckets. Flaps were uncut at the top (forming a hinge), and flap bottoms were even with the bottom of the bucket. Several holes, 0.5 cm in diameter, were drilled into the bottom of the bucket to allow for drainage of rainwater. A 90-mm petri dish bottom was glued to the middle of the floor of the bucket and contained a 1–2-mm layer of fluorescent powder (DayGlo Color, Cleveland OH) and the pheromone lures. Pheromone lures were changed at the same time as the traps and the powder was refreshed as necessary.

Marking stations at different locations around the facility contained unique colors of fluorescent powder. Marking stations were placed near the northwest (Saturn Yellow), southwest (Neon Red), southeast (Fire Orange), and northeast (Signal Green) corners of the property (Fig. 1A). Two marking stations (Horizon Blue) were placed ≈15 m apart and 30 m away from the eastern edge of the building near the loading docks; the midpoint between the two stations is indicated in Fig. 1A and was used for estimating dispersal distances.

Captured insects from both the indoor and outdoor traps were inspected under long-wave (365 nm) UV light (Black-Ray Lamp model UVL-21, UVP Inc., Upland, CA) to determine whether they had visited a marking station and retained any powder on their cuticle. A magnifying lens and a dissecting microscope were 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.

Weather information (maximum, minimum, and average air temperature; rainfall; dew point; average wind speed; resultant or vector wind speed; and resultant or vector wind direction) was obtained from a United States National Oceanic and Atmospheric Administration data set collected from a weather station ≈22 km south of the site. Resultant wind speed and direction are the result of vector addition of wind speeds and directions for each day during the study period. Percentage of relative humidity outside was

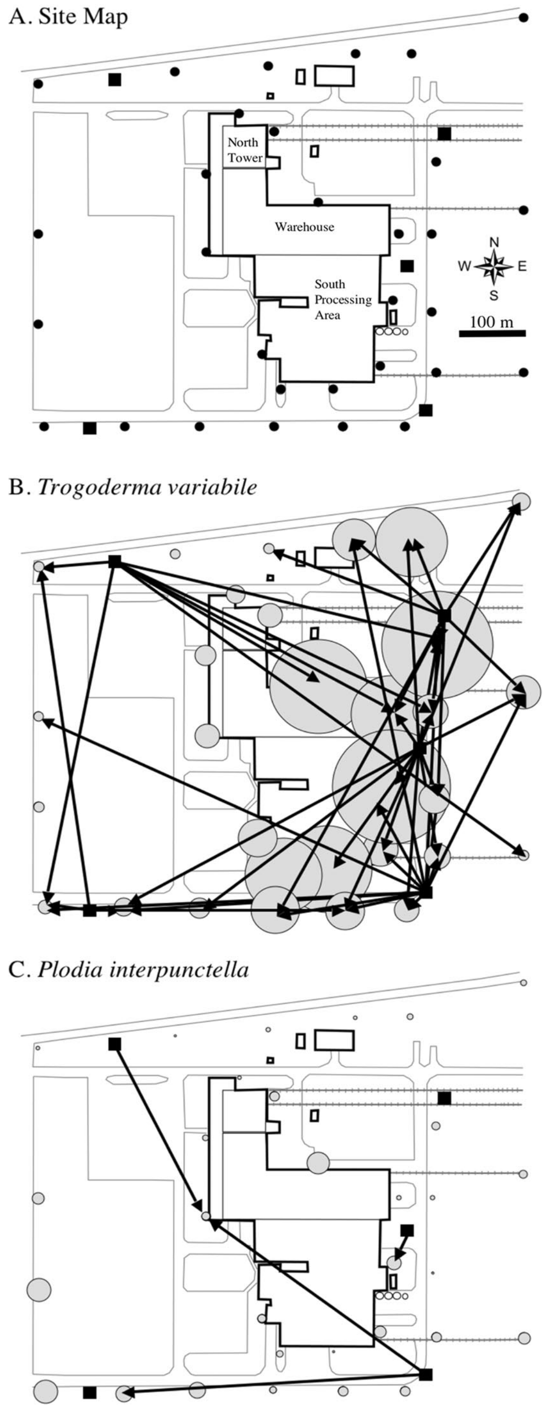

Fig. 1. (A) Site map of the food processing facility with black lines indicating the perimeter of buildings, light gray lines indicating the edges of paved surfaces (e.g., roads and parking lots), and cross-hatched gray lines indicating railroad tracks. The positions of outdoor pheromone traps are indicated with black circles and the positions of the marking stations are indicated by black squares. The black square on the east side of the main building indicates the midpoint between two marking stations. The black bar represents ≈100 m. (B) Total pheromone trap captures of *T. variabile*, the warehouse beetle, at each trap location are represented by gray circles that are proportional in diameter to the number captured. The black arrows indicate the net movement of one or more marked individuals from a marking station to a pheromone trap where the marked individual was recaptured. The arrow point indicates the direction of movement. (C) *P. interpunctella* total pheromone trap captures at each location and movement of marked individuals. Description of the symbols the same as for B.

calculated using average dew point and average temperature data from the weather station. Environmental conditions (air temperature, relative humidity, and wind speed) inside the warehouse were monitored weekly using a Kestrel 3000 environmental meter (Richard Paul Russell Limited, Lymington, United Kingdom) at 69 locations throughout the warehouse. These measurements were taken between 10 a.m. and 12 p.m. 1 d per week from 10 June to 2 August 2000.

Immigration/Emigration. To address the question of movement into and out of the facility an additional experiment was performed between 1 August and 14 September 2001. A mark–recapture program was focused around movement through three sets of warehouse doors associated with loading docks located along the east side of the building (Fig. 4). The same types of traps and marking stations as described above were used for this experiment. Trap positions were selected to surround the potential routes of entry, while avoiding paved and high-traffic areas. Initially, marking stations were placed outside and recapture traps were placed inside the warehouse; then, the placement was reversed, alternating the arrangement between replicates. Marking stations and traps were in position for 2 d for each replication. There were six replicates with the marking stations outside and recapture traps inside; from 1 to 3 August, 8–10 August, 15–17 August, 22–24 August, 29–31 August, and 12–14 September. There were five replicates with the marking stations inside and the recapture traps outside; from 6 to 8 August, 13–15 August, 20–22 August, 27–29 August, and 10–12 September.

The recapture traps were arranged so that they surrounded each set of doors, although exact placement was constrained by features of the facility (Fig. 4). There was a pair of marking stations, one inside and one outside, for each set of doors. Although at any given time only one set of marking stations and pheromone traps (inside or outside) was in place. Each marking station used a unique color of fluorescent powder (DayGlo Color) (Horizon Blue inside and Neon Red outside for the northern most set of doors; Magenta inside and Arc Yellow outside for the central set of doors; Fire Orange inside and Saturn Yellow outside for the southern set of doors).

Analysis. Analysis of Variance (ANOVA) and *t*-tests were performed using Systat version nine for Windows (SPSS Inc., Chicago, IL) and General Linear Models procedures and Tukey's multiple range tests were performed using SAS version 8 (SAS Institute 2000). Data were square root-transformed before analysis to address violations of ANOVA and GLM normal distribution assumptions. Trap capture data were converted to daily capture rates by dividing number captured by the sampling period. Correlations between average daily capture rates inside and outside the facility were performed using Spearman rank procedure (Zar 1999). Average angle and angular deviation were calculated using methods described in Zar (1999). Data are presented in the text as mean ± SEM unless stated otherwise.

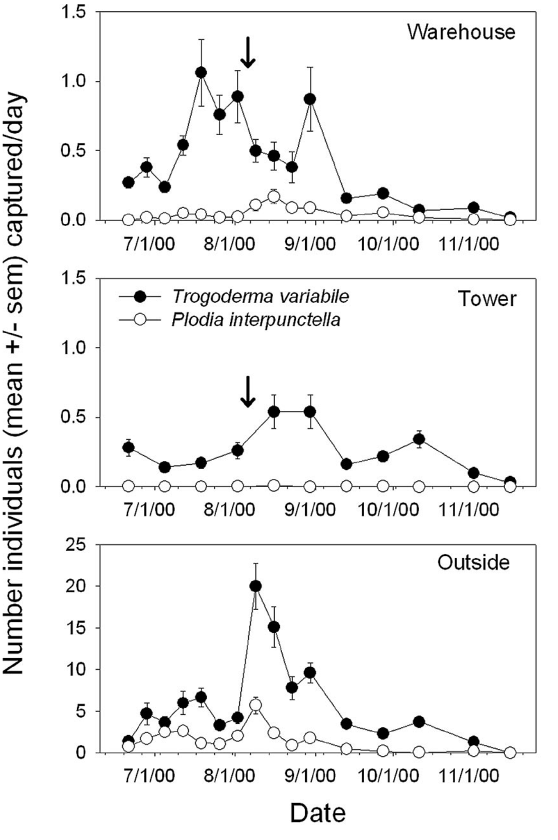

Fig. 2. Trends in number of male *T. variabile* and *P. interpunctella* captured per day in pheromone traps placed inside the food processing facility in the warehouse and tower sections and outside of the facility (see Fig. 1 for trap locations). The arrows indicate a methyl bromide fumigation of the facility.

Results

The warehouse beetle was the most prevalent species captured during the monitoring period both inside (average total capture per trap location ($n = 100$) was 38 ± 3 for *T. variabile* and 3 ± 1 for *P. interpunctella;* two-tailed *t*-test, $t = 10.15$, df = 198, $P < 0.0001$) and outside (average total capture per trap location ($n = 31$) was 688 ± 99 for *T. variabile* and 161 ± 19 for *P. interpunctella;* two-tailed *t*-test, $t = 5.23$, df = 60, $P < 0.0001$) the building (Fig. 2). The total trap captures were lower in the indoor locations (warehouse and tower) than in the outdoor locations for both *T. variabile* (two-tailed *t*-test, $t = -11.8$, df = 129, $P < 0.0001$) and *P. interpunctella* (two-tailed *t*-test, $t = -15.2$, df = 129, $P < 0.0001$) (Fig. 2). Environmental conditions during the monitoring period are presented in Fig. 3. At the time points when interior conditions were measured, relative humidity tended to be lower and wind speed was much lower inside compared with outside. The average resultant or vector wind speed was 2.66 ± 0.12 m/s and the average vector wind direction was from 144° (southeast) with an angular deviation of 80°.

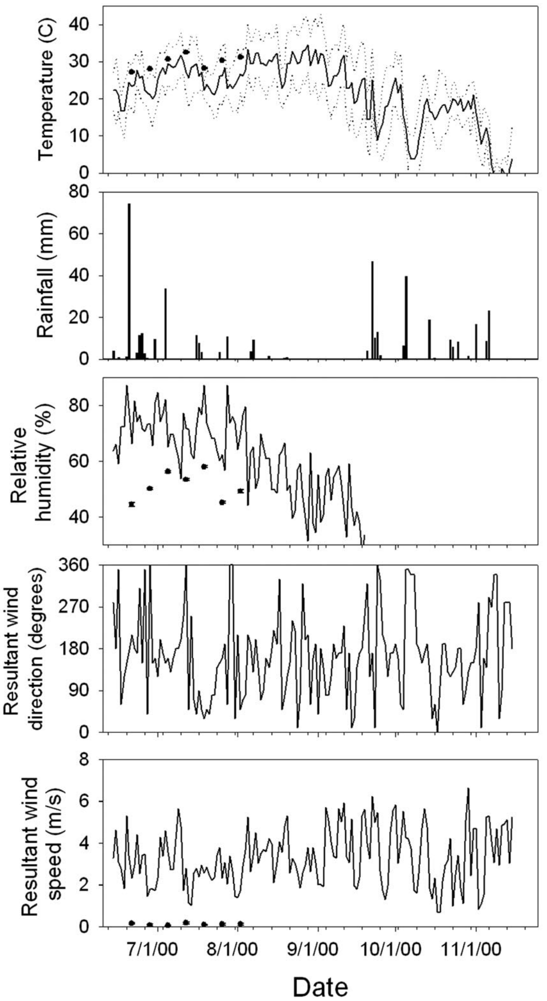

Fig. 3. Average environmental conditions per day outside the plant, as determined by a local weather station, over the monitoring period are represented by solid lines or bars. In the temperature graph, the dashed lines represent the daily high and low temperatures. Circles with error bars represent the mean ± SEM of the corresponding environmental parameter as measured inside the warehouse between 10 a.m. and 12 p.m. on that day. Relative humidity was not calculated after 20 September 2000 due to the low temperatures. Weather information was obtained from a United States National Oceanic and Atmospheric Administration data set.

Outside trap captures of *T. variabile* peaked at ≈20 beetles captured per day, whereas maximum trap captures inside were one beetle per day or less (Fig. 2). Highest trap captures occurred in August through early September, and trap captures declined to close to zero, indoors and outdoors, by November. The fumigation held in August, did not greatly change the trap capture of either species inside the warehouse or tower, but there was a spike in trap capture in the outside traps for both species. There was a significant correlation between the ranked trap captures of *T. variabile* outside the food plant and those in the warehouse (Spearman rank correlation: $r_s = 0.634$, critical value $(r_s)_{0.05(2),16} = 0.503$), but not for *P. interpunctella* (Spearman rank correlation: $r_s = 0.378$, critical value $(r_s)_{0.05(2),16} = 0.503$).

Outside the building, there were differences between the species in the spatial distribution of the trap captures (Fig. 1B and C). Spatial distribution of pheromone trap data are presented using scale-sized circles rather than contour mapping due to issues discussed in Nansen et al. (2003). Significantly more *T. variabile* were captured in the 11 traps around the perimeter of the building (992 ± 188 total beetles per trap) than in the 20 traps away from the building (521 ± 98 total beetles per trap) (two tailed *t*-test, $t = -2.47$, $P = 0.0198$). However, there was no significant difference in total *P. interpunctella* capture between the two locations (two-tailed *t*-test, $t = 0.125$, $P = 0.901$).

There was a bias in the distribution of trap captures between the east and west halves of the study site for *T. variabile* (Fig. 1B) and the north and south halves for *P. interpunctella* (Fig. 1C). Looking at both building and perimeter traps, more *T. variabile* were captured in traps to the east of a north-south line drawn through the center of the building (942 ± 151 total capture per trap location, $n = 16$) than to the west (417 ± 83 total capture per trap location, $n = 15$) (two-tailed *t*-test, $t = -2.98$, $P = 0.006$). There was no significant difference (two-tailed *t*-test, $t = 0.838$, $P = 0.409$) in *P. interpunctella* capture between the west (178 ± 31 total capture per trap location, $n = 15$) and east (146 ± 22 total capture per trap location, $n = 16$) portions of the site. However, there was a significant difference in *P. interpunctella* trap captures between the north and south halves of the site (two-tailed *t*-test, $t = 2.16$, $P = 0.039$) (Fig. 1C). More moths were captured to the south of an east-west line drawn through the center of the facility (201 ± 29 total capture per trap location, $n = 16$) than to the north (124 ± 21 total capture per trap location, $n = 15$). There was no significant difference between north and south regions in *T. variabile* captures (two-tailed *t*-test, $t = 0.123$, $P = 0.902$).

Inside the warehouse, 77.1% of *P. interpunctella*, but only 35.4% of *T. variabile*, were captured in traps near loading docks and doors that opened to the outside (Fig. 4). The 16 trap locations near openings to the outside were in two zones within either 15 m of the eastern-most wall or within 45 m of the western wall of the warehouse. These zones encompassed the doorways and loading docks along the east wall of the northern short arm of the warehouse, along the east wall of the main portion of the warehouse, and off a receiving room in the southwest corner of the warehouse. The remainder of the trap locations ($n = 28$) were in the interior of the warehouse. For *P. interpunctella*, the average trap capture was significantly higher in the zones with exterior openings than in the interior zone (*t*-test, $t = 5.06$, df = 42, $P < 0.001$). For *T. variabile*, although traps near loading docks had high trap captures, there was no significant difference between interior and doorway zones (*t*-test, $t = 0.19$,

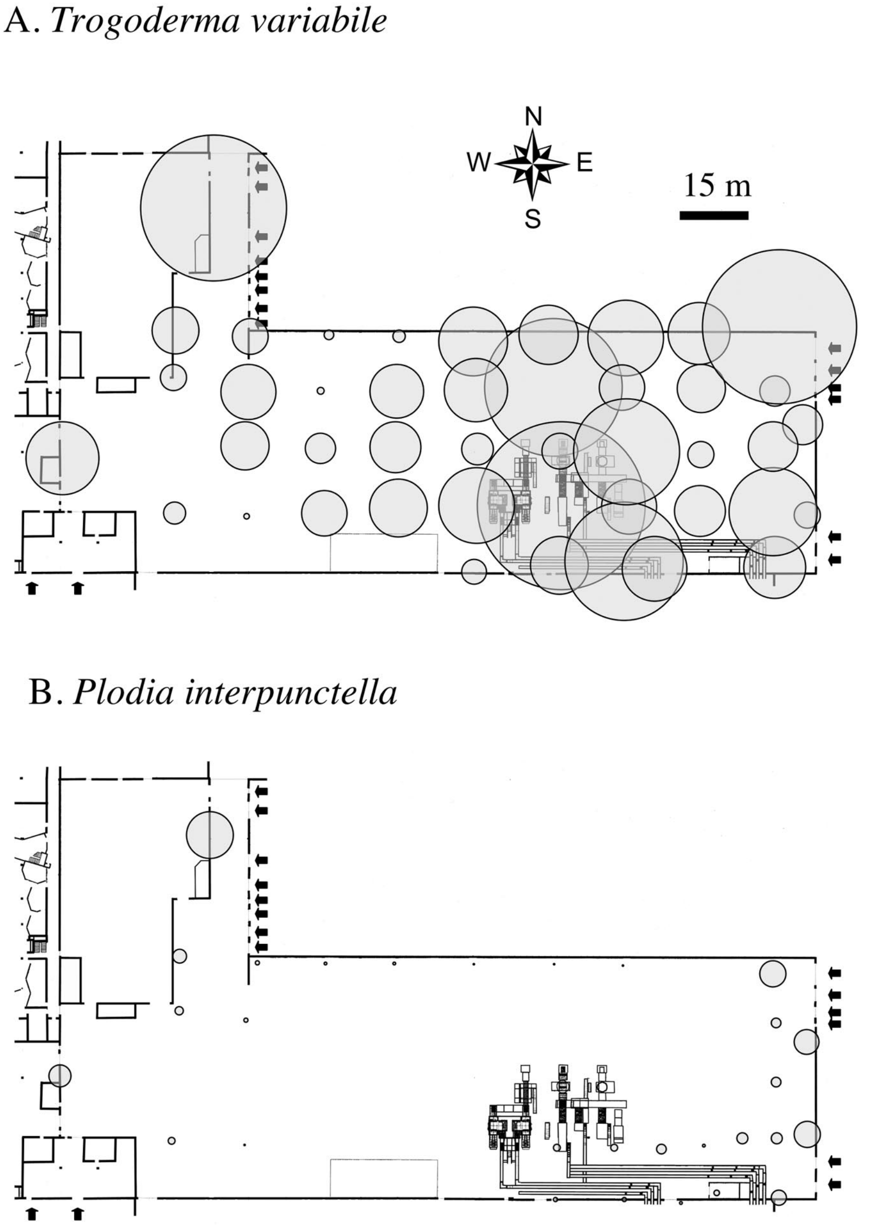

Fig. 4. Distribution of total pheromone trap captures of *T. variabile* (A) and *P. interpunctella* (B) within the warehouse are represented by gray circles centered over each trap location. These circles are proportional in diameter to the total number captured at that location over the monitoring period. All trap locations are represented in Fig. 4A, but in 4B not all trap locations had captured insects. Black arrows indicate breaks in the wall, either doors or loading docks, that open to the outdoors; other wall breaks represent doorways interconnecting interior rooms. Conveyers and pallet wrapping equipment are shown in the floor plan of the warehouse.

df = 42, $P = 0.85$). This lack of significant difference seems to be due to a large number of beetles captured around the pallet wrapping equipment (Fig. 4). This zone had high trap captures in a previous study (Campbell et al. 2002) and tended to have food spillage that could have produced food odor that attracted beetles and also provided food accumulation in cracks and crevices that support population recycling.

The traps outside the building on the third, fifth, and eighth (roof) floors of the tower captured both species during the monitoring period. The average *T. variabile* daily capture rate was 1.0 ± 0.3 on the third floor, 6.9 ± 1.8 on the fifth floor, and 7.2 ± 1.5 on the eighth floor. The average *P. interpunctella* daily capture rate was 0.2 ± 0.1 on the third floor, 0.1 ± 0.0 on the fifth floor, and 0.2 ± 0.1 on the eighth floor.

Table 1. Estimation of dispersal distance and direction based on mark–recapture of *T. variabile* and *P. interpunctella*

Species	Marking station location	Estimated no. marked	No. marked individuals recaptured	Recapture efficiency (%)	Dispersal Distance (m)	Dispersal direction (degrees from north)
T. variabile	SW	288	4	1.4	173.8 ± 79.4	40 ± 67
	SE	441	18	4.1	172.8 ± 30.1	309 ± 45
	NE	1594	43	2.7	72.5 ± 9.08	141 ± 74
	NW	172	7	4.1	310.4 ± 54.5	137 ± 45
	E	1727	129	4.1	46.0 ± 4.4	172 ± 79
	Total	4128	201	4.9	74.8 ± 6.4	
P. interpunctella	SW	351	0	0.0		
	SE	165	2	1.2	266.5	285
	NE	124	0	0.0		
	NW	52	1	1.9	216.4	140
	E	170	3	1.8	21.3	195
	Total	966	6	0.6	135.6 ± 51.7	

For marked *T. variabile* (n = 201), the average recapture distance was 75 m (range 21–508 m) and for marked *P. interpunctella* (n = 6), the average recapture distance was 135.6 m (range 21–276 m). More *T. variabile* (21,333 total individuals; average 688 ± 99 total individuals per trap) were captured outside than *P. interpunctella* (5,004 individuals; average 161 ± 19 total individuals per trap). As a result, the estimated number of marked individuals over the course of the monitoring period, assuming marking stations marked on average as many individuals as were captured on average in the pheromone traps, was also greater for *T. variabile* than for *P. interpunctella* (4,128 compared with 966 individuals). The estimated recapture efficiency for *T. variabile* and *P. interpunctella* for the combined locations and for each individual marking station is presented in Table 1.

Most of the marked *T. variabile* were marked and/or recaptured in the eastern side of the site (Fig. 1). The recapture efficiency, dispersal distance and dispersal direction for each marking station is summarized in Table 1. One *T. variabile* marked at the northeast corner station was recovered in the fifth floor trap on 23 August 2000. None of the warehouse beetles or Indianmeal moths captured in the warehouse (total captures of 2,086 and 251 individuals, respectively) or the tower (total captures of 1,687 and 11 individuals, respectively) were marked with fluorescent powder.

In the immigration/emigration experiment, three *T. variabile* marked outside were recaptured inside, but no *T. variabile* marked inside were recaptured outside and no marked *P. interpunctella* were recaptured in either location (Fig. 5). As in the previous year, the number of *T. variabile* captured outside was higher than inside: total capture of 2,215 beetles and average trap capture per 2-d period of 28.0 ± 3.0 beetles outside compared with a total capture of 158 beetles and average trap capture per 2-d period of 1.8 ± 0.2 beetles inside the facility. The estimated number of beetles marked outside was 415 (0.7% recaptured) and the estimated number marked inside was 25 beetles. The three recaptured *T. variabile* were all marked at the same marking station, but were captured at separate times and at two trap locations. A total of 40 *P. inter-*

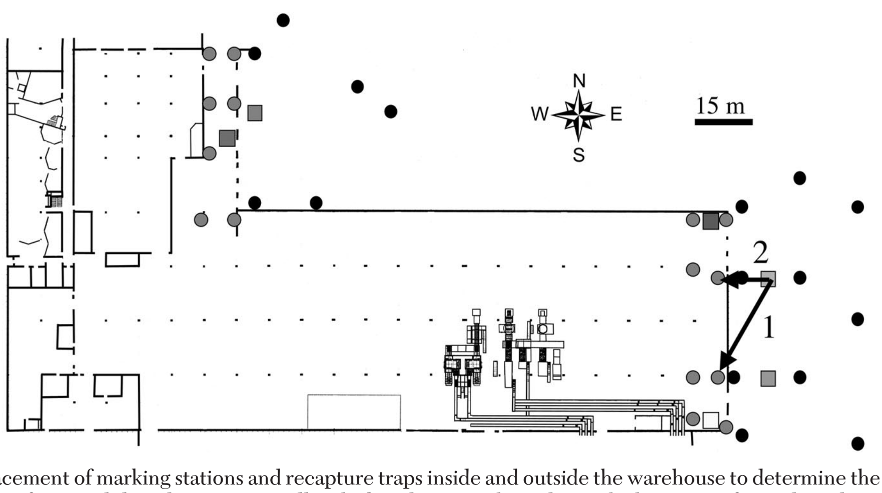

Fig. 5. Placement of marking stations and recapture traps inside and outside the warehouse to determine the immigration and emigration of *T. variabile* and *P. interpunctella*. Black and gray circles indicate the locations of outside and inside recapture traps, respectively. Squares indicate the positions of marking stations. The black arrows indicate the relationship between where a marked *T. variabile* was recaptured and where it was marked and the numbers next to the arrows indicate the number of individuals recaptured with that relationship.

punctella were captured inside (average capture per 2-d period of 0.4 ± 0.1 moths) compared with 152 moths captured outside (average capture per 2-d period of 1.9 ± 0.3 moths). The estimated number of moths marked outdoors and indoors was 28 and seven, respectively.

Discussion

Although it has been widely reported that many species of stored-product insects can be captured outside (Throne and Cline 1989, 1991; Fields et al. 1993; Dowdy and McGaughey 1994, Doud and Phillips 2000), sometimes far from anthropogenic structures (Strong 1970, Cogburn and Vick 1981, Sinclair and Haddrell 1985, Vick et al. 1987), the source and importance of these outside populations is not well understood. In this study, *T. variabile* and *P. interpunctella* males were captured in high numbers outside of a food facility. Outside trap captures of *T. variabile* were 18 times and *P. interpunctella* were 54 times greater than inside trap captures. This difference could reflect a higher density of insects in flight outside compared with inside, but differences in trap type and height, environmental conditions (e.g., amount of air movement), and landscape features also are likely to influence trap capture between locations. Attributing differences in trap capture in different locations to differences in actual insect density is often problematic in these landscapes. Regardless of the absolute numbers of insects in each location, our findings clearly indicate that both of these species were prevalent outside of the building.

In a simple classification scheme, we can think about the insects associated with food facilities occurring in or moving between two types of patch locations: those outside of the food facility and those inside the building (in the structure of the building, spillage, or stored commodity) (Campbell et al. 2004). Doud and Phillips (2000) found high numbers of *P. interpunctella* outside a flour mill and speculated that immigration could be important in pest dynamics inside the mill. Other studies have found stored-product moth trap captures to be high only in the vicinity of storage structures, suggesting that these captures resulted from emigration from inside sources (Cogburn and Vick 1981, Vick et al. 1987). Here, the number of *P. interpunctella* captured in traps next to the building was not significantly different from those captured along the perimeter of the property and individual locations with the highest total capture tended to be on the perimeter. *T. variable* trap captures were lower away from the building, but there was evidence to suggest that they were more likely to be moving toward the building than away. Thus, our findings suggest that for this location these two stored-product pest species are not just originating from source patches inside the facility.

Although only trap captures of *T. variabile* inside and outside the facility were significantly correlated, captures of *T. variabile* and *P. interpunctella,* both inside and outside, declined in the fall. This could result from subpopulations inside the facility and outside being linked by dispersal or by the two population cycles being synchronized, perhaps due to environmental factors. The seasonal decline in trap capture exhibited outside the facility is most likely attributable to decreasing temperatures reducing activity; but inside heated structures, many species of stored product insects continue to develop, reproduce, and fly during the winter. Although *T. variabile* has a facultative diapause, in the previous year, before a major sanitation and structural modification effort that apparently reduced the inside population dramatically, trap capture data did not decline in the fall and was even increasing in some areas of the facility well into December (J.F.C., unpublished data). *P. interpunctella* also has a facultative diapause, but it has been widely reported to continue activity in heated buildings throughout the year (Tzanakakis 1959). The failure of the fumigation treatment to impact trap captures inside as well as outside, the high outside trap captures before and after fumigation, movement toward the facility, and recapture of immigrating individuals also support the hypotheses that populations inside and outside are linked and that inside trap captures are strongly influenced by immigration originating from other locations.

The spatial distribution around the outside of the building differed between the two species. *T. variabile* trap captures were more closely associated with the vicinity of the building: trap captures were higher around the perimeter of the building and to the east of the building and tended to decline in the traps further east. The east side of the building contains most of the doors into the processing and warehouse areas, some bulk storage sites, and most of the exhaust from processing areas. Thus, there is considerable potential for food odor plumes and resource patches to occur outside this portion of the facility. High trap captures outside could be caused by dispersal from sources within the building, sources in the immediate vicinity of the building, or sources off the property. An onsite source for *T. variabile* in the vicinity of the east side of the building is supported by the spatial distribution of trap captures and movement patterns. Possible source patches include blown-out product from the ventilation system, residual buildup in equipment stored, or disposed outside, spillage. However, high trap captures of *T. variabile* are common during the summer, even at locations far from food facilities (J.F.C., unpublished data), and a food processing plant is likely to produce an odor plume that could attract stored-product pests from considerable distances. Infestation of food patches also may increase the level of attraction because the combination of pheromone and food odors can enhance the level of response (Bashir et al. 2001). Alternatively, the beetles could be coming from inside another portion of the building where we were not monitoring, but high pest levels were not reported in these areas by plant management.

In contrast to *T. variabile,* more *P. interpunctella* were captured to the west of the building, with most captured near the southwest corner. Directly south from this corner there was a grain elevator less than a km away that might be a source of dispersing moths. Like *T. variabile,* outdoor monitoring at other locations in this region has indicated high levels of *P. interpunctella* capture during the summer, even far from grain storage or processing facilities. Larger spatial scale monitoring and mark–recapture programs combined with direct sampling of resource patches are needed to address the origins of the individual captured outside.

Although the source(s) of these outside populations are not known, the large number of individuals outside the plant suggests that movement from the outside to the inside is important. Capture of insects at locations outside the building up to the roof of the eighth floor and the recovery of a marked *T. variabile* outside the fifth floor indicate that the facility is not just vulnerable to immigration at ground floor level. No marked individuals were recaptured inside the facility during the initial monitoring period, but this may be due to the relatively low number of trap captures inside and the relatively high percentage of marked individuals recaptured outside causing the probability of recapturing a marked insect inside to be lower. In the additional immigration/emigration study conducted the next year, three *T. variabile* marked at outside stations were recaptured inside, but no beetles were recaptured outside that had been marked inside. Therefore, there is considerable direct and indirect evidence that the dispersal of beetles into this facility from outside sources is occurring.

Information on dispersal distances is limited for stored product insects. In this study, males of *T. variabile* were recaptured up to 508 m and males of *P. interpunctella* were captured up to 276 m. Dispersal distances outside were further than those observed inside this facility (Campbell et al. 2002), but there are also significant differences in amount of air movement, barriers to dispersal, and number and distribution of food patches between the inside and outside of the building. Hagstrum and Davis (1980) reported that another pyralid stored-product moth, *C. cautella*, flew 300 m during a 10-min flight, so it is likely that *P. interpunctella* flight distances reported here are not necessarily long-duration flights. The distances reported in our study are also unlikely to be maximum dispersal distances because the trapping area was constrained by the limits of the property.

Comparing the dispersal angles from different marking stations is confounded by the marking stations being placed near the edges of the trapping area, but in all cases the average *T. variabile* dispersal direction from each perimeter marking station was toward the building. The average dispersal angle for *T. variabile* marked at the east station, where recapture angles were not constrained, was west toward the building. This evidence suggests that the source of beetles is unlikely to be the building and that odors from the building may be attracting beetles. The prevailing wind direction was from the southeast; therefore, the influence of wind direction on dispersal direction does not seem to be correlated on average, but its impact at the specific times that marked beetles were flying between marking stations and traps is unknown. Due to the smaller number of marked *P. interpunctella* recaptured it is more difficult to evaluate dispersal distance and direction, but there does not seem to be as much of a trend to move toward the building compared with *T. variabile.*

The high number of individuals captured outside and their high mobility raise a number of issues for developing pest management programs. Pheromone monitoring in this situation may inaccurately determine the timing or effectiveness of treatments such as fumigation, because only individuals moving between patches are captured and many of these individuals may be originating from source patches outside of the facility. The use of traps with sex pheromone means that only males are captured, and for both species it is unknown whether there are inter-sex differences in dispersal. If we assume that both sexes are present outside facilities and disperse similarly, then infestation resulting from immigration from outside sources may be an important factor. If our results only apply to males, then the high degree of male movement has implications for using pheromone traps to estimate population densities (Wileyto et al. 1994) and the use of mating disruption or mass trapping techniques.

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 IPM programs. The pattern observed in this study is consistent with the monitoring of individuals moving among patches of resource over a larger spatial scale than the building or perhaps even the property monitored in this study. Ecological and behavioral studies are difficult to conduct in commercial facilities due to a variety of constraints, but they do suggest patterns that may not have been apparent in smaller scale controlled laboratory studies. The trends observed at this location are potentially generally applicable to other food processing and warehouse facilities and illustrate the types of information needed to develop and interpret monitoring programs.

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