

# Efficacy of Heat Treatment for Disinfestation of Concrete Grain Silos

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**ABSTRACT** Field experiments were conducted in 2007 and 2008 to evaluate heat treatment for disinfestations of empty concrete elevator silos. A Mobile Heat Treatment Unit was used to introduce heat into silos to attain target conditions of 50°C for at least 6 h. Ventilated plastic containers with a capacity of 100 g of wheat, *Triticum aestivum* L., held *Rhyzopertha dominica* (F.) (Coleoptera: Bostrichidae) and *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae). Polyvinyl chloride containers with a capacity of 300 g of wheat held adults of *Liposcelis corrodens* (Heymons) (Psocoptera: Liposcelididae) and *Liposcelis decolor* (Pearman), which were contained in 35-mm Petri dishes within the grain. Containers were fastened to a rope suspended from the top of the silo at depths of 0 m (just under the top manhole), 10 m, 20 m, and 30 m (silo floor). When the highest temperature achieved was ≈50°C for 6 h, parental mortality of *R. dominica* and *T. castaneum*, and both psocid species was 98–100%. Progeny production of *R. dominica* occurred when there was parental survival, but in general *R. dominica* seemed less impacted by the heat treatment than *T. castaneum*. There was 100% mortality of *L. corrodens* at all depths in the heat treatments but only 92.5% mortality for *L. decolor*, with most survivors located in the bioassay containers at the top of the silo. Results show wheat kernels may have an insulating effect and heat treatment might be more effective when used in conjunction with sanitation and cleaning procedures.

**KEY WORDS** *Rhyzopertha dominica*, *Tribolium castaneum*, *Liposcelis corrodens*, *Liposcelis decolor*, heat treatment

Two major pests of stored grain are *Rhyzopertha dominica* (F.) (Coleoptera: Bostrichidae) and *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae). The former is a major internal-infesting pest of whole cereal, whereas the latter is an important external-infesting pest of cereals and cereal products and is a major pest of mills (Rees 2004). These pests are commonly controlled using insecticides, but development of insecticide resistance (Zettler and Cuperus 1990) and government regulation of insecticides, consumer demand for insecticide residue-free products, and broader commercial needs call for the development of chemical-free management approaches for these pests (Phillips and Throne 2010). Psocids (Psocoptera) contain species in the genus *Liposcelis* that are major pests of stored products (Rees 2004, Phillips and Throne 2010). Before 1990, psocids were not consid-

ered serious pests of stored products; however, in Australia, they have become the most frequently encountered storage pest in some areas (Rees 2003). The increased concerns regarding psocids can be attributed to their varied response to management tactics that have been developed for coleopteran pests, e.g., some psocid species are resistant to residual insecticides and the fumigant phosphine (Nayak et al. 1998, 2002a,b, 2003; Nayak 2006). In addition, markets increasingly view psocids as contaminants (Kučerová 2002, Nayak 2006).

Stored-product insects that infest newly harvested stored grain can rapidly increase in numbers given the right environmental factors (Hagstrum 1989). A common insecticidal treatment worldwide for management of stored grain is fumigation with phosphine (Taylor 1989, Chaudhry 2000). In addition, phosphine is recommended for the disinfestations of empty grain storage structures. Phosphine is cheap, easy to apply, leaves no residues, and can be used in a wide range of storage types and commodities (Nayak and Collins 2008). However, phosphine resistance in stored-product insect pests is already a major problem in many countries, with very high levels of resistance found in some parts of Asia and Africa (Mills 1983, Taylor and Halliday 1986, Taylor 1989, Zettler 1997, Sayaboc et al. 1998) and in the United States as well (Zettler and Cuperus 1990). Therefore, alternatives to phosphine

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fumigation could reduce selection pressure and reduce the frequency of resistance alleles.

Heat treatment is an ecologically based technique that can be used as an alternative to pesticides for the control of stored-product insect pests in food processing facilities and empty grain storages. Since the early 1900s, heat treatments have been recognized as an effective strategy for insect control in flour mills (Dean 1911, 1913). More recently, heat has been used to successfully control insect pests in grain processing facilities (Mahroof et al. 2003a, Roesli et al. 2003). During heat treatment, the temperature of the target structure is raised to 50–60°C and maintained at these elevated temperatures for 24–36 h to kill stored-product insects (Mahroof et al. 2003a,b).

Tilley et al. (2007) conducted studies that demonstrated the potential for using heat to disinfest empty steel grain storage bins. The bins used in these studies were of 109 MT-storage capacity (4,000 bushels), which are relatively small bins for storing grain on-farm. Another study by Beckett and Qaisrani (2003) investigated the use of heat to disinfest empty 50-MT metal silos. They suggested that heat disinfestation is effective and economical when high inlet temperatures are used to produce rapid heating to a temperature where complete insect mortality is guaranteed. In the United States, concrete silos are widely used for grain storage in most country and terminal elevators (Bailey 1992). There is no published study in the scientific literature evaluating heat treatment for managing insect pests in empty concrete silos. Several recent studies have documented extensive insect infestations in residual grain found in the bottoms of elevator silos and in selected areas within the elevator environment (Reed et al. 2003, Arthur et al. 2006). Therefore, the objective of this study was to evaluate the efficacy of heat treatments for disinfestation of concrete silos of *R. dominica*, *T. castaneum*, and two psocid species, *Liposcelis corrodens* (Heymons) (Psocoptera: Liposcelididae) and *Liposcelis decolor* (Pearman).

## Materials and Methods

**Silos and Heat Application.** In total, six empty concrete silos located in Marshall, OK, were used for the experiment in 2007 and 2008. In 2007, heat treatment was conducted from 15 to 17 April and in 2008 from 29 April to 1 May. In both years, the silos were paired for testing so that a heated silo would not share a wall with a control silo on the day of testing. The silos were ≈32 m in height, with a diameter of 6 m. Each silo contained a manhole opening with a cover at the top and an access hole close to the bottom of the silo. Silos used for controls had no introduced heat.

A Mobile Heat Treatment Unit (model MHT-1500, TempAir, Burnsville, MN) with a heat output potential of 440 kW was used to generate heat, which was introduced into the access hole close to the bottom of each test silo via a flexible duct with holes to distribute air. The flexible duct was positioned so that heat would be distributed evenly throughout the silo. When the

temperature in the heat-treated silo reached 50°C, timing was initiated and heating was continued for the next 6 h after which the heater was turned off.

**Beetles.** *R. dominica* were reared on a mixture of 95% whole-wheat kernels and 5% Brewer's yeast (wt: wt) at 28°C and 65% RH, and *T. castaneum* were reared on a mixture of 95% all-purpose wheat flour and 5% Brewer's yeast at 28°C and 65% RH. Voucher specimens of *R. dominica* and *T. castaneum* that were used in this study are deposited at K. C. Emerson Entomology Museum at Oklahoma State University under lot numbers 104 and 105.

**Experimental arenas.** Arenas for the beetle mortality studies were plastic containers (5.7 cm in height and 6.4 cm in diameter, with a 3.8-cm hole cut in the screw-on lids. A screen (U.S. #40 mesh) was mounted over the holes for ventilation. Arenas for *R. dominica* comprised 80 g of infested wheat, *Triticum aestivum* L., plus 2.5 g of dust from the culture jars, which was presumed to contain eggs and neonates (immatures), 15 g of uninfested wheat, 1.5 g all-purpose wheat flour, and 50 adult beetles. For *T. castaneum*, arenas comprised 85 g of newly ground wheat, 1.5 g of flour infested with mixed age larvae and eggs from laboratory cultures, and 50 adult beetles. The arenas were fastened with plastic ties to a rope suspended from the top of the silo at depths of 0 m (just under the top manhole), 10 m, 20 m, and 30 m (silo floor). A HOBO temperature recording device (Onset Computer Corporation, Bourne, MA) also was attached to the rope near the insect containers to record temperature surrounding the containers. Grain temperature in the middle of the arenas was not measured during the 2007 experiment, but because of higher than expected insect survival, measurements were made during the 2008 experiment to determine whether the temperature in the arenas was congruent to that outside.

Ropes with the arenas fastened to them were placed in the silos to be tested on the afternoon before the testing began; testing began the next morning. After heating the heat-treated silo for 6 h at 50°C, the ropes with arenas were removed immediately and the arenas were taken to the laboratory for processing. Adult beetles were removed from the grain using sieves (U.S. Standard #10 sieve with 2-mm openings) and counted as live or dead. Moribund and dead adults were placed in a 9-cm petri dish containing a piece of filter paper moistened with 0.5 ml of water; these insects were then reevaluated after 24 h for recovery. The grain, from which all adult beetles had been removed, was returned to the arenas and placed in a growth chamber held at 28°C and 70% RH. The grain was sifted twice, after 2 and 4 wk, to remove any progeny present. These progeny (*T. castaneum* and *R. dominica*) were counted and summed over the 4-wk period. Three replications were completed, each on consecutive days in the spring and daytime temperatures during this period were consistent. A replication consisted of one heat treated silo and one silo under ambient conditions with no external heat source. The three temporal replications arise from the fact that only one replication was conducted on any given day

**Table 1. Temperature (Celsius) ranges and means ± SE in untreated (control) silos (n = 3)**

Depth (m)	2007		2008	
	Range	Mean	Range	Mean
0 (top)	23.2–31.1	25.2 ± 1.5a	14.9–32.8	23.2 ± 2.2a
10	21.3–29.1	23.0 ± 0.9b	13.3–27.9	20.4 ± 2.7b
20	20.2–31.5	22.2 ± 1.2b	12.9–25.2	19.5 ± 3.4b
30 (bottom)	15.6–22.5	19.4 ± 1.0c	12.2–24.8	17.3 ± 3.3c

Means within a column followed by different letters are significantly different. ANOVA results for 2007 and 2008 temperatures were  $F = 16.2$ ;  $df = 3, 6$ ;  $P < 0.01$  and  $F = 42.6$ ;  $df = 3, 6$ ;  $P < 0.01$ , respectively.

and the study was conducted over three consecutive days.

**Psocids.** Psocids were used in only the 2008 heat treatment. *L. decolor* and *L. corrodens* cultures used in the study were started with insects collected during summer 2006. Individuals for starting the *L. decolor* culture were collected from wheat stored in steel grain storage bins at the Center for Grain and Animal Health Research in Manhattan, KS, and those for *L. corrodens* culture from a grain elevator at the same location. Voucher specimens of *L. corrodens* and *L. decolor* used have been deposited in the Kansas State University Museum of Entomological and Prairie Arthropod Research under lot numbers 204 and 205. Psocids were reared on a mixture of 93% cracked hard red winter wheat, 5% wheat germ, and 2% Rice Krispies (wt:wt) in 0.473-liter glass canning jars covered with mite-proof lids, and cultures were maintained at 30°C and 75% RH.

**Experimental arenas.** Arenas for psocids were constructed of a 10-cm length of 7.6-cm-diameter plastic (polyvinyl chloride) pipe with two end caps. Each end cap had a 3.8-cm hole cut in the center with a screen (U.S. #40 mesh) mounted over the hole for ventilation. Each arena was filled with 300 g of uninfested wheat. Two 35-mm petri dishes, each containing 20 adult female *L. decolor* or *L. corrodens*, 0.5 g of colored psocid diet (Opit and Throne 2008), and 10 particles of cracked hard red winter wheat were placed in each arena. Psocid arenas were suspended at the same depths and adjacent to the beetle arenas as already described. The numbers of live and dead psocids in each petri dish were determined immediately after the experiment was terminated. The experiment had three temporal replications over three consecutive days; each time a different pair of silos was used.

**Data Analysis.** The design for data analysis was a split plot design with temporal replications as blocks, heat or no heat as main effects or treatments, and depths from which insects were suspended as the subplot treatments. Data were percentages of dead insects and number of progeny, which were analyzed by species. The PROC UNIVARIATE statement with the PLOTS option was first used to test the distribution of the data before PROC GLM was used to perform analysis of variance (ANOVA) (SAS version 9.2, SAS Institute, Cary, NC) to determine the effect of heat, depth, and their interaction on insect mortality and progeny production. Percentage of mortality data were transformed using the arcsine square-root transformation to stabilize variances, but untransformed percentages and standard errors are reported to simplify interpretation. Despite the fact that depth had no statistically significant effect on the mortality of *L. corrodens* (at  $\alpha = 0.05$ ), we were concerned that the mortalities of psocids in the control treatment may be different. Therefore, we used the least significant difference (LSD) test for planned comparisons notwithstanding the nonsignificant  $F$  value (Steel and Torrie 1960). Similarly, we were concerned that mortality of *L. decolor* at the top of the heated silos was considerably lower than at 10, 20, and 30 m below the top. Therefore, we used the LSD test for planned comparisons notwithstanding the nonsignificant  $F$  value (Steel and Torrie 1960).

**Results**

**Silo Temperatures in 2007.** In the control (unheated) silos, mean ambient temperatures decreased with depth from 25.2°C at the top of the bins to 19.4°C at the bottom (30 m below the top) and had a range of 15.6–31.5°C (Table 1). The reverse was observed in heated silos where mean temperatures increased with depth from the top (43.6°C) to the bottom (50.6°C) (Table 2), with a range of 17.5–53.5°C. In the heated silos, a target ambient temperature of 50°C was more rapidly attained with increasing depth from the top to the bottom (4.7–2.4 h) (Table 3).

**Silo and Container Temperatures in 2008.** In the control silos, mean ambient temperatures decreased with depth from 23.2°C at the top of the silos to 17.3°C at the bottom (Table 1) with a range of 12.2–32.8°C. In the heated silos, mean temperatures increased with depth from the top (46.9°C) to 20 m (51.3°C) and then

**Table 2. Temperatures (Celsius) (means ± SE) in the heated silos (n = 3)**

Depth (m)	2007		2008		
	Ambient	Ambient	<i>T. castaneum</i> containers	<i>R. dominica</i> containers	Psocid containers
0 (top)	43.6 ± 1.5a	46.9 ± 4.0a	42.2 ± 6.1b	42.7 ± 7.0b	40.6 ± 7.8b
10	45.3 ± 0.3a	49.8 ± 5.8a	45.9 ± 9.4b	46.2 ± 9.5b	
20	48.0 ± 1.1a	51.3 ± 5.7a	51.2 ± 10.5a	51.7 ± 11.1a	49.1 ± 11.6a
30 (bottom)	50.6 ± 9.5a	49.9 ± 8.1a	51.2 ± 10.5a	51.7 ± 11.2a	49.1 ± 11.6a

Means within a column followed by different letters are significantly different. ANOVA results for 2007 and 2008 ambient temperatures were ( $F = 1.3$ ;  $df = 3, 6$ ;  $P = 0.36$ ), ( $F = 0.84$ ;  $df = 3, 6$ ;  $P = 0.52$ ), ( $F = 11.2$ ;  $df = 3, 6$ ;  $P < 0.01$ ), ( $F = 14.42$ ;  $df = 3, 6$ ;  $P < 0.01$ ), and ( $F = 15.24$ ;  $df = 2, 4$ ;  $P < 0.02$ ), respectively.

**Table 3.** Time (mean  $\pm$  SE) to attain 50°C under ambient conditions and in containers with *T. castaneum*, *R. dominica*, and psocids in concrete silos

Depth (m)	2007		2008		
	Ambient	Ambient	<i>T. castaneum</i> containers	<i>R. Dominica</i> containers	Psocid containers
0 (top)	4.7 $\pm$ 0.4a	3.3 $\pm$ 0.8a	6.3 $\pm$ 0.6a	6.3 $\pm$ 0.6a	
10	3.7 $\pm$ 0.3ab	2.2 $\pm$ 1.16a	4.3 $\pm$ 1.0ab	4.1 $\pm$ 1.1ab	
20	2.8 $\pm$ 0.1b	1.8 $\pm$ 1.0a	2.8 $\pm$ 1.1b	2.8 $\pm$ 1.1b	3.6 $\pm$ 1.2a
30 (bottom)	2.4 $\pm$ 0.6b	1.8 $\pm$ 1.0a	2.8 $\pm$ 1.1b	2.8 $\pm$ 1.1b	3.6 $\pm$ 1.2a

Means within a column followed by different letters are significantly different. ANOVA results for ambient (2007) and ambient (2008), and *T. castaneum*, *R. dominica*, and psocid containers were ( $F = 5.8$ ;  $df = 3, 8$ ;  $P = 0.02$ ), ( $F = 0.6$ ;  $df = 3, 8$ ;  $P = 0.64$ ), ( $F = 2.9$ ;  $df = 3, 8$ ;  $P = 0.10$ ), ( $F = 2.8$ ;  $df = 3, 8$ ;  $P = 0.11$ ), and ( $F = 0.0$ ;  $df = 1, 4$ ;  $P = 1.0$ ), respectively.

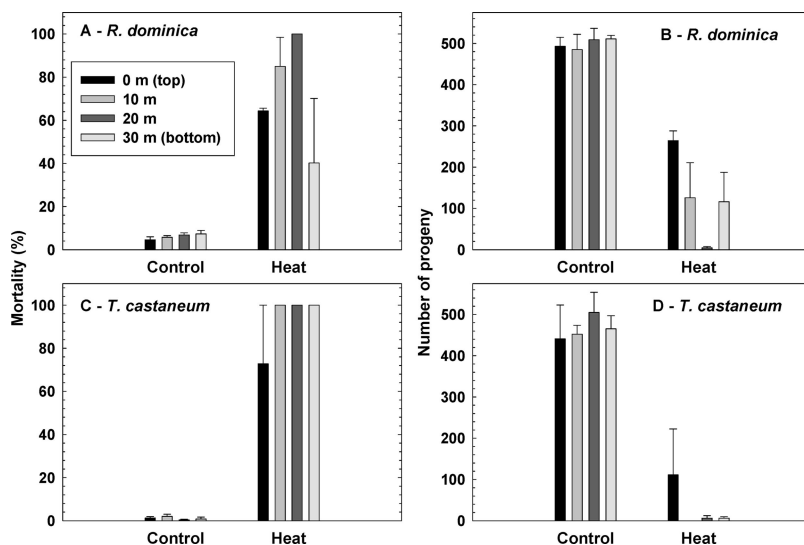
decreased to 49.9°C at the bottom (Table 2), and had a range of 12.3–63.5°C. The target temperature of 50°C was more rapidly attained with increasing depth in the heated silos (Table 3). In the *T. castaneum* containers and in the *R. dominica* containers, the target ambient temperature of 50°C was more rapidly attained with increasing depth from the top to bottom (Table 3). In the psocid containers, a temperature of 50°C was not attained at the top and no data were collected at a depth of 10 m because the HOBO malfunctioned. At 20 m and at the bottom, the target of 50°C was attained after 3.6 h (Table 3).

**Beetles, 2007. *R. dominica*.** The pattern of adult beetle mortality at the four silo depths was similar in the control and heated silos ( $F = 2.9$ ;  $df = 3, 12$ ;  $P = 0.08$ ; Fig. 1A). Depth had no significant effect on mortality ( $F = 2.8$ ;  $df = 3, 12$ ;  $P = 0.08$ ). As expected, heat treatment affected mortality ( $F = 74.3$ ;  $df = 1, 2$ ;  $P < 0.01$ ; Fig. 1A); mean mortalities in the control and heated silos were  $6.1 \pm 1.0$  and  $72.4 \pm 9.7\%$ , respectively. Progeny production of *R. dominica* at the four silo depths was different in controls and treatments ( $F = 5.5$ ;  $df = 3, 12$ ;  $P < 0.02$ ; Fig. 1B). This significant interaction between heat treatment and depth in relation to progeny production is a result of a similar

number of progeny (485–511) produced in the arenas from the four depths in the control silos and variable progeny production in the arenas from the four depths in the heated silos (Fig. 1B).

***T. castaneum*.** The pattern of adult beetle mortality at the four silo depths was similar in the control and heated silos ( $F = 1.1$ ;  $df = 3, 12$ ;  $P = 0.40$ ; Fig. 1C). Depth had no significant effect on mortality ( $F = 0.9$ ;  $df = 3, 12$ ;  $P = 0.49$ ). As with *R. dominica*, heat treatment affected mortality ( $F = 205.7$ ;  $df = 1, 2$ ;  $P < 0.01$ ; Fig. 1C); mean mortalities in the control and heated silos were  $1.1 \pm 0.4$  and  $93.2 \pm 6.8\%$ , respectively. The pattern of *T. castaneum* progeny produced at the four silo depths was similar in the control and heated silos ( $F = 0.8$ ;  $df = 3, 12$ ;  $P = 0.52$ ; Fig. 1D). Depth had no significant effect on number of progeny ( $F = 0.5$ ;  $df = 3, 12$ ;  $P = 0.71$ ), whereas heat treatment affected progeny production ( $F = 128.1$ ;  $df = 1, 2$ ;  $P < 0.01$ ; Fig. 1C); mean numbers of progeny in the control and heated silos were  $465.9 \pm 23.1$  and  $31.0 \pm 27.6$ , respectively.

**Beetles, 2008. *R. dominica*.** The pattern of adult beetle mortality at the four silo depths was different in the control and heated silos ( $F = 7.9$ ;  $df = 3, 12$ ;  $P < 0.01$ ; Fig. 2A). This significant interaction between



**Fig. 1.** Effects of heat treatment on *R. dominica* adult mortality (A) and progeny production (B) and on *T. castaneum* adult mortality (C) and progeny production (D) in 2007.

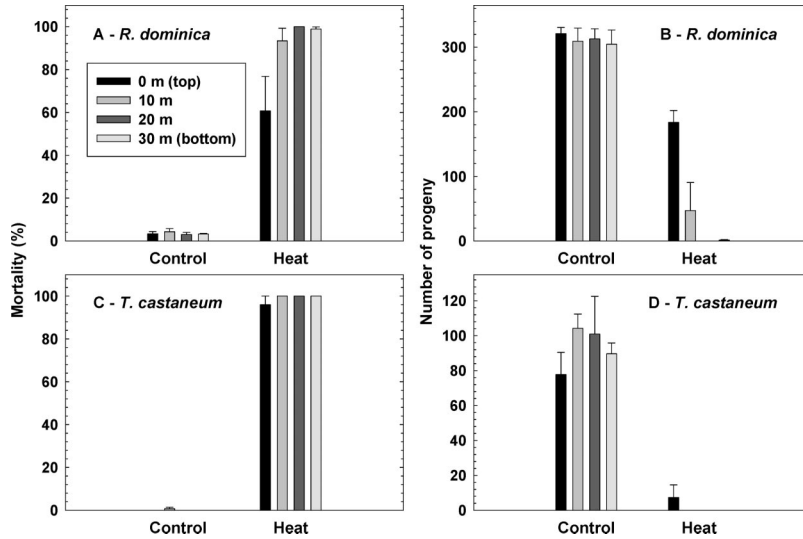


Fig. 2. Effects of heat treatment on *R. dominica* adult mortality (A) and progeny production (B) and on *T. castaneum* adult mortality (C) and progeny production (D) in 2008.

treatment and depth in relation to adult beetle mortality is a result of similar mortality of 3–4% occurring at the four depths in the control silos and mortality increasing from 61% at the top of the heated silos to 100% at depths of 20 m and at the bottom (Fig. 2A). The pattern of number of *R. dominica* progeny produced at the four silo depths was different in the control and heated silos ( $F = 11.0$ ;  $df = 3, 12$ ;  $P < 0.01$ ; Fig. 2B). As in 2007, progeny production in untreated controls at the four depths was similar (304–321), whereas progeny production in the heated silos decreased from an average of 184 at the top of the heated silos to few or none at the bottom (Fig. 2B).

*T. castaneum*. The pattern of adult beetle mortality at the four silo depths was similar in the control and heated silos ( $F = 0.8$ ;  $df = 3, 12$ ;  $P = 0.53$ ; Fig. 2C). Depth had no significant effect on mortality ( $F = 1.2$ ;  $df = 3, 12$ ;  $P = 0.34$ ), but heat treatment did ( $F = 2318.5$ ;  $df = 1, 2$ ;  $P < 0.01$ ; Fig. 2C). Mean mortalities in the control and heated silos were  $0.2 \pm 0.18\%$  and  $99.0 \pm 1.0\%$ , respectively. The pattern of *T. castaneum* progeny production in the arenas from the four silo depths was similar in the control and heated silos ( $F = 1.6$ ;  $df = 3, 12$ ;  $P = 0.25$ ; Fig. 2D). Depth had no significant effect on progeny production ( $F = 0.1$ ;  $df = 3, 12$ ;  $P = 0.95$ ), but heat treatment did ( $F = 507.2$ ;  $df = 1, 2$ ;  $P < 0.01$ ; Fig. 2D). Mean numbers of progeny in the control and heated silos were  $93.2 \pm 6.6$  and  $1.8 \pm 0.38$ , respectively.

*Psocids*. The pattern of *L. corrodens* mortality at the four silo depths was similar in the control and heated silos ( $F = 1.0$ ;  $df = 3, 12$ ;  $P = 0.44$ ; Table 4). Depth had no significant effect on mortality ( $F = 1.0$ ;  $df = 3, 12$ ;  $P = 0.44$ ), but heat treatment did ( $F = 287.7$ ;  $df = 1, 2$ ;  $P < 0.01$ ; Table 4). Mean mortalities in the control and heated silos were  $38.3 \pm 9.0$  and  $100.0\%$ , respectively. Similar results were found for *L. decolor* where the pattern of mortality at the four silo depths was

similar in the control and heated silos ( $F = 1.9$ ;  $df = 3, 12$ ;  $P = 0.19$ ; Table 4). Depth had no significant effect on mortality ( $F = 1.9$ ;  $df = 3, 12$ ;  $P = 0.18$ ) but heat treatment did ( $F = 150.5$ ;  $df = 1, 2$ ;  $P < 0.01$ ; Table 4). Mean mortalities in the control and heated silos were  $15.8 \pm 4.8$  and  $92.5 \pm 5.4\%$ , respectively.

Discussion

Based on the results of this study, the Mobile Heat Treatment Unit with a heat output potential of 440 kW, can produce enough heat in concrete silos to maintain temperatures of 50°C for 6 h—the target conditions of the heat treatment. With the exception of the bottom of the silos, slightly higher temperatures were attained during heat treatment in 2008 compared

Table 4. Effect of heat treatment on mortality of *L. corrodens* and *L. decolor*

Species	Treatment	Depth (m)	Mortality (%)
<i>L. corrodens</i>	Control	0 (top)	31.7 ± 16.4a
		10	46.7 ± 26.0a
		20	43.3 ± 15.9a
		30 (bottom)	31.7 ± 22.4a
	Heat	0	100.0 ± 0.0b
		10	100.0 ± 0.0b
<i>L. decolor</i>	Control	0	18.3 ± 15.9a
		10	13.3 ± 1.7a
		20	11.7 ± 9.3a
		30	20.0 ± 11.5a
	Heat	0	70.0 ± 17.3a
		10	100.0 ± 0.0a
		20	100.0 ± 0.0a
		30	100.0 ± 0.0a

For each species, means within a column followed by different letters are significantly different.

with 2007 despite the silos being a little cooler in 2008. Because of the heat introduction at the bottom of silos, the venting of the heating gas at the top of the heated silos, and air draft outside the silos, temperatures in heated silos increased with depth, i.e., target ambient temperatures of 50°C were not achieved at the top of the silos. Ways of mitigating this heat loss need to be found for heat treatments in concrete silos to achieve the desired target conditions.

We found that when temperature was  $\approx 50^\circ\text{C}$  for 6 h, parental mortality of *R. dominica* and *T. castaneum*, and both psocid species was 98–100%. The production of beetle progeny in cases where parental mortality was as high as 98–100% is explained by the fact that 85 g of infested wheat and 2.5 g of dust from the *R. dominica* culture and 1.5 g of flour from the *T. castaneum* culture comprised the media used in containers for these two species. It is very likely the aforementioned infested wheat, dust, and flour had immature stages of these two species that may have survived the heat treatment and were counted two and 4 wk after treatment. In addition, adults could easily have laid eggs before they died. This is because containers were placed in the silos the afternoon before testing began (testing began the next morning), which means adult insects had several hours to lay eggs before they got killed or were removed during counting.

In general, parental mortality of *R. dominica* was less than parental mortality of *T. castaneum*, resulting in greater progeny production of *R. dominica* compared with *T. castaneum*. Previous studies have indicated that *R. dominica* has higher progeny production at 32 than at 27°C, and may mean that it is less impacted by elevated temperatures compared with *T. castaneum* (Vardeman et al. 2006, Chanbang et al. 2007). Actual heat tolerance of these species could be determined by examining their lag periods (time in minutes where their survival is 100%) (Boina et al. 2008) or by estimating lethal times (LTs), for example,  $LT_{50}$  and  $LT_{99}$  (Finney 1971). In addition, the grain kernels apparently offered some protection for immature *R. dominica*. Even though the target temperature of 50°C was attained at most of the silo depths some progeny production occurred, which shows the insulating properties of the wheat in which insects were placed. We found that the 86.5, 99, and 300 g of wheat, in which insects were placed, provided good insulation from heat. Temperature reduction in insect containers was proportional to the amount of wheat placed in them, i.e., greater insulation in the psocid containers compared with the beetle containers. This result emphasizes the importance of sanitation and cleaning before heat treatment to remove organic material that could help insulate insects from heat. *R. dominica* is the most serious insect pest of stored small grains (Phillips and Throne 2010) and our finding that it tolerates recommended heat treatment conditions should be considered when applying heat to empty grain silos for pest control.

In a study that investigated the use of heat to disinfest 50-MT metal silos, Beckett and Qaisrani (2003) found that a temperature of 54°C was sufficient to kill

all *T. castaneum* adults and that grain temperatures of 53.4 and 55.2°C for periods of 4 and 3 h, respectively, caused 99.99% mortality of the earliest immature stages of *R. dominica*. Based on this information, a temperature of 54°C for 6 h would have, perhaps, provided complete mortality of all stages of *T. castaneum* and *R. dominica* and adult *L. decolor* and *L. corrodens* during the current study. Beckett and Qaisrani (2003) also suggest that heat disinfestation is effective and economical when high inlet temperatures are used to produce rapid heating to a temperature where complete mortality is guaranteed.

Heat treatment is effective against *L. decolor* and *L. corrodens*. We found *L. decolor* to be less impacted by heat than *L. corrodens*. This is because there was 100% mortality of *L. corrodens* in all depths in the heated bins whereas 30% survival of *L. decolor* occurred at the top of the silos where ambient and psocid container temperatures did not reach 50°C but were 46.9 and 40.6°C, respectively. Our results for *L. decolor* are consistent with those of Beckett and Morton (2003). Their research indicates eggs are the most heat-tolerant *Liposcelis* stage and eggs of *L. decolor* were more heat tolerant than those of *L. bostrychophila* and *L. paeta* at temperatures from 46 to 51°C. However, they found that below 46°C, *L. paeta* became considerably more tolerant than the other two species. Based on our results and those of Beckett and Morton (2003), *L. corrodens* seems to have a lower heat tolerance than *L. decolor*, *L. paeta*, and *L. bostrychophila*. The tolerance of the last three preceding species may point to their adaptation to warmer conditions; in fact, the relative hardness of *L. decolor* may be a key reason why the species thrives in the considerable temperature range of the southern Australian climate (Beckett and Morton 2003).

A possible means through which *Liposcelis* species such as *L. decolor* may tolerate heat is via the expression of small heat-inducible proteins (Guedes et al. 2008). In their study, Guedes et al. (2008) found higher variability and tolerance to heat shock stress in the stored-product psocid *L. entomophila* than in *Lepinotus reticulatus* Enderlein (Psocoptera: Trogiidae). Heat shock protein of 70 kDa (HSP 70) was not detected in either of the psocid species, but they found that *L. entomophila* expresses small heat-inducible proteins (23 and mainly 27 kDa) sharing a common epitope with HSP 70, which were not detected in *L. reticulatus* and seem to underlay the higher heat shock tolerance of *L. entomophila*. They concluded that the lack of heat-inducible proteins in *L. reticulatus* may be responsible for the adverse effects of high temperatures on this species. *L. decolor*, *L. entomophila*, *L. paeta*, and *L. rufa* have been shown to have higher optimal temperatures for development and will probably occur commonly in warmer environments (Gautam et al. 2010 and references therein). According to them, this observation may also explain why these species are commonly found in large numbers during warmer periods of the year when temperatures in grain storages are extremely high.

The mortalities of *L. corrodens* and *L. decolor* in the control silos were 38.3 and 15.8%, respectively. The higher mortality of *L. corrodens* compared with that of *L. decolor* may indicate that the latter is more tolerant to low relative humidity conditions that may have existed during the experiment than the former. According to Devine (1982), psocids maintain body water levels by absorbing atmospheric water vapor when relative humidity is  $\geq 60\%$ ; however, below this level, more water is lost than gained resulting in dehydration and death. Therefore, we suggest that it is likely that *L. decolor* may be better adapted at absorbing atmospheric water vapor at low relative humidities than *L. corrodens*.

As mentioned, psocid eggs are the most heat-tolerant stage (Beckett and Morton 2003). Therefore, it is quite likely that the treatments conducted would be less effective against mixed-age populations of psocids. This means temperatures of 50°C would have to be achieved and maintained for longer, and greater pre-treatment hygiene would be required for heat treatment to be effective.

In conclusion, heat treatment for empty elevator bins would help in the adoption of integrated pest management (IPM) strategies for stored-product insects (Hagstrum and Flinn 1996, Hagstrum and Subramanyam 2000). Reducing reliance on phosphine for empty silo fumigation also would be compatible with the IPM approach. In the disinfestations of empty grain storages, IPM programs could comprise sanitation and cleaning along with heat treatments, however, because the presence of residual grain could compromise efficacy, additional research to evaluate the insulating properties of small amounts of grain would be necessary. Perhaps a longer time period for heating or higher temperatures would be necessary to complete disinfestations, and a thorough sanitation and cleaning of the silo before heat treatment would undoubtedly increase efficacy.

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