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Spatio-temporal distribution of stored-product insects around food processing and storage facilities

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ABSTRACT

Grain storage and processing facilities consist of a landscape of indoor and outdoor habitats that can potentially support stored-product insect pests, and understanding patterns of species diversity and spatial distribution in the landscape surrounding structures can provide insight into how the outdoor environment can be more effectively monitored and managed. The spatial and temporal distribution of stored-product pests was assessed at three food processing facilities using two types of traps and the influence of landscape features on their outside distribution was evaluated. For corrugated traps, targeting walking individuals, placed both inside and outside facilities, the predominant groups, accounting for 59% of captures, were *Cryptolestes* spp. (Coleoptera: Laemophloeidae), *Oryzaephilus surinamensis* (L.) (Coleoptera: Silvanidae) and *Sitophilus* spp. (Coleoptera: Curculionidae). Numbers captured in outside corrugated traps tended to be less than captures inside structures, and while level of species diversity was similar fungal feeding species were more common in outside traps. In outside corrugated traps, *Cryptolestes* spp., *Typhaea stercorea* (L.) (Coleoptera: Mycetophagidae) and *O. surinamensis* were most abundant and in outside Lindgren traps that targeted flying individuals, *T. stercorea*, *Cryptolestes* spp. and *Ahasverus advena* (Waltl) (Coleoptera: Silvanidae) were most abundant. No correlation was observed between total captures and species diversity between inside and outside traps. Distribution of stored-product insects in corrugated traps tended not to be spatially clustered (Global Moran's *I* values ranged from −0.25 to 0.22). However, Anselin local Moran's *I* indicated that at local level some traps with greatest captures had traps in the vicinity with similar values, but these specific locations were temporally variable. Landscape around each outside corrugated trap was characterized, and increased captures were associated with proximity to grain storage or processing structures, but not with presence of spillage as originally hypothesized. Overall, results support hypothesis that there is considerable movement of insects in landscape surrounding facilities, resulting in limited spatial pattern other than temporally variable hot spots inside or near structures.

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1. Introduction

Food processing facilities where grain is stored and processed after harvest are human dominated environments consisting of multiple buildings and storage structures situated within a broader urban and agricultural landscape mosaic. Both interior and exterior patches in this landscape can be populated by a diverse community of arthropods. Approximately 1660 insect species in the orders Coleoptera, Diptera, Hemiptera, Hymenoptera, Lepidoptera and Psocoptera are associated with stored-products, including species that are granivores, fungivores, omnivores, and natural enemies (Hagstrum and Subramanyam, 2009). In general, research on monitoring and management of stored-product pests has focused on populations inside the structure of the building or grain in a storage bin. However, stored-product insects have been readily captured outside of structures (Throne and Cline, 1989, 1991; Fields et al., 1993; Dowdy and McGaughey, 1994, 1998; Doud and Phillips, 2000; Likhayo and Hodges, 2000; Campbell and Arbogast, 2004; Campbell and Mullen, 2004; Trematerra et al., 2004; Kučerová et al., 2005; Campbell et al., 2006), and immigration of insects into facilities

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can have a significant impact on monitoring and pest management programs (Campbell and Arbogast, 2004; Toews et al., 2006).

Sources of stored-product insects recovered outside can be individuals dispersing from other structures containing stored-products, either short-range dispersal from other structures on site or long-range dispersal from other locations, or food material accumulations in the landscape surrounding structures. Grain spillage and residues inside grain elevators are exploited by stored-product pests (Kučerová et al., 2003; Reed et al., 2003; Arthur et al., 2006), and while it is likely that they also exploit outside spillage the evidence is more limited (Kučerová et al., 2005). Examples of outside spillage include whole grain accumulations near unloading areas, dust and other excess material from processing that is blown out of facilities and accumulates in areas outside, trash containers and excess equipment stored outside which contains residual food material. The persistence of these outside food accumulations and their quality as resources for specific stored-product pest species is likely to be highly variable. These outside food patches can be exploited by stored-product insects as locations for reproduction or provide food and shelter for dispersing adults and thus attract dispersing adults into the proximity of structures. The potential importance of sanitation programs to eliminate these outside food accumulations has been widely acknowledged in food industry pest management programs, but the association of stored-product insects with spillage accumulations or other features of the landscape outside of structures has not been evaluated.

Basic structural characteristics of the landscape can affect species abundance and distribution (Turner, 1989; Wiens, 1997; French et al., 2004), and the abundance and distribution of stored-product insects outside food facilities is also likely to be affected by the landscape at a food facility (Trematerra et al., 2004). The landscape immediately outside of structures at a food facility can consist of a mosaic of pavement, gravel, and plantings of grass and ornamentals, surrounded in turn by a broader landscape of urban development, agricultural fields, and natural habitats. The distribution of food spillage outside and proximity to structures containing grain and processed commodities are the most likely landscape features that will impact the number and distribution of stored-product insects outside. However, where outside spillage accumulates and how rapidly the spillage is degraded are likely to influence its suitability as a resource for a given species. Degradation of food material with increased moisture and fungal growth may favor exploitation by fungivore stored-product insects and reduce exploitation by species such as *Cryptolestes* spp. and *Sitophilus* spp. often found associated with spillage inside grain elevators (Reed et al., 2003; Arthur et al., 2006). Variation in other environmental and physical features may also influence stored-product insect distribution through different mechanisms such as providing shelter and encouraging food accumulation. For example, higher temperature and flour dust accumulation have been shown to be associated with *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae) distribution inside a flour mill (Semeao et al., 2012a). Different stored-product pests were shown to have different patterns of spatial distribution outside a rice storage facility (Trematerra et al., 2004). A practical benefit from knowing the distribution of the community of stored-product pests outside storage and processing facilities, and the relationship between distribution and features in the landscape is that it can help managers target outside monitoring and pest management tactics in order to reduce the risk of immigration into facilities.

One of the major pests in wheat and rice mills worldwide is the red flour beetle, *T. castaneum* (Sokoloff, 1974). The distribution of *T. castaneum*, and to a lesser extent that of *Tribolium confusum* Jacquelin du Val, inside structures such as flour mills, warehouses, and retail stores has been studied (Ho and Boon, 1995; Campbell et al., 2002; Trematerra and Sciarretta, 2004; Semeao et al., 2012a; Trematerra et al., 2007). Response of *T. castaneum* populations to structural fumigations of wheat mills has suggested that populations are relatively self-contained within individual structures (Campbell and Arbogast, 2004; Toews et al., 2006; Small, 2007; Campbell et al., 2010a,b), although the potential for movement of beetles from either outside sources or from other structures in the proximity of the facility exists. *T. castaneum* has been captured outside both in the proximity of, and far from, food facilities (e.g., Sinclair and Haddrell, 1985; Dowdy and McGaughey, 1994; Subramanyam and Nelson, 1999; Trematerra et al., 2004; Daglish et al., 2010; Ridley et al., 2011). Recent population genetic studies indicate greater potential for *T. castaneum* gene flow between facilities than previously suspected (Drury et al., 2009; Ridley et al., 2011; Semeao et al., 2012b), which suggests that a better understanding of outside activity of this species is needed.

Due to the lack of information showing patterns of spatial distribution of stored-product pests in food processing facility landscapes, the objectives of this study were: (1) evaluate the species composition and spatial and temporal distribution patterns of stored-product pests at three grain processing and storage facilities, and (2) determine which features of the exterior landscape influence outside insect distribution patterns. Two types of traps were utilized that targeted walking and flying individuals, respectively, and allowed potentially different spatial scale in movement patterns to be detected. Because the two traps were only baited with grain, with the exception of *T. castaneum* pheromone in the walking insect trap, a less biased estimation of species diversity and spatial pattern can be obtained than in previous studies that have relied on pheromone baited trapping.

2. Materials and methods

2.1. Study sites

This study was conducted at three sites (herein coded as site A, B, and C) located in the central USA (Figs. 3A, 4A, and 5A). Site A is a commercial processing facility and contains multiple buildings including a five-floor flour mill (~4531 m^3) with attached elevator with concrete silos, warehouse and packaging building, small metal three-floor feed mill, variety of office and storage shed buildings, a second grain elevator with concrete silos, one large metal bin, and two ground bunker storage locations. Surrounding these structures the landscape primarily consisted of areas of gravel and mown grass within the property line of the facility. Accumulations of food spillage consisting of wheat and corn kernels, chaff, and flour dust were observed in areas near the mill and grain elevators. The property is bordered by residential areas, a paved road and agricultural fields. Site B is small feed mill (~280 m^2) composed of one metal building used for processing animal feed which has large doors that are often open allowing for easy movement into and out of the facility. In the proximity of the feed mill, there are 20 metal bins in which either grain (primarily corn) or processed feed are stored. The landscape around the feed mill is primarily gravel and grass, with the site bordered by paved roads and an open field. Site C (Kansas State University, Hall Ross Flour Mill) is a relatively new concrete pilot-scale flour mill (2044 m^2) composed of five floors. In the proximity of the mill, there are eight metal storage bins. The facility is designed for research and education purposes and does not operate continuously. The area immediately surrounding the building is composed primarily of grass lawn, brush and open field, and paved areas.

2.2. Stored-product insects monitoring

Monitoring was conducted using two types of traps. The first trap (i.e., corrugated trap) was a modified design of a corrugated cardboard trap (Likhayo and Hodges, 2000; Daglish, 2006) that captures walking insects and was predicted to primarily detect localized insect activity. The corrugated traps consisted of two layers of corrugated plastic held between two metal plates. Each layer consisted of four pieces of corrugated plastic (9 cm × 3 cm and 2 mm thick) arranged to form a square 9 cm × 9 cm. For the bottom layer, pieces were glued to a square piece of metal (9 cm × 9 cm) leaving a square space in the middle (3 cm × 3 cm). For the top layer, pieces were glued in the same arrangement to a square piece of clear plastic (9 cm × 9 cm) with a circular hole in the center (∼2 cm diameter). One *Tribolium* spp. pheromone lure (Trécé, Adair, OK) and ∼3 g of cracked wheat were placed in the space in the center of the corrugated plastic pieces. After adding pheromone and cracked wheat, a second piece of metal was added to the top of the stack. Both top and bottom metal plates had a hole in the center, through which a machine bolt was inserted from underneath and the trap layers held together by tightening a wing nut on the portion of the bolt projecting from the top of the trap. The hole in the metal bottom piece was countersunk on the underside so that trap could lay flat with the bolt inserted. The other trap type used was the six funnel Lindgren trap (Phero Tech Inc., Delta, BC, Canada) (Lindgren, 1983). This trap was used to capture flying individuals and thus was predicted to detect insect activity occurring over a much broader spatial scale. The collection reservoir of the traps contained cracked wheat (∼200 g) on top of a piece of window screen inserted into the reservoir to elevate the wheat 2 cm from the bottom of the trap. This was done to avoid spoilage due to grain sitting in any water that could accumulate in the bottom of the trap. No pheromone lures were used in the Lindgren traps.

The corrugated traps were distributed in an irregular grid pattern at each site, with most traps placed outside buildings but within limits of the property line (Figs. 3A, 4A, and 5A). Trap positions were also selected in order to get adequate representation of the different habitat types in the landscape at each site. The number of traps in each site was defined according to the evaluation of the complexity of the landscape (i.e., number of different habitats) and the size of the property; 50 traps at site A, 40 traps at site B, and 25 traps at site C. The geographic coordinates of each trap location were recorded using a Global Positioning System (GPS) receiver (Garmin GPS Map 76, Olathe, KS). Monitoring with corrugated traps was conducted between July and October in 2007 and 2008 for sites A and B (Table 3). At these two sites, monitoring took place during six monitoring periods (three in 2007 and three in 2008). Site C was monitored only in 2007 (three monitoring periods) since there were few captures outside at this site (Table 3). In each monitoring period, corrugated traps were in place for 48 h, then collected and placed individually in plastic bags and returned to the laboratory where individuals were identified to genus or, when possible species, and total number in each group determined.

Lindgren funnel traps were distributed in the landscape surrounding the facilities; 10 traps at site A, 6 traps at site B, and 4 traps at site C. Because there was a smaller number of Lindgren traps, these were distributed in order to have at least one trap in each different habitat type in the landscape at each site. Monitoring with Lindgren traps was conducted in 2008 and 2009 and traps were kept continuously at the sites from August to October of both years (Table 3), with contents of the traps collected every two weeks. Contents of each trap were placed individually in plastic bags and returned to the laboratory. All recovered individuals were identified to species when possible or at least to genus, and total number of each group counted. Reference specimens, from both types of trap, were deposited in the Kansas State University Museum of Entomological and Prairie Arthropod Research (KSU-MEPAR) under the voucher #214.

In order to compare the community of stored-product insects associated with traps at these facilities, Simpson's index of diversity was calculated (Simpson, 1949) as applied to trapping data in Larson et al. (2008). Values of Simpson's index of diversity can vary from 0 to 1 in which values close to 0 indicate low species diversity and values close to 1 indicate high species diversity. The diversity index may not reflect the overall diversity in the environment since do not know if different species are recovered in traps in proportion to their diversity in the environment. A species-specific attractant was used for *Tribolium* spp. in the corrugated traps, which could elevate captures of this species relative to the others, but since this species represented such a small proportion of the captures it was unlikely to significantly impact estimation of diversity.

2.3. Analysis of spatial and temporal distribution of stored-product insects

For analysis of spatial distribution, only data collected with the corrugated traps were used because of the number and distribution of trap locations, while analysis of temporal distribution was assessed using both corrugated and Lindgren traps. For the spatial distribution analysis, the geographic coordinates of trap locations and the capture data were imported into ArcGIS 9.3 software (ESRI®, Redlands, CA). Average Nearest Neighbor analysis tool in software was used to assess if the pattern of distribution of traps at each site could potentially be clustered since they were distributed in an irregular fashion. Three different methods of interpolation were evaluated for producing contour maps of stored-product pests: radial basis function (RBF), kriging, and inverse distance weighting (IDW). Preliminary evaluation of the three methods indicated that while all three gave similar results, assumptions behind RBF (only considered informative when working with large datasets and attributes that gently vary [e.g., elevation]) and kriging (assumes spatial autocorrelation among points) were not always met, so IDW was selected. Final contour maps of stored-product pest spatial distribution were developed using the Spatial Analyst extension in ArcGIS. Maps were made using Inverse Squared Distance Weighting (ID^2W) method for each monitoring period in each site. The search radius for site A was set for 40 m and 10 m for sites B and C. The larger radius was used at site A because of its larger size and greater distance between trap locations.

Spatial autocorrelation of stored-product insect captures was assessed at each site using two spatial statistical approaches. All species considered as stored-product insects (Tables 1 and 2) were pooled together for analysis because captures of individual species were often too low to be considered individually. First, Global Moran's Index (I) was computed (Moran, 1948) for each site and monitoring period to evaluate whether the pattern of distribution was clustered, dispersed or random. Moran's I values range from +1 (strong positive autocorrelation) to −1 (strong negative autocorrelation), with a value of 0 indicating random distribution. Second, Anselin local Moran's Index (Z) was computed (Anselin, 1995), which unlike the global-scale Global Moran's I, computes spatial autocorrelation at each sampling location based on neighboring values within a local neighborhood search. A high positive Z score for a trap location indicates that the surrounding traps have similar values (either high or low).

Evaluation of temporal dynamics of stored-product insects was conducted by calculating, for the captures with corrugated and Lindgren traps, the average number of insects/trap/day at each site. Also, the proportions of each species or species group were plotted for each monitoring period at each site using the sum of individuals caught during each monitoring period. Contour maps

Table 1
Total number of individuals of all stored-product insect species or species groups recovered each year (2007 and 2008) with corrugated traps placed inside (I) and outside (O) structures at three different food processing facility sites (A, B, and C). Site C was only monitored in 2007.

Species	Site A				Site B				Site C			
	2007		2008		2007		2008		2007		2008	
	I	O	I	O	I	O	I	O	I	O	I	O
Tribolium castaneum	26	12	2	5	3	7	1	0	145	4	–	–
Ahasverus advena	0	45	1	26	5	6	0	1	1	0	–	–
Rhyzopertha dominica	0	0	0	0	0	0	0	0	8	0	–	–
Trogoderma variabile	4	7	1	2	6	0	11	2	0	0	–	–
Oryzaephilus surinamensis	0	4	7	0	32	30	10	1	113	176	–	–
Palorus subdepressus	0	3	3	0	0	0	0	0	0	0	–	–
Plodia interpunctella	8	3	1	3	2	0	0	0	0	0	–	–
Sitophilus spp.	67	7	50	29	97	0	57	0	11	3	–	–
Cryptolestes spp.	18	5	15	11	19	321	3	3	287	15	–	–
Stegobium paniceum	0	0	0	0	36	0	6	2	0	0	–	–
Tenebrio spp.	0	1	0	0	93	1	98	6	0	0	–	–
Typhaea stercorea	2	10	3	192	0	20	5	0	2	0	–	–
Litargus balteatus	0	0	0	14	0	0	0	0	0	0	–	–
Cryptophagus spp.	0	47	0	49	0	0	0	16	0	0	–	–

were also created for each monitoring period so that temporal patterns in spatial distribution could be assessed.

2.4. Environmental data and landscape features at trap locations

Environmental conditions such as temperature, relative humidity (r.h.), and wind speed were collected at the beginning and end of each monitoring period at each corrugated trap location using a handheld weather meter (Kestrel® 3000, Nielsen-Kellerman, Boothwyn, PA) held ~50 cm above trap location. Wind speed was measured in the prevailing wind direction at each trap location. Also, for selected traps at each location, temperature and r.h. were recorded over the entire course of the trapping period using HOBO data loggers (Onset Computer, Bourne, MA). The number of data loggers varied among sites and monitoring periods, and depended on the availability of the loggers: site A (14, 37, 37, 37, 37, 34 loggers for monitoring periods one through six, respectively); site B (12, 15, 15, 40, 39, 40 loggers for monitoring periods one through six, respectively); and site C (5, 9, 11 loggers for monitoring periods one through three, respectively). Data loggers were placed near traps (within ~10 cm) and they were covered with a Dome trap lid (Trece, Adair, OK) for protection and a metal wire cage staked to the ground to keep them in place. When available, both sources of data (handheld weather meter and data loggers) were used to determine averages at each trap location.

Landscape features around each trap were assessed by taking digital photographs of each trap location and based on these images calculating the proportion of each landscape type in the proximity of the trap. A digital camera was held horizontally 1 m above the trap when taking photographs and from the digital images, the percent coverage of grass, gravel, and concrete within a 1 m^2 area around the traps was determined by tracing outlines and calculating area of shapes using Image J software (Abramoff et al., 2004).

Shade over the trap had two classes: (1) no shade over the trap and (2) presence of shade over the trap. Shade was determined by directly observing the traps in the field and by analyzing pictures using Image J software as described above. Shade levels will obviously change over the course of the day, so time was standardized between 10:00 a.m. and 12:00 p.m. Spillage was defined as any material that was observed such as grain, flour or any other grain derived material obtained from processing. The presence of spillage within a 1 m^2 area around a trap was measured and quantified as 0: no spillage observed, 1: up to 50% of the area covered with spillage, and 2: between 50 and 100% of the area covered with spillage. These indices were determined by visually assessing each trap location during site visits and by analyzing digital pictures with Image J software.

The proximity of vertical surfaces, associated with the sides of building or storage structures, was indicated as either present (vertical surface inside the 1 m^2 square area around the trap) or absent. Distance to closest storage structure (e.g., metal bin, elevator) and distance to mill building (i.e., flour mill in site A and C, feed mill in site B) was also determined by measuring the straight line distance from each trap location to the closest outside wall of the facility

Table 2
Total number of individuals of all stored-product insect species or species groups recovered each year (2008 and 2009) with Lindgren traps placed outside at three different food processing facility sites (A, B, and C).

Species	Site A		Site B		Site C	
	2008	2009	2008	2009	2008	2009
Tribolium castaneum	0	11	1	0	1	2
Ahasverus advena	28	95	10	16	18	18
Rhyzopertha dominica	2	1	6	2	1	0
Trogoderma variabile	67	31	4	5	2	0
Oryzaephilus surinamensis	0	4	0	0	0	0
Palorus subdepressus	0	0	1	0	0	0
Plodia interpunctella	1	7	0	0	0	2
Sitophilus spp.	15	8	0	0	0	0
Cryptolestes spp.	51	87	15	66	6	4
Stegobium paniceum	0	2	0	2	0	0
Tenebrio spp.	0	0	0	0	0	0
Typhaea stercorea	193	339	7	9	7	5
Litargus balteatus	0	0	0	21	0	6
Cryptophagus spp.	28	114	0	6	0	3

Table 3
Mean ± SE of the number of stored-product species recovered per day in two trap types (corrugated and Lindgren) within each monitoring period at three food processing facility sites (A, B, and C). Corrugated traps were not placed at site C during 2008.

Location ID	Trap type	Monitoring period	Start date	End date	Inside: mean ± SE (*n*)	Outside: mean ± SE (*n*)
Site A	Corrugated	1	07/24/07	07/26/07	1.68 ± 0.54 (11)	0.47 ± 0.22 (38)
		2	09/04/07	09/06/07	2.45 ± 1.38 (11)	0.41 ± 0.14 (39)
		3	10/09/07	10/11/07	1.55 ± 0.91 (11)	0.97 ± 0.21 (39)
		4	08/06/08	08/08/08	2.00 ± 1.14 (11)	1.01 ± 0.44 (39)
		5	09/14/08	09/16/08	1.05 ± 0.68 (11)	2.38 ± 1.21 (39)
		6	09/30/08	10/02/08	0.73 ± 0.42 (11)	0.85 ± 0.40 (39)
	Lindgren	1	08/06/08	08/19/08		0.08 ± 0.04 (10)
		2	08/19/08	09/04/08		1.21 ± 0.30 (10)
		3	09/04/08	09/14/08		0.64 ± 0.20 (10)
		4	09/14/08	09/30/08		0.39 ± 0.28 (10)
		5	09/30/08	10/09/08		0.62 ± 0.30 (10)
		6	08/13/09	08/20/09		2.84 ± 0.99 (10)
		7	08/20/09	09/03/09		1.69 ± 0.60 (10)
		8	09/03/09	09/17/09		0.74 ± 0.37 (10)
		9	09/17/09	10/01/09		1.10 ± 0.23 (10)
		10	10/01/09	10/15/09		0.01 ± 0.01 (10)
		11	10/15/09	10/29/09		0.04 ± 0.02 (10)
Site B	Corrugated	1	08/01/07	08/03/07	7.28 ± 2.58 (9)	0.21 ± 0.15 (31)
		2	08/20/07	08/22/07	7.67 ± 3.03 (9)	5.79 ± 4.78 (31)
		3	09/25/07	09/27/07	1.33 ± 0.54 (9)	0.21 ± 0.13 (31)
		4	07/30/08	08/01/08	1.94 ± 1.06 (9)	0.10 ± 0.07 (31)
		5	08/13/08	08/15/08	2.56 ± 1.36 (9)	0.10 ± 0.05 (31)
		6	10/07/08	10/09/08	6.11 ± 4.28 (9)	0.31 ± 0.12 (31)
	Lindgren	1	07/25/08	08/11/08		0.25 ± 0.17 (6)
		2	08/11/08	09/02/08		0.06 ± 0.02 (6)
		3	09/02/08	09/23/08		0.08 ± 0.04 (6)
		4	08/04/09	08/17/09		0.68 ± 0.29 (6)
		5	08/17/09	09/03/09		0.25 ± 0.10 (6)
		6	09/03/09	09/18/09		0.26 ± 0.16 (6)
		7	09/18/09	10/09/09		0.17 ± 0.10 (6)
		8	10/09/09	10/26/09		0.03 ± 0.02 (6)
Site C	Corrugated	1	08/01/07	08/03/07	15.25 ± 9.72 (8)	1.26 ± 0.74 (17)
		2	08/21/07	08/23/07	8.69 ± 1.86 (8)	2.95 ± 1.54 (22)
		3	09/25/07	09/27/07	11.50 ± 2.45 (8)	0.57 ± 0.30 (22)
	Lindgren	1	07/28/08	08/11/08		0.14 ± 0.04 (3)
		2	08/11/08	08/25/08		0.31 ± 0.09 (3)
		3	08/25/08	09/18/08		0.13 ± 0.13 (3)
		4	09/18/08	09/30/08		0.19 ± 0.19 (3)
		5	08/04/09	08/21/09		0.18 ± 0.14 (4)
		6	08/21/09	09/10/09		0.18 ± 0.09 (4)
		7	09/10/09	10/01/09		0.17 ± 0.04 (4)

using a metric tape measure and/or a handheld laser meter (Disto™ classic, Leica Geosystems AG, Heerbrugg, Switzerland).

To explore the relationship between environmental and physical factors and capture of stored-product pests in corrugated traps outside the food processing and storage facilities, two different approaches were used. First, measured variables were compared between trap locations with and without captures by applying Student's *t*-test or chi-square test for contingency table analysis (Sigmaplot v. 11, Systat Software Inc., Chicago, IL). Second, stepwise regression (SAS software, v. 9.2, SAS Institute, Cary, NC) was used to determine the most significant variables associated with stored-product insect captures. For stepwise regression, only variables with significance level of $P < 0.15$ were entered into the analysis.

3. Results

3.1. Species associated with food storage and processing facilities

A total of 3678 stored-product insects from 13 species or species groups were recovered across all the facilities, monitoring years and trap types (Tables 1 and 2). A total of 1098 individuals (30%) were species that are considered primarily fungus feeders (Tables 1 and 2): i.e., the hairy fungus beetles *Typhaea stercorea* (L.) (Coleoptera: Mycetophagidae) and *Litargus balteatus* LeConte (Coleoptera: Mycetophagidae), and the silken fungus beetle *Cryptophagus* spp. (Coleoptera: Cryptophagidae). For the corrugated traps placed on the ground to capture walking insects, the average number of insects recovered was 1.9 ± 0.2 individuals/trap/day. While this average capture varied among monitoring periods there was no apparent temporal pattern to captures in the monitoring periods evaluated (Table 3). The three most predominant species in corrugated traps placed both inside and outside, accounting for 59% of captures, were *Cryptolestes* spp. (Coleoptera: Laemophloeidae) (29.7%), followed by *Oryzaephilus surinamensis* (L.) (Coleoptera: Silvanidae) (15.9%) and *Sitophilus* spp. (Coleoptera: Curculionidae) (13.7%).

For the corrugated traps, there was a trend for more insects to be recovered inside (4.4 ± 1.1 individuals/trap/day) than outside (1.1 ± 0.7 individuals/trap/day) ($t = 3.35$, df = 479, $P < 0.001$) and no correlation in captures between the inside and outside ($r = 0.26$; $P = 0.36$). Considering only corrugated traps located outside, the most abundant species recovered was *Cryptolestes* spp. (32.6%), followed by *T. stercorea* (20.4%) and *O. surinamensis* (19.4%). Considering just the inside traps, *Cryptolestes* spp. (27.2%) was again the most abundant species followed by *Sitophilus* spp. (22.4%).

The Lindgren traps that target flying insects outside had an average capture of 0.5 ± 0.1 individuals/trap/day and the most abundant species recovered was *T. stercorea* (42.1%), followed by *Cryptolestes* spp. (17.2%) and *Ahasverus advena* (Waltl) (Coleoptera: Silvanidae) (13.9%). As with the corrugated traps, while the average number recovered varied among monitoring periods there was no apparent temporal pattern to captures (Table 3).

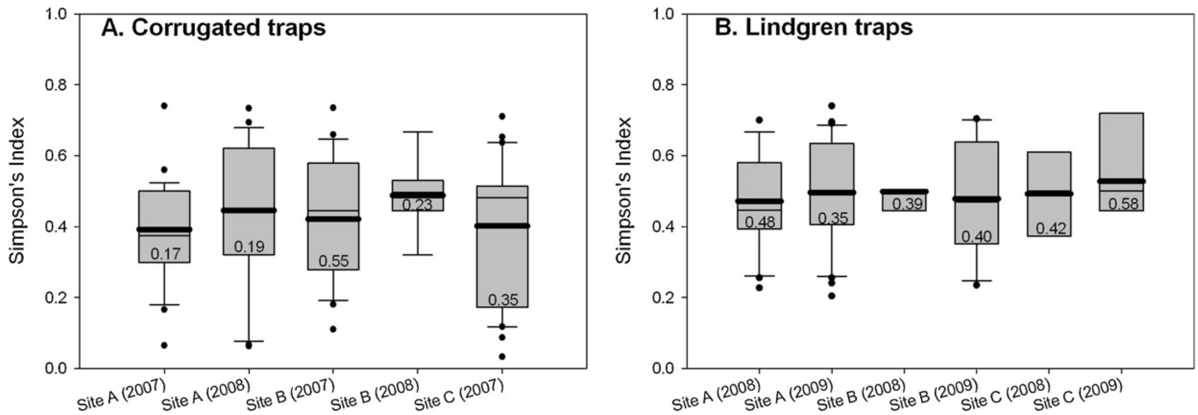

Fig. 1. Simpson's index of species diversity for stored-product insects recovered at each of three sites (A, B, and C) in 2007, 2008, and 2009 as a function of trap type (corrugated trap and Lindgren trap). Gray boxes represent 50% of the data, bars represent 95% of the data, and individual points represent individual trap locations outside of the 95% distribution. Traps that had no recovery and traps with only one species recovered were excluded, and number inside the boxes indicates the proportion of the total trap locations that were included for the estimation of the index. Indices were estimated for each year by grouping data of all monitoring periods in that year.

The predominant species recovered outside differed among the sites, but at a site the predominant species recovered tended to be similar between trap types (Tables 1 and 2). At site A the predominant species recovered in corrugated and Lindgren traps was *T. stercorea* (42.5% and 49.1%, respectively), followed by *Cryptophagus* spp. (20.2% and 13.1%, respectively). At site B, the predominant species recovered was *Cryptolestes* spp.: 77.9% of captures in corrugated traps and 47.4% of captures in Lindgren traps. Lindgren traps also captured *A. advena* (15.2%) and *L. balteatus* (12.3%). At site C, the predominant species recovered in corrugated traps was *O. surinamensis* (88.9%) and in Lindgren traps was *A. advena* (48.0%), followed by *T. stercorea* (16.0%) and *Cryptolestes* spp. (13.3%). The difference between the trap types at site C is probably due to *O. surinamensis* being unable to fly and thus less likely to be captured in Lindgren traps (although at site A some were captured in Lindgren traps, presumably by walking up the pole and into the trap). Although there were differences in the predominant species recovered among sites, the range of species recovered was similar, with only *Palorus subdepressus* (Wollaston) (Coleoptera: Tenebrionidae) and *Tenebrio* spp. (Coleoptera: Tenebrionidae) being recovered at sites A and B, but not site C.

The Simpson's index of species diversity in captures varied from low to moderate at the three sites and was similar across years and trap types (Fig. 1). Pairwise comparison between the two types of traps at a site, showed no significant differences in species diversity: corrugated trap index was 0.45 ± 0.06 and Lindgren trap index was 0.49 ± 0.03 ($Z = -0.51$; $P = 0.31$). There was considerable variation in species diversity among trap locations (Fig. 1) and monitoring periods (Fig. 2). Similar to total number captured in traps, the species diversity outside was not significantly correlated with species diversity inside ($r = 0.02$; $P = 0.94$).

The stored-product pest *T. castaneum* was recovered (total of 220 individuals) at the three facilities and in both types of traps (Tables 1 and 2), with most *T. castaneum* recovered inside structures with corrugated traps (80.5%). Considering all species, *T. castaneum* represented 14.1% of the total recovered inside and 2.2% of the individuals recovered outside with corrugated traps, and 1.2% of the captures with Lindgren traps.

3.2. Spatial distribution of stored-product pests

Location of corrugated traps had a dispersed distribution at all three locations: site A (nearest neighbor ratio = 1.5, Z score = 6.4, $P < 0.001$), site B (nearest neighbor ratio = 1.6, Z score = 7.4, $P < 0.001$), and site C (nearest neighbor ratio = 1.7, Z score = 6.9, $P < 0.001$). Because accurate analysis of spatial trends requires a certain minimal number of sample points, analysis of spatial distribution was not performed on Lindgren trap data. The accuracy of the IDW interpolation method was evaluated using cross validation tables generated by the Geostatistical Wizard tool in ArcGIS which uses estimates of trend and autocorrelation models generated from the complete data to predict values at each measured location as if that measured location was not part of the dataset. Evaluation of the cross validation report and the prediction errors (Table 4) showed that prediction at low capture points tended to be overestimated and predictions at high capture points tended to be underestimated.

In most cases, Global Moran's I indicated that the distribution of total stored-product insects recovered in corrugated traps were not spatially clustered (i.e., did not have positive spatial autocorrelation). Moran's I values ranged from -0.25 to 0.22, and only the last period of monitoring at site A had a significant positive autocorrelation (Table 4). However, Anselin local Moran's I indicated that some trap locations with high values had traps in the proximity with similar high values. This pattern in the distribution can also be seen in the contour maps which indicate that captures do not appear evenly distributed across the landscape (Figs. 3–5).

At all three sites, foci of higher insect capture appeared to be associated with specific locations at the sites, but their location and species composition tended to change over time. At site A, stored-product insect captures tended to be higher in the area around the two elevators (outside or in tunnel under elevator) and in the open space between these two structures (Fig. 3). In the first monitoring period of 2008, one foci of capture was identified near the bunker storage location where corn was being temporarily stored. In this case, *Sitophilus* spp. represented 71% of the total captures. At site B the foci of insect captures was centered at the feed mill, specifically in the area designated for receiving grain (Fig. 4). Large amounts of spillage were observed to accumulate in this area. However, in the second monitoring period of 2007, an infestation of *Cryptolestes* spp. was detected in the traps near one of the outside bins. In this monitoring period, *Cryptolestes* spp. captures represented 89% of the total capture. At site C, two major foci of insect capture could be identified; one located inside the flour mill and one located near one of the bulk grain storage bins (Fig. 5). Inside the mill, two locations accounted for most of the captures and *O. surinamensis* was the major species recovered.

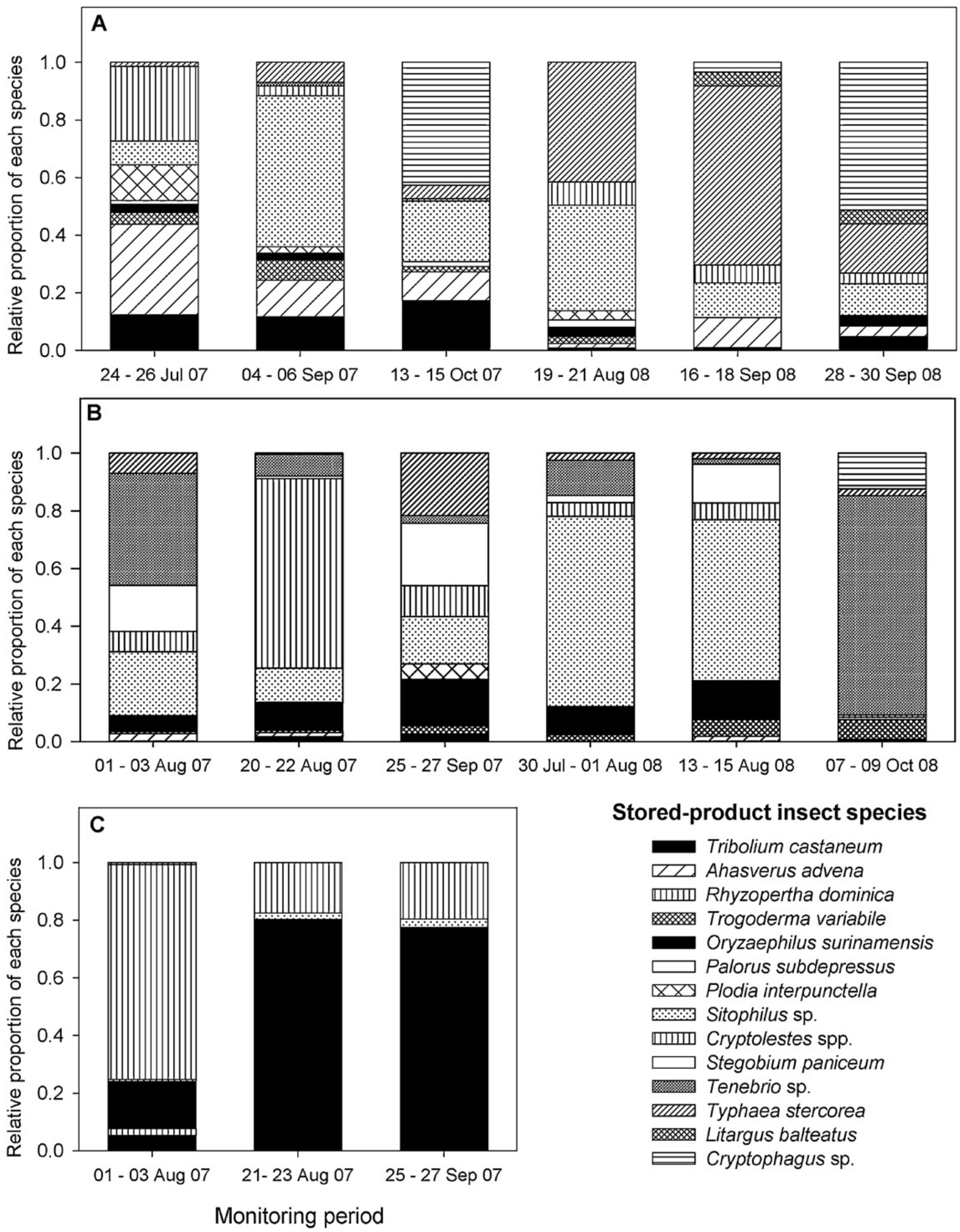

Fig. 2. Relative proportion of each species of stored-product insect recovered with corrugated traps in each site and monitoring period. The *x*-axis represents monitoring periods at each site and the exact range of dates for each monitoring period can be obtained in Table 3.

3.3. Environmental/physical factors and trap captures

There was variation in all environmental factors measured across outside corrugated trap locations. Mean temperature was 23.9 ± 0.2 °C, and ranged from 12.8 °C to 33.5 °C. Average r.h. was 52.7 ± 0.6%, and ranged from 21.5% to 86.0%. Average wind speed was 1.5 ± 0.1 m/s, and ranged from 0.0 m/s to 6.7 m/s. The physical landscape around traps also varied: 21.1% of the traps were located in areas only composed of grass, 17.5% of the traps were located in areas only composed of gravel, and 10.6% of the traps were located in areas only composed of concrete. The remaining traps (50.8%) were located in areas that were a combination of two or three landscape types.

Stepwise regression of number of stored-product insects recovered in outside corrugated traps against the measured environmental factors, physical landscape types, and indices of proximity to structures for the combined sites resulted in three variables being included in the model (F = 3.1; df = 3; P = 0.03): distance to closest storage structure (R^2 = 0.01; P = 0.08), distance to mill (R^2 = 0.01; P = 0.08), and wind speed (R^2 = 0.02; P = 0.09). Some of the predominant species were also analyzed separately using stepwise regression. For *O. surinamensis*, four variables

Table 4
Mean and standard deviation of prediction error in total stored-product insect captures from IDW interpolation for each trap location in the landscapes of three food processing facility sites (A, B, and C) and the Global Moran's *I* spatial autocorrelation measures for the distribution of insect captures with associated *Z* scores and *P* values, with significant nonrandom distributions indicated with an asterisk (*).

Trapping periods	Prediction error (standard deviation)	Moran's *I*	*Z* score	*P*-value
Site A				
24–26 July 2007	0.33 (3.15)	0.07	1.10	0.27
4–6 September 2007	0.64 (5.16)	0.03	0.72	0.47
9–11 October 2007	0.39 (3.66)	−0.11	−1.29	0.20
6–8 August 2008	0.25 (4.65)	0.04	0.84	0.40
14–16 September 2008	0.27 (2.69)	0.10	1.44	0.15
30 September–2 October 2008	0.16 (1.34)	0.22	2.97	<0.01*
Site B				
1–3 August 2007	1.33 (9.95)	0.07	1.03	0.30
20–22 August 2007	−1.51 (48.37)	0.01	0.61	0.54
25–27 September 2007	0.16 (1.97)	−0.01	0.22	0.83
30 July–1 August 2008	0.30 (3.48)	0.03	0.8	0.42
13–15 August 2008	0.31 (4.29)	0.004	0.40	0.69
7–9 October 2008	0.91 (13.61)	−0.02	0.12	0.91
Site C				
1–3 August 2007	1.69 (12.53)	−0.25	−1.63	0.10
21–23 August 2007	1.63 (15.90)	0.001	0.33	0.74
25–27 September 2007	1.00 (8.06)	−0.23	−1.32	0.19

were included in the model ($F = 8.3$; df = 4; $P < 0.001$): temperature ($R^2 = 0.03$; $P < 0.001$), distance to closest storage structure ($R^2 = 0.04$; $P = 0.004$), distance to mill ($R^2 = 0.06$; $P = 0.004$) and r.h. ($R^2 = 0.07$; $P = 0.13$). For *Cryptolestes* spp., only r.h. was included in the model ($F = 2.4$; df = 1; $P = 0.12$; $R^2 = 0.01$). For *T. stercorea*, two variables were included in the model ($F = 3.8$; df = 2; $P = 0.02$): temperature ($R^2 = 0.01$; $P = 0.005$) and grass area ($R^2 = 0.02$; $P = 0.06$).

With the following exceptions, corrugated trap locations with and without stored-product insect captures did not differ in the measured environmental and physical factors ($P > 0.05$). Presence of structure vertical surfaces was associated with greater probability of capturing insects ($\chi^2 = 20.6$; df = 1; $P < 0.001$): 77.1% of trap locations with captures had vertical surfaces within a 1 m^2 radius around the trap, while 22.9% of trap locations without captures had vertical surfaces nearby. Presence or absence of shade also differed between trap locations with and without captures ($\chi^2 = 14.5$; df = 1; $P < 0.001$). Trap locations with stored-product insect captures had equal likelihood of having shade (49%) or no shade (51%), but locations without insect captures tended to not have shade (69%). At these sites, the presence of shade was typically caused by the structures, however the presence of vertical surfaces was not statistically associated with shade ($\chi^2 = 0.1$; df = 1; $P = 0.80$), probably due to only vertical edges in close proximity to the trap being measured and the angle of the sun at the time shade was measured. If traps

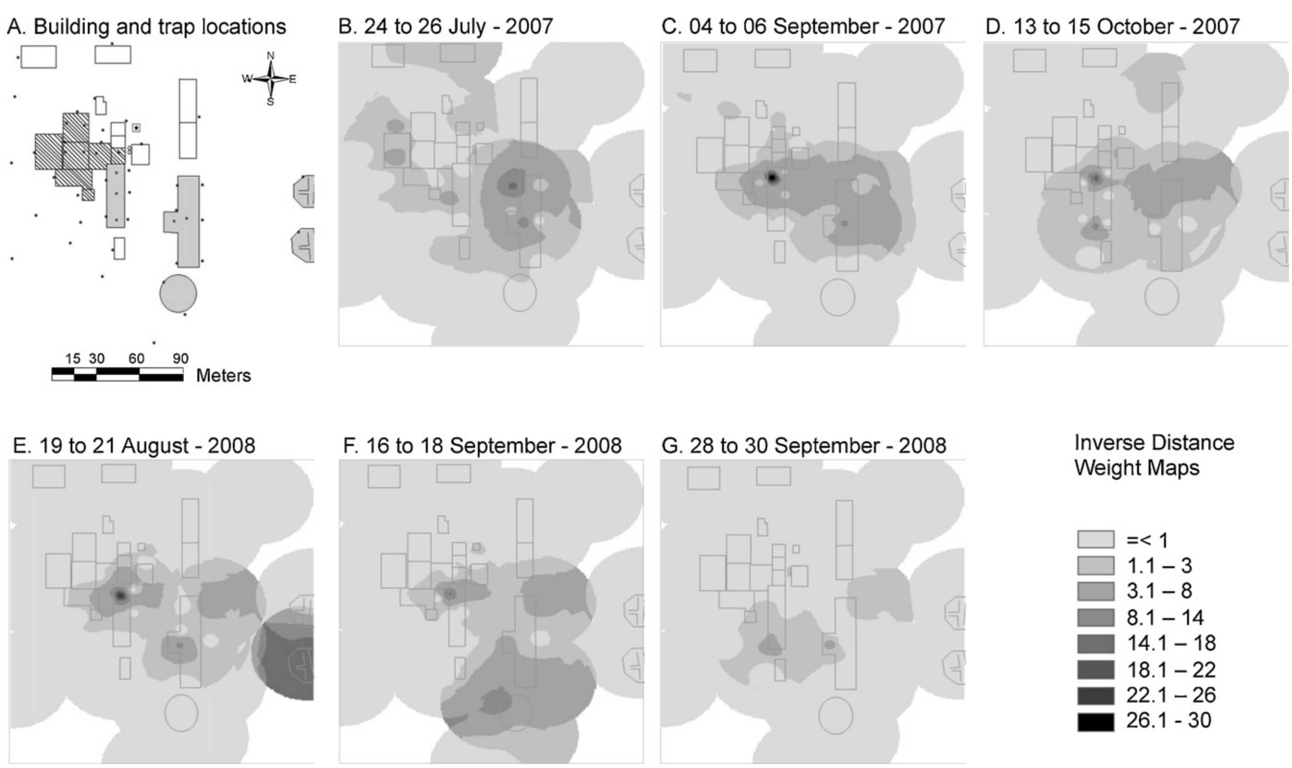

Fig. 3. Map of the landscape at site A indicating structures, with buildings in gray representing structures for storage of grain, hatched buildings represent structures for processing and storage of grain based products, and black dots representing corrugated trap locations (A). Inverse distance weighting contour maps illustrate the spatial distribution of the total number of stored-product insects recovered with corrugated traps during each sampling interval (B–G).

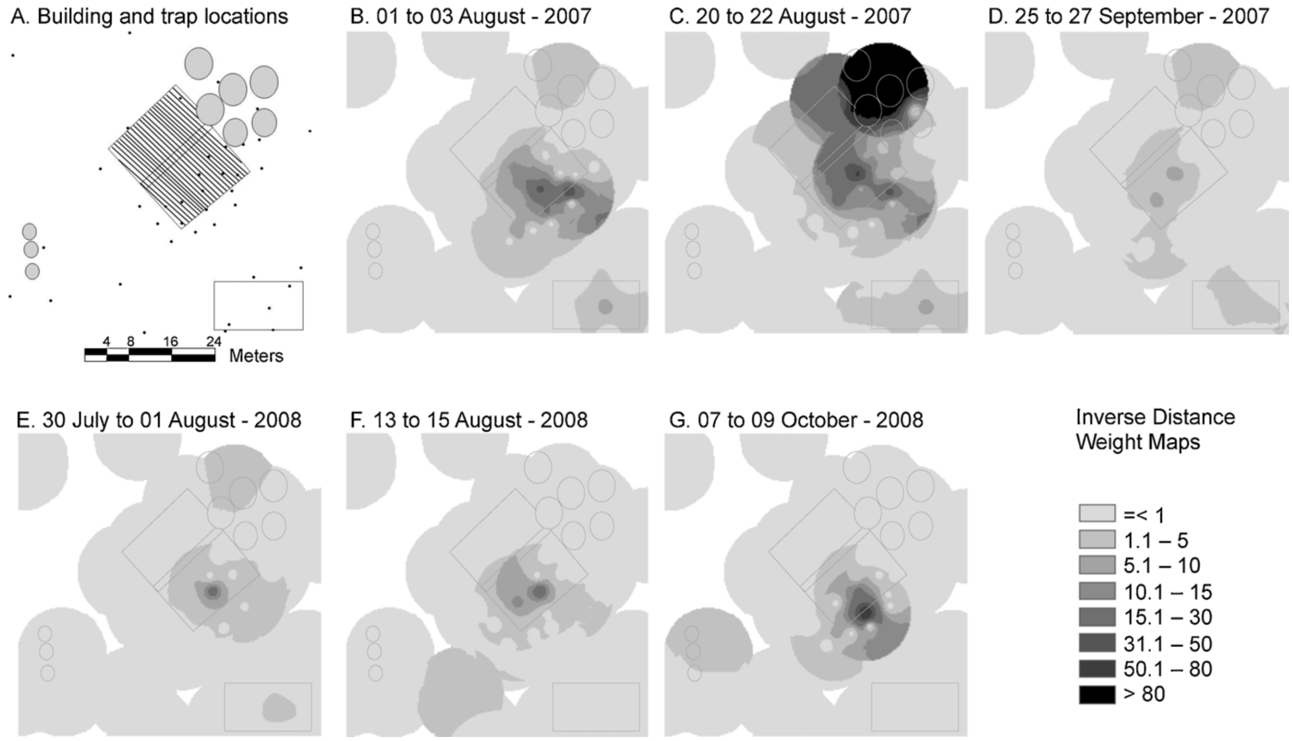

Fig. 4. Map of the landscape at site B indicating structures, with buildings in gray representing structures for storage of grain, hatched buildings represent structures for processing and storage of grain based products, and black dots representing corrugated trap locations (A). Inverse distance weighting contour maps illustrate the spatial distribution of the total number of stored-product insects recovered with corrugated traps during each sampling interval (B–G).

had shade, than 72% of them were located near structures, but only 58% of traps located near structures were shaded.

Spillage accumulation occurred outside structures at all three sites, with 24% of all the trap locations outside having some level of observable accumulation. Considering all species and locations, presence of spillage was not associated with increased capture of stored-product insects ($\chi^2 = 0.1$; df = 1; $P = 0.38$). Corrugated trap locations with spillage held on average 1.6 ± 0.2 individuals/trap and traps without held 2.5 ± 0.9 individuals/trap. Even for fungus feeding species which might be predicted to be associated with

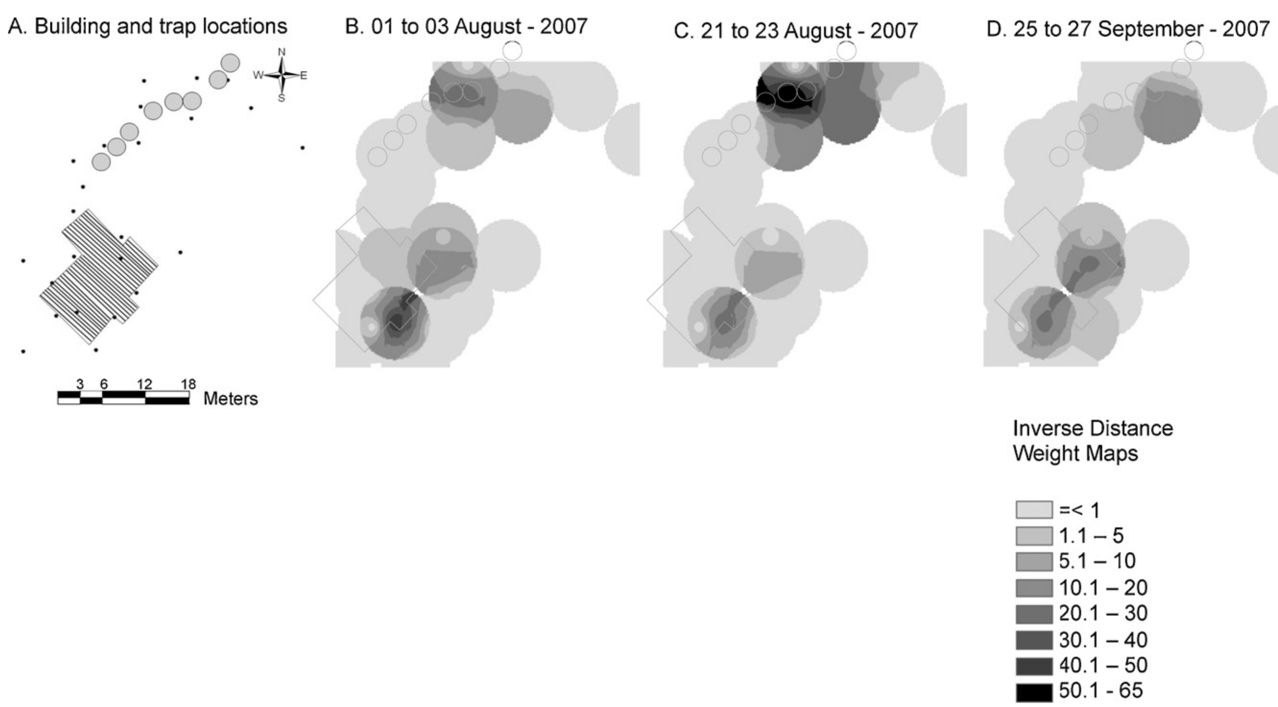

Fig. 5. Map of the landscape at site C indicating structures, with buildings in gray representing structures for storage of grain, hatched buildings represent structures for processing and storage of grain based products, and black dots representing corrugated trap locations (A). Inverse distance weighting contour maps illustrate the spatial distribution of the total number of stored-product insects recovered with corrugated traps during each sampling interval (B–G).

degrading outside spillage, there was no difference between locations with and without spillage ($\chi^2 = 0.1$; df = 1; $P = 0.60$). Traps in locations with spillage held on average 0.6 ± 0.1 individuals/trap and locations without spillage held 0.8 ± 0.3 individuals/trap.

4. Discussion

The community of stored-product insects recovered in corrugated traps placed outside had similar low to moderate species diversity among the three sites. Species diversity and abundance in corrugated traps inside and outside of structures was not correlated, although all but one species were recovered both inside and outside facilities. Corrugated traps with cracked wheat were used in this study because they are efficient at retaining stored-product insects walking on surfaces and are predicted to have a limited attractive space around them. This type of trap should therefore provide a better picture of localized insect activity and the community of species colonizing grain spillage at a particular location, than traps capturing flying individuals.

The species detected in the current study are similar to those found in other studies evaluating walking insect activity outside food processing and storage structures (Dowdy and McGaughey, 1994, 1998; Trematerra et al., 2004; Kučerová et al., 2005). For evaluation, the stored-product species recovered can be grouped into three categories: fungal feeders that exploit degrading grain (e.g., *T. stercorea* and *A. advena*), economically important stored-product pests that exploit grain and grain products and can reach damaging levels (e.g., *T. castaneum*, *T. variabile*, *Cryptolestes* spp., *Sitophilus* spp., *O. surinamensis*), and other less commonly found storage pests that typically do not reach significant levels in stored grain or processing facilities. The overall taxonomic diversity levels, and most of the species, found in the current study were similar to those reported by Larson et al. (2008) at feed mills in the midwestern USA, although that study used pheromone and kairomone baited traps. The predominant beetle species recovered outside in this study were *T. variabile* (pheromone used), *Cryptolestes* spp., *T. castaneum* (pheromone used), *A. advena*, and *T. stercorea*. Kučerová et al. (2005) used grain-based baits placed around a grain storage structure in the Czech Republic to evaluate outside insect activity, which is an approach similar to the traps used in the current study. The species recovered infesting grain baits outside included *Sitophilus granarius* (Linné), *Cryptolestes ferrugineus* (Stephens), *T. castaneum*, *O. surinamensis*, *T. stercorea*, *A. advena*, and *Cryptophagus* sp. In baited traps placed outside at a rough rice storage facility in Brazil the major pest species were similar, *Sitophilus oryzae* L. was the most abundant species recovered, but *C. ferrugineus*, *R. dominica*, *O. surinamensis*, and *T. castaneum* were also commonly recovered, but no fungal feeding species were reported (Trematerra et al., 2004). A common feature of most of these studies is the significant prevalence of fungal feeding species outside.

When the stored-product insect community in grain residues inside structures is evaluated, the abundance and species diversity of fungal feeding species decreases relative to outside, while the economically important pest species listed above become predominant (Kučerová et al., 2003; Arthur et al., 2006). However, the species abundance and diversity in grain residues inside elevators can be different from that found infesting bulk stored product (Reed et al., 2003; Arthur et al., 2006). At feed mill locations, Larson et al. (2008) also found similar beetle species composition in traps placed inside and outside, but number of species, and for most species, number of individuals recovered was greater inside than outside. However, relatively few traps were placed outside in this study and only total numbers captured are reported, so the relative abundance of insects outside is probably greater. Also, since pheromones for some economically important pests were used, this potentially biases the species composition in the traps. The percentage of fungal feeding species out of total species captured also appeared to decrease in the traps inside the mills compared to outside. As with the grain residue sampling, trap captures inside structures can have different species diversity from that actually found infesting the finished product (Roesli et al., 2003; Campbell and Arbogast, 2004).

Differences in the distribution of fungal feeding species and major stored-product pest species suggests relative differences in their sources. The greater recovery of fungal feeding species, such as *A. advena*, *T. stercorea*, and *Cryptophagus* sp., in outside environments is consistent with the idea that accumulations of grain and grain fractions will become moist and promote fungal growth, which would then make them attractive to fungal feeding species and support growth and development. However, a significant association between these species and spillage accumulations outside was not detected in the current study. Variation in the quality of these grain-based residues as a resource for fungal feeding species may be obscuring this relationship, since these residues are likely to go through a succession of stages that will favor different species of stored-product insect as the resource is degraded. In addition, adults may be exploiting other resources not closely associated with spillage areas that are influencing distribution. Spatial variation in rate of degradation due to environmental and physical conditions and variation in the rate of introduction of new spillage material may also influence this relationship.

Species that tended to be more abundant inside in the current study and in earlier work (Kučerová et al., 2003; Reed et al., 2003; Arthur et al., 2006), included several important grain pests such as *T. castaneum*, *Sitophilus* sp., *O. surinamensis*, and *Cryptolestes* spp. Previous studies have also shown the potential for movement into and out of buildings and storage bins (Campbell and Arbogast, 2004; Ridley et al., 2011) and the current study found greater captures near structures, particularly for important pest species. For example, large numbers of *Sitophilus* spp. were recovered in a trap near a bunker full of corn and large numbers of *Cryptolestes* spp. were detected in trap near one of the outside bins. This suggests that resource patches in indoor locations may be the more important source of insect activity outside, but the importance of exterior resource patches in dispersal and population persistence on the landscape remains in need of further research. Recovery of primarily adult fungal feeding species such as *T. stercorea* and *L. balteatus* (47% of adult beetles) in residue samples collected at site A in 2009 (A. Semeao, unpublished data) supports the hypothesis that these outside accumulations may be an influence on their abundance, but low numbers of both adult and immature pest species such as *T. castaneum* and *T. variabile* were also found in these spillage samples.

T. castaneum was a species of particular interest in this study because of its importance as a pest in mills and previous evaluations indicating outside activity, but that population dynamics indicated a population primarily contained within the mill (Campbell and Arbogast, 2004; Campbell et al., 2010a). However, recent research by Ridley et al. (2011) has shown dispersal of adults from grain stores and greater levels of dispersal and gene flow than previously suspected. Semeao et al. (2012b) found that there is more gene flow among different mill locations, one of which was site A, than expected if populations inside were relatively self-contained within mills. Current results showed generally low numbers recovered outside, but recovery of individuals both walking and flying and preliminary data suggesting development in outside spillage highlight the need for further evaluation of the movement patterns and origin of *T. castaneum* immigrating into mills.

Similarities in the species recovered in the Lindgren and corrugated traps, with the exception of *O. surinamensis* which does not fly, suggests that two trap types were not sampling different communities. This would indicate that individuals are alternating between walking and flying and that both traps may be sampling primarily dispersing individuals rather than detecting exploitation of specific habitats in the external landscape. The limited influence of landscape type and spillage on captures also supports the hypothesis that there is much transition between walking and flying and limited influence of fine scale landscape features on distribution. However, it could also be that presence of spillage reduces capture in the traps due to other competing attractants and this is interfering with the detection of pattern. The most important factors appear to be proximity to structures, which could result from insects leaving these structures (e.g., insects dispersing from stored grain or residues in elevators), or that are attracted to odors emanating from grain and grain products within these structures, or because the vertical edges create favorable conditions for aggregation either because of their influence on the environment and spillage accumulation or because insects tend to follow these vertical edges.

The contour maps indicate spatial pattern to the total captures in corrugated traps, with an overall consistent pattern of distribution at each site across monitoring periods, but with temporally dynamic foci of higher captures. Visually the areas of greater captures in the contour maps were centered in and between structures and declined with increased distance from these areas. Trematerra et al. (2004) also found temporal variation in spatial pattern and a tendency for foci of captures to be near structures. Similar patterns have sometimes been found using pheromone baited traps targeting flying individuals (Doud and Phillips, 2000; Campbell and Mullen, 2004). However, for almost all sites and monitoring periods there was typically a lack of positive spatial autocorrelation in the data, which indicates that there was not an overall clustering of the data. Even with no global clustering of insect captures, Anselin local Moran's I was large for some trap locations indicating some local clustering of captures. This discrepancy can result if there is not homogeneity to the relationship between distance and trap captures, which might occur due to differences in the relationship between interior traps and exterior traps or between traps near and far from structures. This lack of homogeneity is consistent with some of the observed influences of structures on outside captures and lack of correlation between inside and outside captures. Increasing the density of traps, particularly in the vicinity of structures while challenging to perform may increase the detection of spatial structure in insect distribution.

In this study, the spatial distribution of stored-product pests captured outside was not significantly explained by most of the measured environmental and physical variables in the landscape in which the trap was placed. In the cases where regressions were significant, low R^2 values indicated poor explanatory value of relationships between measured landscape variables and trap captures. However, it is reasonable to assume that the spatial distribution of species will follow the distribution of resources that are favorable to their development and reproduction. However, as with traps placed inside food facilities, if the traps are primarily placed outside of the resource patches being exploited, they may only be detecting dispersing individuals and not closely linked with specific landscape features (Semeao et al., 2012a). The specific factors that did seem to be important, such as vertical edges and shade, in most situations was a result of traps being located near the walls of the facilities. It is possible that additional types of variables that were not measured might explain more of the pattern or that the spatial or temporal resolution of the data did not allow pattern to be explained.

Management of the exterior landscape and exclusion of insects from entering a facility are important components of an IPM program, however many questions remain about the relative importance of the sources of these insects trying to enter food processing facilities. This study, and the one by Campbell and Mullen (2004), are among the few evaluating the spatial distribution of stored-product insects in the proximity of food processing facilities. Other studies should extend the temporal scale of monitoring through the seasons and also increase the resolution of the monitoring grid, making it possible to better detect locations with early signs of outside activity, giving a better idea of possible primary foci. As with any study of this type the degree to which the results are influenced by the temporal and spatial scale of the sampling needs to be evaluated. In addition, more evaluation of the role of outside spillage is needed in terms of how it is exploited as a resource and what role it plays in influencing insect distribution. This area of research could help improve the implementation and interpretation of monitoring programs and the targeting of inspection and sanitation programs.

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