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Stored-grain insect population commingling densities in wheat and corn from pilot-scale bucket elevator boots☆

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ABSTRACT

Grain elevator boot and pit areas facilitate the commingling of insects with the grain moving through the elevator leg. A removable boot was developed to facilitate residual grain removal and preservation in the boot and to quantify the commingling magnitude as a function of stored-product insect density. This study included two species that develop inside kernels, *Rhyzopertha dominica* and *Sitophilus oryzae*, and three species that develop outside kernels, *Tribolium castaneum*, *Oryzaephilus surinamensis* and *Cryptolestes ferrugineus*. The removable boots were loaded with infested residual grain and remained undisturbed for 0, 8, 16, or 24 weeks (wk). After each time point, uninfested grain was transferred through the infested boot. The adult beetles that commingled with the clean grain were sifted and counted. Further, the commingled lots were examined after 8 wk for adult progeny. The insect densities in the infested bucket elevator leg boots affected the insect densities transferred through the elevator leg to other locations. The insect density in clean wheat or corn transferred over infested boots was 1 insect/kg immediately after transfer, but this density doubled in 8 wk. More internally developing insects were collected by the elevator buckets when the clean grain flowed over the infested grain compared with the externally developing insects. β-Cyfluthrin application as a residual insecticide reduced the insect densities in the elevator boot, which consequently reduced the insect transfer to clean grain. Cleaning the bucket elevator boot area and applying residual insecticide monthly should minimize clean grain contamination.

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1. Introduction

Commercial grain storage facilities quickly become infested with stored-product insect pests (Reed et al., 2003; Arthur et al., 2006). Infestations of newly harvested grain are caused by previously infested grain carried over from one crop year to the next (Good, 1937). Many areas in a grain elevator, including handling equipment dead spots, collect residue or accumulate grain (Dowdy and McGaughey, 1996; Reed et al., 2003; Arthur et al., 2006), and are potential insect pest harborage sites where insects are carried over from one year to the next.

The elevator boot is an enclosed space at the bottom of a bucket elevator leg casing, where residual grain accumulates during use and is not manually cleaned on a regular basis in most grain elevators. The elevator boot is typically located in the basement or a sub-basement pit area and is an ideal habitat for insect population growth. The area surrounding the boot is also an important insect pest infestation source, especially if grain is allowed to accumulate (Good, 1937). Any infestations in the boot-pit area can spread to other locations in a facility. Arthur et al. (2006) showed that boot-pit areas have one of the two highest insect densities out of five areas surveyed over two years for nine elevators. The insect species detected in this study were the lesser grain borer, *Rhyzopertha dominica* (F.), and the rusty grain beetle, *Cryptolestes ferrugineus* (Stephens), which are common wheat pests in Kansas, and the rice weevil, *Sitophilus oryzae* (L.), which was common in the trash samples but rare in the bulk wheat storage for Kansas.

Residual insecticide sprays are often applied to floor, wall, and equipment surface areas inside grain-handling facilities to control stored-product insects. Sanitation improves the efficacy of applied residual insecticides (Ingemansen et al., 1986; Herron et al., 1996). Residual grain accumulation in the elevator boot likely contributes to insect and grain commingling or mixing through the elevator leg.

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Studies have not investigated the insect infestation dynamics for the elevator boot-pit, insect commingling, and the likely transfer of insects via elevator buckets to additional areas in the elevator grain-handling system. The objectives of this research were to (1) measure the stored-grain insect population commingling densities in wheat and corn from pilot-scale bucket elevator boots, (2) identify the dynamics that spread infestations from this area to other sections in a facility, and (3) examine the impact from a residual insecticide application to the boot-pit on insect density commingling.

2. Materials and methods

2.1. Boot hardware

Three model B-3 bucket elevator legs (Universal Industries, Cedar Falls, Iowa, USA) (Fig. 1) were retrofitted with experimental boots that could be inserted and removed with ease from the leg casing bottom. These removable boots replaced the bucket elevator leg casing standard enclosed base, where residual grain accumulates when moving grain. The boot area (29.8 by 11.4 by 6.4 cm) retained 1.9 kg of residual grain. The elevator leg function and grain flow were unaffected by the new boot, but this design permitted boots containing residual grain to be removed from the leg and incubated, while the leg was used for an additional test with a different boot installed.

2.2. Boot grain infestation

The residual hard red winter wheat (1.9 kg) in the pilot-scale elevator boot was infested with mixed ages of unsexed adults of *R. dominica*, *C. ferrugineus*, and the red flour beetle *Tribolium castaneum* (Herbst) at different insect population densities (0, 50, 100, and 200 insects/kg/species four days before testing). In contrast, yellow dent corn was infested with adults of *S. oryzae*, *T. castaneum* and the sawtoothed grain beetle, *Oryzaephilus surinamensis* (L.), at the same density levels as for the wheat four days before testing. The average moisture contents of the wheat and corn treatments were 12.4% and 14.6%, respectively. Each grain type and treatment was independently tested using a pilot-scale bucket elevator boot; thus, each grain treatment used a separate removable boot. Prior to each treatment, an empty boot was installed in the bucket elevator leg to prepare for grain loading. The control treatment included insect-free grain treated as described below (Sections 2.3 and 2.4). The boot area temperature and relative humidity (r.h.) were monitored each minute throughout the test period using a HOBO® data logger (Onset Computer Corporation, Bourne, MA, USA).

2.3. Boot-loading process

Grain was acquired from a commercial grain elevator in Manhattan, Kansas, USA and stored at −13 °C for at least 4 weeks (wk) to kill any insects. Several 2 kg lots were removed from the freezer, placed in a 10 L plastic bucket, and warmed to room temperature. After re-warming for 24 h, each 2 kg lot was infested with one of four adult insect treatment densities (0, 50, 100, and 200 insects/kg/spp.). The infested lots were placed in 10 L plastic buckets and sealed with a plastic bucket lid cover; the lid cover had a hole in the center 8.25 cm in diameter covered with a 381 μm opening mesh. The infested lots in plastic buckets were held for 4 d in an environmental chamber (model CTH-811, Percival Scientific, Perry, IA, USA) at 27.5 ± 0.5 °C and 65 ± 5% r.h. prior to passing the grain through the pilot-scale elevator legs to load the boot.

The infested grain was transferred through the leg at 1.72 ton/h, which filled the boot with infested residual grain. Certain boots filled with infested grain remained installed in the bucket elevator leg, and clean grain was immediately transferred through the leg (time 0 wk). This construction simulated a recently infested boot with only the first-generation adult insects and few, if any, infested kernels that could be collected during the clean grain transfer. The grain-filled boots were covered with a 381 μm opening sieve to facilitate air diffusion but prevent insect escape; they were then incubated in the environmental growth chamber (27.5 ± 0.5 °C and 65 ± 5% r.h.) for 8, 16, and 24 wk.

Fig. 1. Pilot-scale bucket elevator leg boot arrangement.

Loading the empty boots with infested grain using a bucket elevator leg produced a natural curved grain surface on top of the residual grain in each boot due to the moving cups. The infested grain in boots was incubated for 0, 8, 16, or 24 wk and then installed at the bottom of the leg where it remained undisturbed for two 30 min acclimation periods. During the first 30 min period, the elevator leg was off and not operated. During the second 30 min period, the leg was on and operated at empty and without grain flowing. During the two 30 min acclimation periods, the insects adjusted to the environment before the legs were operated at a 1.72 MT/h feeding rate. After the acclimation periods, 15 kg of insect-free grain (wheat or corn) was transferred through the boot, and the discharged grain was collected and retained for analysis and further processing.

2.4. Processing elevator grain discharge treatments

The 15 kg of grain that passed through the infested elevator leg was discharged through the elevator head section. Each discharged grain treatment was collected and weighed after passing over and commingling with the infested grain in the boot. After each treatment, the grain was sifted twice using an Insectomat (Samplex Ltd., Willow Park, UK) with a vibrating inclined sieve (89 cm × 43 cm with 1.6 mm sieve openings). The live adult insects that passed through the sieve were collected, counted, and recorded for each grain treatment. After the adults were removed, each discharge grain treatment was passed through a Boerner divider (Seed Trade Reporting Bureau, Chicago, IL, USA) twice to generate four representative samples. One of the four samples was randomly selected and equally divided to yield three representative samples that each weighed 5 kg. The three representative samples were (1) a reference sub-treatment stored at −13 °C, (2) a grain quality sub-treatment evaluated using the Federal Grain Inspection Standards (FGIS, 1997), and (3) an incubated sub-treatment that was placed in an above-described sealed 10 L plastic bucket. The bucket was placed in the environmental growth chamber for 8 wk to allow any larvae developing inside the kernel to emerge as adults (Hagstrum and Milliken, 1988). After 8 wks, the incubated sub-treatment was sifted using an Insectomat, which removed the adult progeny. The adult insects from the incubated sub-treatment were counted and recorded. Additionally, after passing 15 kg through the leg, the commingled boot treatment with uninfested and infested grain was sifted on the Insectomat to document the increased population from the new progeny. The grain treatment order through the bucket elevator legs was randomized using the Microsoft (2007) Excel RAND function with each grain type, boot incubation period, replication and insect density as the components.

2.5. Insecticide treatments

β-Cyfluthrin (Tempo SC Ultra, Bayer CropScience, Research Triangle Park, NC, USA) at 11.8% purity (120 mg active ingredient (AI)/ml) was formulated in water and applied to the enclosed area in empty boots at the high label rate of 20 mg (AI)/m^2 in 3.7 ml/m^2. Each boot was sprayed to produce run off, then fully dried prior to initial loading with an infested grain lot. Only the infested grain lot exposed to the highest insect density (600 insects/kg) was transferred through the spray-treated boot. The incubation period and insect-free grain transfer over the insecticide-treated boot followed the same boot-loading process (Section 2.3) and grain discharge treatment processing (Section 2.4).

2.6. Data analysis

Each grain type, insect species, density, and boot-holding time combination was independently replicated three times using a factorial arrangement for the treatments through a randomized design. The insect data were standardized as live adults/kg of grain, and the insect counts included the insects in treatments immediately after sieving and those that emerged after 8 wk.

A two-way analysis of variance (ANOVA) was used for the number of insects in the boot residual grain or discharge grain treatments to determine the differences between the insect densities or mortalities and boot-holding times (SAS Institute, 2008). When the effects of the model variables were significant, one-way ANOVA and the Ryan–Einot–Gabriel–Welsch multiple range test (REGWQ) were used to separately analyze treatment differences ($P \le 0.05$) among the insect densities or mortalities or among boot-holding times, following the approach used by Sehgal et al. (2013) to separate mean treatment differences. Insects in the initial and 8 wk sievings were combined across species, and the percentage of each species was calculated. The insect density correlation between boot hold times and discharge grain after a clean grain transfer was calculated for both grain types.

3. Results

The control treatments (uninfested treatments) for both grain types showed no infestation for both boot lots and discharge grain treatments for each boot-holding time.

Table 1
The live adult (mean ± SE)[a] *R. dominica*, *T. castaneum*, and *C. ferrugineus* in the residual grain and discharge grain treatment sieving after 15 kg of clean wheat was transferred over an infested bucket elevator boot, which was held for 0, 8, 16, and 24 wk.

Location	Sieving periods	Density (insects/kg)	Boot-holding time (wk)			
			0	8	16	24
Boot	Initial	150	137.4 ± 28.4	737.1 ± 530.2	128.4 ± 15.9	1184.0 ± 246.9b
		300	229.7 ± 58.3	1612.3 ± 756.9	1263.0 ± 1162.0	689.3 ± 346.1b
		600	230.9 ± 76.5C	2558.7 ± 1109.4B	555.1 ± 158.2BC	5186.6 ± 204.9Aa
	After 8 wk	150	224.1 ± 33.6	5311.4 ± 3850.9	143.5 ± 18.3	116.1 ± 80.9b
		300	93.6 ± 38.5	1250.9 ± 554.7	1794.6 ± 1533.7	43.9 ± 22.8b
		600	175.3 ± 114.1	5746.4 ± 4242.5	4064.2 ± 1085.2	4734.9 ± 552.1a
Discharge	Initial	150	2.0 ± 0.6	1.9 ± 0.8	0.5 ± 0.2	1.0 ± 0.3
		300	1.6 ± 0.1	1.3 ± 0.9	1.2 ± 1.0	3.8 ± 2.4
		600	0.6 ± 0.1	3.6 ± 1.4	0.9 ± 0.8	2.2 ± 0.2
	After 8 wk	150	1.9 ± 1.1	472.8 ± 462.6	5.5 ± 1.8	8.1 ± 4.6
		300	2.7 ± 1.7	6.7 ± 2.4	144.9 ± 138.8	39.3 ± 31.9
		600	11.8 ± 5.9	99.5 ± 91.0	63.9 ± 30.3	18.1 ± 2.3

[a] The mean adult insects were analyzed separately by location and sieving period; the upper-case letters represent the analysis between boot hold times, and the lower-case letters represent the analysis between densities.

Table 2
The live adults (mean ± SE) and species percentages in the residual grain and discharge grain treatment sieving after 15 kg of clean wheat was transferred over an infested bucket elevator boot, which was held for 0, 8, 16, and 24 wk.

Sample location	Density (insects/kg)	Boot hold time (wk)	Mean ± SE			
			Total (insects/kg)	Percent of insects for each species		
				R. dominica	*T. castaneum*	*C. ferrugineus*
Boot	150	0	361.5 ± 20.7	69.8 ± 7.7	10.8 ± 2.2	19.4 ± 6.4
	300	0	323.3 ± 69.7	57.9 ± 6.9	15.5 ± 5.0	26.5 ± 11.8
	600	0	406.3 ± 182.3	50.8 ± 5.1	30.1 ± 12.1	19.1 ± 9.4
	150	8	6048.5 ± 4374.9	93.5 ± 2.9	3.3 ± 2.3	3.2 ± 0.7
	300	8	2863.3 ± 1195.7	95.7 ± 2.1	0.7 ± 0.3	3.6 ± 1.8
	600	8	8305.1 ± 5171.6	84.8 ± 6.0	5.5 ± 4.4	9.7 ± 4.7
	150	16	271.9 ± 18.2	85.2 ± 4.9	3.8 ± 0.9	11.0 ± 4.0
	300	16	3057.6 ± 3695.4	98.5 ± 0.6	0.4 ± 0.2	1.0 ± 0.4
	600	16	4619.3 ± 1157.2	96.2 ± 1.5	1.7 ± 0.5	2.1 ± 1.2
	150	24	1300.1 ± 192.7	97.2 ± 0.5	1.2 ± 0.4	1.6 ± 0.6
	300	24	733.2 ± 352.6	95.6 ± 2.2	2.3 ± 1.3	2.0 ± 1.0
	600	24	9921.4 ± 349.2	82.4 ± 5.3	0.6 ± 0.2	17.0 ± 5.4
Discharge	150	0	3.9 ± 1.5	42.7 ± 13.6	50.9 ± 14.8	6.4 ± 3.8
	300	0	4.3 ± 1.8	35.7 ± 8.5	42.3 ± 17.0	22.0 ± 22.0
	600	0	12.4 ± 5.9	18.5 ± 5.3	79.8 ± 6.5	1.7 ± 1.7
	150	8	474.7 ± 463.4	85.5 ± 9.7	12.7 ± 10.4	1.8 ± 1.5
	300	8	8.0 ± 2.9	78.8 ± 4.2	9.9 ± 4.5	11.3 ± 8.1
	600	8	103.0 ± 91.7	77.0 ± 11.3	8.4 ± 6.7	14.5 ± 9.5
	150	16	5.9 ± 2.0	98.3 ± 1.3	1.7 ± 1.3	0.0 ± 0.0
	300	16	146.0 ± 139.9	100.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
	600	16	64.8 ± 30.9	99.6 ± 0.4	0.4 ± 0.4	0.0 ± 0.0
	150	24	9.1 ± 4.9	99.0 ± 0.7	1.0 ± 0.7	0.0 ± 0.0
	300	24	43.1 ± 34.3	92.4 ± 5.9	7.1 ± 6.1	0.4 ± 0.4
	600	24	20.3 ± 2.1	99.4 ± 0.4	0.6 ± 0.4	0.0 ± 0.0

3.1. *Insects in the wheat boot and discharge treatments: wheat*

Insects in the elevator boot residual grain commingled with the wheat moving through the elevator leg during the experiments, and they were transported out of the boot in the discharged (transfer) grain (Table 1). The insects in the boot wheat lots immediately after sieving differed significantly among the insect densities ($F = 9.14$; df = 2, 24; $P = 0.0013$) and boot-holding times ($F = 8.84$; df = 3, 24; $P = 0.0003$). The insect density and holding time interaction was also significant ($F = 4.90$; df = 6, 24; $P = 0.0021$). The insects in wheat after 8 wk in the boot lots were similar among the insect densities ($F = 2.97$; df = 2, 24; $P = 0.0705$) and boot-holding times ($F = 2.57$; df = 3, 24; $P = 0.0778$). The insect density and boot-holding time interaction was not significant ($F = 0.88$; df = 6, 24; $P = 0.5271$). *Rhyzopertha dominica* adults composed the greater percentage of species in each boot location after 15 kg of clean wheat was transferred over the infested bucket elevator boot for each holding time and density level (Table 2).

For the initial sieving, approximately 2- to 23-fold more insects were detected after 24 wk at the insect density 600 insects/kg compared with the remaining holding times (Table 1). Insects at the 600 insects/kg density in the initial sieving significantly increased over time, except between the holding times 8 and 16 wk when there was a significant decrease over time. For the three initial sieving insect densities, the numbers of insects at 16 wk were lower than at 8 or 24 wk with the exception of 300 insects/kg where, while 16 wk was lower than 8 wk, the insect numbers at 24 wk declined further rather than increasing again.

Relative to the number of insects in the boot residual grain, few insects were detected in the discharged grain treatments. The insect density (df = 2, 24), boot-holding time (df = 3, 24), insect density and holding time interaction (df = 6, 24) were not significant for the insects in the wheat discharge treatments both for the initial and 8-wk sievings (F, range = 0.36–1.57; P, range = 0.2222–0.7034). Similar to the wheat boot lots, the adult *R. dominica* composed a higher percentage of the species in the discharge grain sieving (Table 2). However, *T. castaneum* adults were the predominate species among the treatments for initial discharge grain sieving at higher density levels (300 and 600 insects/kg) and the 24 wk boot hold time.

The insect densities from the wheat boot after the 8 and 16 wk holding times correlated well with the number of insects recorded immediately after a clean grain transfer. As expected, the correlations (8 wk $r = 0.91$, $n = 9$ and $P = 0.001$; 16 wk $r = 0.82$, $n = 9$ and $P = 0.007$) between insects in the infested boots and after a clean grain transfer indicate that the number of insects in the discharged grain correlates to the number of insects in the residual grain.

3.2. *Insects in the boot and discharge treatments: corn*

Insects in residual grain from the boot commingled with the corn moving through the elevator leg during the experiment and were transported out of the boot in the discharged (transfer) grain. However, few insects were detected in the corn discharge treatments compared with the boot lots (Tables 3 and 4).

For the insects in the boot corn lots immediately after sieving, no differences were detected among the insect densities ($F = 1.03$; df = 2, 24; $P = 0.3727$) and boot-holding times ($F = 1.99$; df = 3, 24; $P = 0.1431$). The insect density and holding time interaction was not significant ($F = 0.37$; df = 6, 24; $P = 0.8887$). For the initial sieving, 5–6 times more insects were detected after a 24 wk holding time at 600 insects/kg compared with the remaining holding times. The highest insect density (600 insects/kg) for residual grain in the boot after the progeny emerged at the 8-wk holding time was significantly different ($P < 0.05$), but not at the remaining two density levels. Additionally, the progeny from the residual grain at the highest density differed initially and at the 8 wk boot-holding time, but not for the 16 and 24 wk times. The number of insects in corn after 8 wk in the boot lots did not differ significantly among the insect densities ($F = 3.4$; df = 2, 24; $P = 0.0500$) and boot-holding times ($F = 2.777$; df = 3, 24; $P = 0.0634$). The insect density and boot-holding time interaction was not significant ($F = 1.75$; df = 6,

Table 3
The live adult (mean ± SE)[a] *S. oryzae*, *T. castaneum*, and *O. surinamensis* in the residual grain and discharge grain treatment sieving after 15 kg of clean corn was transferred over an infested bucket elevator boot, which was held for 0, 8, 16, and 24 wk.

Sample location	Sieving period	Density (insects/kg)	Boot hold time (wk)			
			0	8	16	24
Boot	Initial	150	165.9 ± 34.4	252.5 ± 31.9	446.6 ± 206.9	937.8 ± 500.9
		300	207.5 ± 40.6	462.3 ± 141.6	1120.9 ± 566.9	1412.1 ± 1347.9
		600	502.1 ± 134.4	611.5 ± 137.7	973.8 ± 88.0	3174.7 ± 2515.9
	After 8 wk	150	262.7 ± 52.9	140.8 ± 7.9b	278.9 ± 118.5	440.9 ± 419.6
		300	247.1 ± 73.3	560.9 ± 248.0ab	1416.2 ± 615.6	384.6 ± 129.0
		600	332.4 ± 116.0 B	994.2 ± 119.5Aa	842.6 ± 184.1AB	588.0 ± 48.7AB
Discharge	Initial	150	0.3 ± 0.3	0.9 ± 0.7	0.9 ± 0.5	2.8 ± 2.4
		300	0.2 ± 0.2	2.8 ± 1.5	4.9 ± 3.9	1.7 ± 1.4
		600	1.2 ± 0.5	3.2 ± 1.6	1.6 ± 0.2	3.9 ± 1.9
	After 8 wk	150	5.7 ± 3.0	19.9 ± 17.7	15.0 ± 7.2	17.4 ± 3.6
		300	4.3 ± 1.9	44.8 ± 20.7	42.3 ± 28.9	6.1 ± 2.6
		600	7.1 ± 2.6	74.4 ± 36.0	14.9 ± 1.2	23.5 ± 10.9

[a] The mean adult insects were analyzed separately by location and sieving period; the upper-case letters represent the analysis between the boot hold times, and the lower-case letters represent the analyses between densities.

24; $P = 0.1529$). Live adult *S. oryzae* composed the highest percentage of the three species in the residual grain from the boot after 15 kg of clean corn was transferred over the infested boot for each boot-holding time and 150, 300, and 600 adults/kg, except after 24 wk at the lowest density where *T. castaneum* predominated (Table 4). Secondary pests, such as *T. castaneum*, typically cohabitate or follow primary pests (*S. oryzae*) especially during long-term storage of grain. In our experimental design both insect species are present at the same time to simulate this typical scenario where secondary pests follow primary pests and cohabitate.

The insect density (df = 2, 24) as well as insect density and holding time interaction (df = 6, 24) were not significant for insects in the corn discharge treatments both for the initial and 8 wk sievings (*F*, range = 0.69–1.08; *P*, range = 0.3976–0.6566, Table 4). The number of insects detected among the insect densities in the initial boot-holding time was not significant ($F = 1.09$; df = 2, 24; $P = 0.3715$); however, the number of insects among the various densities differed for the 8 wk holding time ($F = 3.529$; df = 2, 24; $P = 0.0302$). Similar to the wheat boot lots, the adult *S. oryzae* composed the higher densities detected in the corn discharge treatments compared with the other species, except after the initial sieving at the lowest density, and 24 wk at 150 and 300 adults/kg, where *T. castaneum* was more abundant.

The mean number of insects in the corn boot at the 16 wk boot-holding time correlated ($r = 0.90$, $n = 9$ and $P = 0.001$) with the number of insects immediately following a clean grain transfer. Similar to the wheat experiments, the infested boot insect density and insects in the discharged grain correlated to the insect density in the residual grain.

3.3. *Insects in the insecticide-treated boot and discharge treatments for both corn and wheat*

Insecticide and non-insecticide boot and discharge treatments were randomized among the three bucket elevator legs. Dedicated boots were sprayed with the insecticide prior to infested grain lot

Table 4
The live adults (mean ± SE) and species percentages in the residual grain and discharge grain treatment sieving after 15 kg of clean corn was transferred over an infested bucket elevator boot, which was held for 0, 8, 16, and 24 wk.

Sample location	Density (insects/kg)	Boot hold time (wk)	Mean ± SE			
			Total (insects/kg)	Percent of insects for each species		
				S. oryzae	*T. castaneum*	*O. surinamensis*
Boot	150	0	428.7 ± 19.6	63.2 ± 5.7	20.6 ± 3.8	16.1 ± 2.1
	300	0	454.6 ± 107.4	62.2 ± 1.4	22.4 ± 4.7	15.4 ± 5.2
	600	0	834.5 ± 210.2	46.1 ± 3.7	31.2 ± 1 5.6	22.6 ± 1.9
	150	8	393.3 ± 28.5	72.4 ± 12.6	15.2 ± 3.4	12.4 ± 9.7
	300	8	1023.2 ± 196.1	85.9 ± 3.4	8.3 ± 2.4	5.8 ± 1.2
	600	8	1605.7 ± 235.0	74.6 ± 4.5	21.4 ± 3.7	4.0 ± 1.1
	150	16	725.4 ± 285.5	86.1 ± 1.5	13.3 ± 1.2	0.6 ± 0.3
	300	16	2537.1 ± 1151.8	79.0 ± 9.5	18.9 ± 10.3	2.0 ± 1.2
	600	16	1816.4 ± 172.8	79.2 ± 11.3	19.8 ± 1.0	1.0 ± 0.5
	150	24	1378.7 ± 910.6	32.7 ± 10.9	42.7 ± 21.1	24.7 ± 19.7
	300	24	1796.7 ± 1394.6	60.3 ± 24.6	35.6 ± 26.5	4.2 ± 3.9
	600	24	3762.7 ± 2541.6	43.3 ± 8.9	36.2 ± 11.4	20.5 ± 20.2
Discharge	150	0	6.1 ± 2.9	37.3 ± 3.9	57.6 ± 2.1	5.1 ± 2.7
	300	0	4.5 ± 2.2	42.1 ± 15.8	31.5 ± 12.2	26.4 ± 20.2
	600	0	8.2 ± 2.9	53.3 ± 3.1	29.9 ± 10.7	16.8 ± 8.2
	150	8	20.8 ± 18.4	84.7 ± 6.9	11.5 ± 7.4	3.8 ± 3.6
	300	8	47.6 ± 21.5	90.3 ± 6.8	9.3 ± 6.9	0.4 ± 0.4
	600	8	77.6 ± 37.6	91.7 ± 2.9	6.0 ± 1.9	2.2 ± 2.2
	150	16	15.9 ± 7.5	86.1 ± 6.7	13.9 ± 6.7	0.0 ± 0.0
	300	16	47.3 ± 32.8	86.3 ± 6.6	13.7 ± 6.6	0.0 ± 0.0
	600	16	16.6 ± 1.3	80.9 ± 11.4	19.1 ± 11.4	0.0 ± 0.0
	150	24	20.2 ± 2.8	26.3 ± 13.1	39.3 ± 19.7	34.4 ± 32.8
	300	24	7.8 ± 2.8	46.0 ± 23.1	53.0 ± 22.2	1.0 ± 0.9
	600	24	27.5 ± 9.6	84.0 ± 13.0	16.0 ± 13.0	0.0 ± 0.0

loading and insect-free transfer. However, the elevator component parts, such as the cups and leg casing, may have been contaminated from the insecticide-treated boot. The potential minimal contamination did not affect insect mortality from the non-insecticide-treated boot (F, range = 27.65–77.57; P = 0.0001) and transfer (F, range = 1295.61–4938.05; P = 0.0001) treatments for both grain types.

The mean number of insects from each of the three species in the insecticide-treated boots with wheat for each boot-holding time did not vary among the insect densities (F = 0.55; df = 3, 8; P = 0.6647) but did vary among the densities for the discharge (transfer) treatments (F = 7.55; df = 3, 8; P = 0.0102) (Table 5). The mean number of *R. dominica* (F = 0.24; df = 3, 8; P = 0.8663), *T. castaneum* (F = 3.50; df = 3, 8; P = 0.0694), and *C. ferrugineus* (F = 0.96; df = 3, 8; P = 0.4586) detected in the boot lots among the insect densities for each boot-holding time showed no differences among treatments. Similarly, the mean numbers of *R. dominica* (F = 2.04; df = 3, 8; P = 0.1869), *T. castaneum* (F = 3.31; df = 3, 8; P = 0.0781), and *C. ferrugineus* (F = 0.730; df = 3, 8; P = 0.5607) detected in discharge treatments for each boot-holding time did not differ among the treatments.

The total number of insects in insecticide-treated boots filled with corn for each boot-holding time significantly differed among the insect densities (F = 8.20; df = 3, 8; P = 0.0080); similarly, significant differences were detected among the insect densities for the discharge treatments (F = 4.74; df = 3, 8; P = 0.0349, Table 6). The mean number of *S. oryzae* in the boot lots for each boot-holding time differed among the insect densities (F = 7.42; df = 3, 8; P = 0.0107), but such differences were not observed for the number of *T. castaneum* (F = 3.65; df = 3, 8; P = 0.0636) and *O. surinamensis* (F = 0.83; df = 3, 8; P = 0.5148). The mean number of *S. oryzae* in discharge treatments differed among the insect densities (F = 4.77; df = 3, 8; P = 0.0343) but not for *T. castaneum* (F = 1.50; df = 3, 8; P = 0.2869) and *O. surinamensis* (F = 2.0; df = 3, 8; P = 0.1927).

4. Discussion

Our results clearly show that clean wheat and corn transferred over infested boots collected approximately 1 insect/kg during the process; after 8 wk, this density doubled. The number of insects transferred from the infested boot varied with insect density (150, 300, and 600 insects/kg), boot-holding time, grain type, and insect species.

The mean number of adult progeny immediately after sieving the residual grain from the wheat boots only slightly differed among the initial insect density levels or across boot-holding times. After the immature insects emerged from the residual wheat in the boot, the longest boot-holding time (24 wk) yielded more adult progeny at the highest insect density compared with the other two lower densities. Additionally, in residual wheat, the number of adult progeny insects tended to increase as a function of boot-holding time, except at 16 wk. Adult progeny insects may have declined during week 16 due to over-population issues but seemed to rebound by week 24.

Wheat treatments showed slight differences in the number of mean adult progeny, with considerable variations among the treatment combinations. Transforming the data and non-parametric statistics did not yield normality. Wheat discharge treatments yielded far fewer adult progeny compared with the boots, and the mean did not differ for either insect density or the boot-holding times.

After 8 wk of incubation (one insect generation cycle), many *R. dominica* progeny adults emerged from the infested wheat boot lots. Greater insect densities for *R. dominica* adults were detected compared with *T. castaneum* and *C. ferrugineus* for the 8 wk sieving from the discharge treatments probably because externally developed adult insects (*T. castaneum* and *C. ferrugineus*) were mobile and could shift away from the scooping bucket cups, while immature insects inside grain kernels were collected by the cups during the transfer of grain. There were no microfungi observed in these tests but other debris was common after insects had damaged the residual grain during boot-holding times. As a result, many *R. dominica*-infested kernels were collected by passing the clean grain over the infested grain in the boot. Storey et al. (1982) reported low levels of (4%) initial insect infestation from grain samples collected in 79 U.S. elevators. However, after incubating the samples (4–6 wk), further inspection showed that 16% of the samples were infested with *R. dominica*. Grain kernels infested by *R. dominica* may show no exterior indication of hidden larvae. The hidden larvae immobilized in the residual grain commingled with the clean grain that passed through the infested boot and were discharged from the bucket elevator leg. For most cases, the

Table 5
The live adult insect densities (mean ± SE)[a] and mortality percentages from the residual grain and discharge grain treatments after an insecticide (10% cyfluthrin SC ultra) spray treatment for the slip-boot and 15 kg of clean wheat was transferred over the insecticide-treated boot for the boot hold times 0, 8, 16, and 24 wk.

Sample location	Insect species and total	Density (insect/kg), % mortality	Boot hold time (wk)			
			0	8	16	24
Boot	*R. dominica*	Density	147.1 ± 73.2	199.2 ± 56.8	163.4 ± 70.3	214.4 ± 51.6
		% Mortality	100 ± 0	100 ± 0	100 ± 0	100 ± 0
	T. castaneum	Density	117.8 ± 18.3	130.9 ± 18.8	63.1 ± 8.8	230.3 ± 69.1
		% Mortality	100 ± 0	100 ± 0	100 ± 0	100 ± 0
	C. ferrugineus	Density	178.8 ± 88.9	92.0 ± 10.8	97.6 ± 21.5	72.9 ± 26.5
		% Mortality	90 ± 1 0	100 ± 0	100 ± 0	100 ± 0
	Total	Density	147.9 ± 34.8	140.7 ± 23.5	107.1 ± 25.9	172.5 ± 36.1
		% Mortality	97.2 ± 0	100 ± 0	100 ± 0	99 ± 0.1
Discharge	*R. dominica*	Density	0.4 ± 0.2	0 ± 0	0.2 ± 0.1	0 ± 0
		% Mortality	52.4 ± 0.3	0 ± 0	66.7 ± 0.3	0 ± 0
	T. castaneum	Density	1.0 ± 0.5	0.1 ± 0.1	0.2 ± 0.2	0 ± 0
		% Mortality	77.8 ± 0.2	66.7 ± 0.3	33.4 ± 0.3	0 ± 0
	C. ferrugineus	Density	0 ± 0	0 ± 0	0 ± 0	0 ± 0
		% Mortality	0 ± 0	0 ± 0	0 ± 0	0 ± 0
	Total	Density	0.5 ± 0.2a	0.1 ± 0.1b	0.1 ± 0.1b	0.1 ± 0.1b
		% Mortality	54 ± 0.2	33 ± 0.2	33 ± 0	33 ± 0.2

[a] The mean adult insect densities and mortality percentages were analyzed separately by location; lower-case letters represent the differences in insect species among the boot hold times that were significant as determined through a one-way ANOVA and the Ryan–Einot–Gabriel–Welsch multiple range test (REGWQ), which were used to separately analyze such treatment differences ($P \leq 0.05$).

Table 6
Total adult insect densities (mean ± SE)[a] and mortality percentages from the residual grain and discharge grain treatments after an insecticide (10% cyfluthrin SC ultra) spray treatment for the slip-boot and 15 kg of clean corn was transferred over the insecticide-treated boot with the boot hold times 0, 8, 16, and 24 wk.

Sample location	Insect species and totals	Density (insect/kg), % mortality	Boot hold time (wk)			
			0	8	16	24
Boot	*S. oryzae*	Density	237.7 ± 82.2b	400.0 ± 105.5b	480.6 ± 182b	5935.7 ± 2031.0a
		% Mortality	0 ± 0B	0 ± 0B	96 ± 0A	33 ± .3AB
	T. castaneum	Density	177.2 ± 36.7	237.2 ± 43.8	62.4 ± 18.6	97.3 ± 56.6
		% Mortality	33.3 ± 0.3	0 ± 0	90.9 ± 0	66.5 ± 0.3
	O. surinamensis	Density	120.7 ± 40.5	192.4 ± 22.8	88.9 ± 36.7	89.2 ± 89.2
		% Mortality	33 ± 0.3	0 ± 0	98.5 ± 0	33 ± 0.3
	Total	Density	178.5 ± 33.1	276.6 ± 46.1	210.7 ± 86.5	2040.7 ± 1137
		% Mortality	22.3 ± 14.6BC	0 ± 0C	95.1 ± 0A	44.5 ± 0.1B
Discharge	*S. oryzae*	Density	1.6 ± 0.6	0.2 ± 0.2	0.5 ± 0.2	24.9 ± 11.0
		% Mortality	0 ± 0	0 ± 0	61 ± 0.2	36 ± 0.3
	T. castaneum	Density	0 ± 0	0.1 ± 0.1	0 ± 0	0 ± 0
		% Mortality	0 ± 0	0 ± 0	0 ± 0	0 ± 0
	O. surinamensis	Density	0.1 ± 0	0.1 ± 0	0 ± 0	0 ± 0
		% Mortality	0 ± 0	0 ± 0	0 ± 0	0 ± 0
	Total	Density	0.5 ± 0.3	0.1 ± 0.1	0.2 ± 0.1	8.3 ± 5.2
		% Mortality	0 ± 0	0 ± 0	31.5 ± 0.1	11.9 ± 0.1

[a] The mean adult insect densities and mortality percentages were analyzed separately by location; the lower-case letters represent the differences in insect densities among the boot hold times that were significant and the upper-case letters represent the differences in insect mortality among the boot hold times that were significant, as determined using a one-way ANOVA and the Ryan–Einot–Gabriel–Welsch multiple range test (REGWQ) to separately analyze the treatment differences ($P \leq 0.05$).

numbers of adult progeny produced were reduced in the 16 and 24 wk boot-holding times compared to the 8 wk boot-holding times (Table 1), perhaps due to depleted food resources or competition due to over-population or cannibalism. Sinha and Watters (1985) reported that *T. castaneum* adults and larvae are omnivorous and cannibalistic insects. Cannibalism has been detected in crowded and over-populated areas, where the insects feed on eggs and pupa (occasionally larvae) from their own or other species, so reducing the adult progeny produced.

The mean number of adult progeny produced in the infested corn boot and discharge treatments did not differ among the insect densities and boot-holding times, likely due to the higher standard errors observed among the treatment combinations. The mean number of adult progeny in the corn boot peaked at the 8 wk boot-holding time, irrespective of the insect density, and the majority of insects was *S. oryzae*. The residual and discharged grain transferred over the infested corn boot typically yielded more *S. oryzae* than *T. castaneum* or *O. surinamensis* for each insect density and boot-holding time. In a few cases, the number of *T. castaneum* was greater for the boot lot and discharge treatment.

The percent of total insects in the boot residual grain for *T. castaneum* and *O. surinamensis* was reduced after the initial boot hold time (0 wk), before rebounding during the 24 wk boot hold time at each insect density level (Table 4). The reduction prior to the rebound may be due to over-population, inter- and intra-specific competition, and/or cannibalism. However, for *S. oryzae*, the percent of total insects increased during the 8 and 16 wk boot-holding times, before being reduced during the 24 wk boot hold time at each insect density level, which may have been due to the reduced number of whole grain kernels available after the heavy infestations at 8 and 16 wk.

Sitophilus oryzae develop through immature life stages inside the grain kernel and cannot escape as the elevator bucket passes over the residual infested corn boot lot. Therefore, more *S. oryzae* were collected from the discharge treatments, and the insects in immature life stages developed into adults by 8 wk. Similarly, many *S. oryzae* were detected in the boot lots due to less competition because the life stages develop in the kernels, not outside of the kernels, as with *T. castaneum* or *O. surinamensis*.

Results from studies by Samson and Parker (1989) and Arthur (1994) showed that both higher application rates of cyfluthrin and longer exposure intervals were required to yield the same mortality control levels for *S. oryzae*. Arthur (1998) showed that cyfluthrin residues persist on concrete surfaces for 24 wk. Our results show *S. oryzae* and total insect counts have significantly higher mortality rates during the 16 wk boot hold time for corn samples (Table 6). The greatest insect mortality was detected after 16 wk from both the boot lot and discharge treatments. In the latter case, mortality may have been due to initial exposure in the boot and/or due to impact from the moving grain, especially for the external feeders.

Infested grain accumulation in the elevator boot contributes insect commingling when uninfested grain moves through the elevator leg and is transferred to additional locations, such as storage bins, for either short- or long-term storage. The numbers of insect in the boot and in the discharged grain correlated due to commingling. Additionally, our results suggest that cleaning the bucket elevator leg boot will aid in greatly reducing insect pest infestation levels for the boot area. Insect pest infestation levels and insect pest commingling in the boot area could be reduced through cleaning the bucket elevator leg boot area monthly with residual grain removal and disposal. The time between monthly cleanings for the boot area is approximately the same as the shortest length of time for one insect generation or life cycle. Additionally, an insecticide treatment in the elevator boot would complement such cleaning and reduce insect infestations. Our recommended sanitation practices in the elevator boot and pit area are consistent with those proposed by Good (1937) in cleaning the boot area frequently and fumigating it to manage insect pests in flour mills.

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