Cost and Risk Analysis of Heat and Chemical Treatments

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ABSTRACT An economic evaluation of newly developed methods for disinfesting empty grain storage bins by heat treatment will be a useful tool for decision-making by grain storage managers. An economic empirical model of heat treatment and chemical applications was developed using minimization of costs at a target risk level associated with the grain-damaging insects *Tribolium castaneum* (Herbst), *Sitophilus oryzae* (L.), and *Rhyzopertha dominica* (F.). Risk was measured as a deviation below a target mortality goal (Target MOTAD). Insect mortality and air temperature during heat treatment were evaluated for empty storage bins with a full drying floor, along with a similar evaluation of insect mortality for two application rates of a contact pyrethroid insecticide, cyfluthrin 20% active ingredient (AI) wettable powder. A high-output propane heater (29 kW) had the lowest cost and risk level of all heating systems and produced 100% mortality in 2 h for the three insect species at all test locations. An electric duct-heater system (18 kW) also produced 100% mortality at all test locations after 40 h, but it had significantly higher costs. The other heating system configurations in the study had significantly higher risk levels of insect mortality, and the electric systems were not cost-effective. Both chemical rates had low costs and risk levels, with high mortality results.

KEY WORDS *Tribolium castaneum*, *Sitophilus oryzae*, *Rhyzopertha dominica*, heat treatment, risk analysis

Insect damage to stored on-farm grain is a risk the farmer assumes before filling a bin. Cleanup efforts before filling include sweeping and removal of debris inside and outside of the grain bin, plus treatment with contact insecticides applied to the bin floors and walls. The plenum below bins equipped with full perforated drying floors is generally inaccessible, however, allowing debris to accumulate and maintain ideal conditions for insect growth (Raney 1974). Removal of the perforated drying floor is not a common practice due to the amount of time and work required. The economic impact from the risk of insect damage to stored-products and the sanitation costs of cleanup efforts all influence the profit margins of a farming operation, and methods of disinfesting empty grain storage bins will vary for each individual operation. However, all on-farm grain storage has an associated risk from stored-product insects and an economic impact from potential losses due to direct damage to the grain.

Applying a registered insecticide to the walls and floors of empty bins supplements, but does not replace, cleanup efforts. Insecticide residues help control insects that may have remained in hard-to-clean cracks and crevices or beneath the perforated floor. Sprays should be applied to the point of runoff; applicators should thoroughly treat all cracks and crevices and around doors (Raney 1974). Directing extra spray to and through perforated flooring—carefully reading and following all label instructions—will provide some control of insects in the subfloor plenum, but maximum control of insects in this space requires fumigation or removal of the perforated floor and thorough cleanup. Although often effective, chemical spray and fumigants may pose a health or environmental risk, are usually toxic to species other than those they are intended to control, and the continued use of a single insecticide or class of insecticides often leads to resistance within insect populations (Subramanyam and Hagstrum 1995).

Heat treatments provide another option for disinfesting empty grain storage bins. A heat treatment target temperature of at least 50°C is needed for successful disinfestations (Wright et al. 2002). Mahroof et al. (2003) developed a time–mortality relationship for all stages of red flour beetle, *Tribolium castaneum* (Herbst), at elevated temperatures. Generally, mortality of each stage increased with an increase in temperature and exposure time. All life stages of *T. castaneum*, with the exception of young larvae, required

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<2 h of exposure time at elevated temperatures ≥50°C. Exposure for young larvae, at temperatures ≥50°C, required a minimum of 7.2 h. These data suggest that required treatment times to kill young larvae of *T. castaneum* should be approximately 5 to 6 h longer than for killing adults for bin treatments with temperatures at ≥50°C. Successful heat treatment of a grain bin with a drying floor requires a minimum temperature of 50°C in the subfloor plenum area, which is the critical area to target (Tilley et al. 2007). Failure to reach the minimum temperature in the subfloor plenum area will increase the risk of grain infestation.

Hardaker et al. (2004) defined risk in various ways. One definition of risk is to expose oneself to a significant chance of injury or loss. A risk of grain infestation exposes an operator to a significant degree of grain commodity loss. Hardaker et al. (2004) illustrates examples of risk with trade-offs between multi-objective decision analysis, and some of these objectives are modeled with a noneconomic aspect. A risk of grain infestation exposes an operator to a significant degree of grain commodity loss. During heat treatment, the decision maker plans to achieve a certain mortality goal—a percentage of dead insects that gives an acceptable level of risk of grain infestation. The risk of grain infestation in this situation can be modeled as the sum of all deviations below the target mortality goal set by the decision maker.

Target MOTAD Model. Currently, there is no literature available on the economic evaluation of heat treatment or an economic comparison to chemical application methods for disinfesting grain storage bins before filling. However, target minimization of total absolute deviations (MOTAD) is a two-attribute model of risk-and-return (Tauer 1983, Watts et al. 1984) that can be used to model the risk of grain infestation. Risk and return are directly related; an increase in return is associated with an increase in risk; conversely, a decrease in return is associated with a decrease in risk. Return is measured as net return or gross revenue less expenses (Kay et al. 2004). The Target MOTAD model examines the trade-off between net return and risk, which is measured as deviations below a target net return. This measure of risk is an analogous concept to measuring risk as deviations below a target mortality goal for heat treatments. It is common to use a graph to show the trade-off between risk and net return. The curves that are generated are typically referred to as frontiers and represent optimal solutions. To generate specific trade-off points for the Target MOTAD frontier, net return is maximized subject to a specific level of allowable deviations below a target net return. The frontier is traced out on a two-dimensional plot by changing the level of allowable deviations. The Target MOTAD model has a linear objective function and linear constraints. Thus, the model can be solved with a linear programming algorithm. Target MOTAD is a beneficial analytical tool, useful to decision makers who want to maximize expected return but are cautious about net returns falling below a critical target.

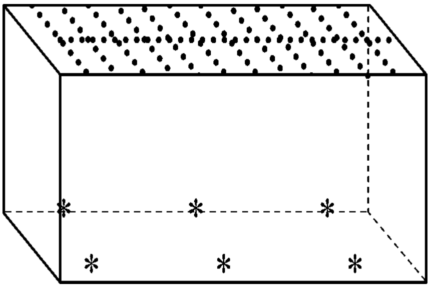

Fig. 1. Chemical treatment container, 0.23 m^2 by 0.35 m in depth, with a removable perforated metal top. The container was loaded with six arenas positioned at the (*) location. Formulated solution of 20% cyfluthrin WP was used to spray arenas with and without the metal top. Each arena, with a 4–5-mm concrete base, contained a total of 15 insects—five each of *T. castaneum*, *R. dominica*, and *S. oryzae*. The arenas were removed from the container after runoff of the formulated solution was complete and held in an environmental chamber, with insect mortality checked and recorded at three time intervals.

The objective of this research was to develop an empirical model for each heating system and chemical application that minimized costs at a target risk level associated with grain-damaging insects. A modified version of the Target MOTAD model is used in this study, with risk measured as deviations below a target mortality goal. The empirical model uses safety-first analysis, which typically focuses on downside risk. Safety-first rules can be used to rank choices by the decision maker and to examine the trade-off between two or more goals (Hardaker et al. 2004).

Materials and Methods

Overview of Heat Treatment. Heat treatment data were reported by Tilley et al. (2007) for empty grain storage bins with five different heating systems: three systems using electric power and two systems using propane as the heat source. The electric systems were 1) an 18-kW duct heater with an interior fan distribution system; 2) an 18-kW duct heater with recirculation of warm air; and 3) a 15-kW portable heater with recirculation. The two propane systems were 1) a 29-kW system and 2) a 19-kW system. Bin temperatures were recorded during treatments and insect mortality was assessed using arena cages containing live insects of *Tribolium castaneum* (Herbst), *Rhyzopertha dominica* (F.), and *Sitophilus oryzae* (L.) both above and below the drying floor.

Procedure for Chemical Treatments. Mortality data for conventional chemical application, comparable with the heat treatment data, were obtained using two plywood containers to simulate a perforated drying floor in a grain bin (Fig. 1). These containers measured 0.23 m^2 and were 0.35 m in depth to match the depth of the perforated floor in a grain bin. One container was fitted with a perforated metal floor at the top, simulating a grain bin with a perforated floor, whereas the other container was left open at the top. The perforated metal flooring was a type commonly used in grain bins that have drying systems. The perforated metal flooring had ≈3% open area available for chemical dispersion.

Each container was loaded with six insect arenas positioned either below the perforated metal floor (Fig. 1) or inside the open-top container. Each arena contained a 1.5-cm-deep concrete base and the vertical interior side wall was coated with fluon solution, which prevented the insects from escaping. Each arena was loaded with 15 adult insects, five from each of the following species: red flour beetle, *Tribolium castaneum* (Herbst); rice weevil, *Sitophilus oryzae* (L.); and lesser grain borer, *Rhyzopertha dominica* (F.).

Chemical solutions were formulated as follows. The chemical was cyfluthrin 20% Ultra wettable powder (WP), and the product label specifies a low and a high application rate. The low label rate is 9.5 g of product into 3,784 ml of water to treat an area measuring 94 m^2 (1,000 $feet^2$). The equivalent volume for the area of the plywood arena would be 40.8 ml/m^2 of this formulated spray. The high label rate is specified as 19 g of product in 3,784 ml, but the same doubling of active ingredient could be achieved by spraying double the water volume of spray formulated for the low rate, which would be 81.6 ml/m^2 of formulated product. These respective spray solutions were applied with a multipurpose, 2-gallon sprayer equipped with an R10C/GT 810895 nozzle (Truserv, Chicago, IL) to spray the floor surface of the bottom of the plywood containers.

The arenas remained in the test location ≈10 min to allow runoff of the solution from the perforated metal flooring to the bottom of the container where the subfloor arenas were located. Six control arenas were set up using the same method but with no chemical spray treatment. Insects were not provided with food or water. Both chemical-treated and control arenas were transferred to an environmental chamber and held at 27°C and 65% RH. Insect mortality was checked and recorded as described above at time intervals of 1, 2, and 4 h, respectively. Three separate replications were conducted for each test.

Data were analyzed separately for each chemical spray rate, with main effects of application rate and exposure time interval of each application, using the Statistical Analysis System (SAS) (SAS Institute 2002). The General Linear Models procedure was used for data analysis and to separate means when main effects were significant. Treatment means were separated for time intervals using the Waller–Duncan *k*-ratio *t*-test in SAS, with significance determined at $P < 0.05$. The chemical data were transformed at each independent location by taking the square root of each mean mortality to normalize variances. The transformed data allowed mean comparisons between low and high chemical rates for each species between floor levels of each time interval using a two-tail *t*-test at $P < 0.05$.

Empirical Risk Model. This study used a modified Target MOTAD model that minimized costs as opposed to maximizing returns as done in the conventional Target MOTAD model described above. There were three different lengths of tests selected to be suitable for each heating system (Tilley et al. 2007). The length of each test was 12, 27, and 40 h for the electric systems, and 2, 3, and 4 or 4, 6, and 8 h for the propane systems. Each test length corresponded to a time activity in the model. Cost was measured as the sum of the expected variable costs of each time activity multiplied by the individual activity proportion, in the model, for each optimal solution. The activity proportion is generated by the model for each optimal solution result.

Risk was measured as the sum of the deviations below the target mortality goal. Thus, risk was determined as the total cumulative percentage of all deviations below the target mortality goal for each of the 18 experimental measurements of mortality for each heating system test. This cumulative percentage of all deviations occurs in the model as the sum of 18 inequality constraints indicating percentage of mortality as seen in Table 1. Risk was measured consistently across all systems as a noneconomic objective within the framework of the empirical model. Mortality goal frontiers were traced out using the 99, 95, and 90% mortality-goal levels. These levels of mortality-goal frontiers were chosen to illustrate the trade-offs between cost and risk, and it would be straightforward to trace out the trade-offs for other mortality goals. A separate empirical model was used for each heating system or chemical treatment application used to reduce the level of grain-damaging insects in a grain bin. All of the risk-level boundaries of each frontier (Fig. 2) were determined using the empirical model. An upper and lower risk-level boundary was determined for each system. The upper risk boundary represented the risk level at the lowest possible cost for a given system ($41.42 for 99, 95, and 90% mortality-goal frontiers; Fig. 2). The lower risk boundary represented the lowest possible risk level for that system ($79.46 for 99, 95, and 90% mortality-goal frontiers; Fig. 2). Risk-level boundaries between the upper and lower limits were uniformly spaced for tracing out the frontier.

Although a combination of heat treatment and chemical application could be used, this is not commonly done in the field and was not investigated. The economic problem is to choose the most cost-effective approach to meet acceptable mortality results for grain-damaging insects. The economic problem was formulated as follows, with $E(z)$ being the expected variable cost of the planned heat treatment or chemical application and z representing all input variables that determine the expected variable cost:

$$\underset{xi}{Min}\ E(z) = \sum_{i=1}^{N} C_i X_i, \qquad [1]$$

Thus, the sum of the variable costs over all activities is minimized subject to three conditions:

$$\sum_{j=1}^{j} d_j = T, \qquad [2]$$

Table 1. Empirical model with minimization of variable costs for three time-period activities

Constraint - species - location	Time (h)			Deviations			Sum of deviations	Sum product	Inequality sign	Mortality goal
	12	27	40	d_1^-	. . .	d_{18}^-				
1 - RW - above	1	1	1	1			0.00	1.00	≥	0.95
2 - RW - below	0.96	1	1				0.00	0.99	≥	0.95
3 - RW - above	1	1	1				0.00	1.00	≥	0.95
4 - RW - below	1	1	1				0.00	1.00	≥	0.95
5 - RW - above	1	1	1				0.00	1.00	≥	0.95
6 - RW - below	1	1	1				0.00	1.00	≥	0.95
7 - RFB - above	1	1	1				0.00	1.00	≥	0.95
8 - RFB - below	0.44	0.64	0.80				0.38	0.95	≥	0.95
9 - RFB - above	1	1	1				0.00	1.00	≥	0.95
10 - RFB - below	0.84	0.80	0.80				0.14	0.95	≥	0.95
11 - RFB - above	1	1	1				0.00	1.00	≥	0.95
12 - RFB - below	0.40	0.80	0.84				0.29	0.95	≥	0.95
13 - LGB - above	1	1	1				0.00	1.00	≥	0.95
14 - LGB - below	0.40	0.60	0.84				0.42	0.95	≥	0.95
15 - LGB - above	1	1	1				0.00	1.00	≥	0.95
16 - LGB - below	0.80	0.80	0.80				0.15	0.95	≥	0.95
17 - LGB - above	1	1	1				0.00	1.00	≥	0.95
18 - LGB - below	0.40	0.80	0.80			1	0.28	0.95	≥	0.95
Sum of deviations				1	. . .	1	1.66			
Sum activity proportion								1.00		
Min. variable costs										54.77

LGB, lesser grain borer; RFB, red fluor beetle; RW, rice weevil.

The three activity levels indicate the proportion of operating hours for each activity. The model has 18 inequality constraints indicating percentage of mortality for each activity. Variable costs (41.42, 61.80, 79.46) and activity proportion (0.345, 0.655, and 0.000) for 12, 27, and 40 h, respectively.

which accounts for all J constraints from the experimentally measured mortalities,

$$\sum_{i=1}^{N} X_i = 1, \qquad [3]$$

which enforces that the activity proportions sum to 1, and

$$\sum_{i=1}^{N} m_{ji}X_i + d_j \geq M, \text{ for } j = 1 \ldots 18, \qquad [4]$$

which requires that sum of the total mortality plus the absolute value of the deviation is equal to the mortality goal, where J is total number of constraints, N is number of activities, m is observed mortality of activity i, C_i is variable cost of activity i, X_i is level of activity i, d_j is absolute value of expected sum of the negative deviations of the solution results; T is sum of the negative deviations below the mortality goal; M is Target mortality goal, i is index of activities or time treatments $(1 \ldots N)$, and j is index of constraints $(1 \ldots J)$ for all X_i and $d_j \geq 0$. The 18 constraints included in the empirical model, mentioned above, were calculated as follows:

$$(3 \text{ insect species}) \times (2 \text{ locations}) \times (3 \text{ replications}) = 18 \qquad [5]$$

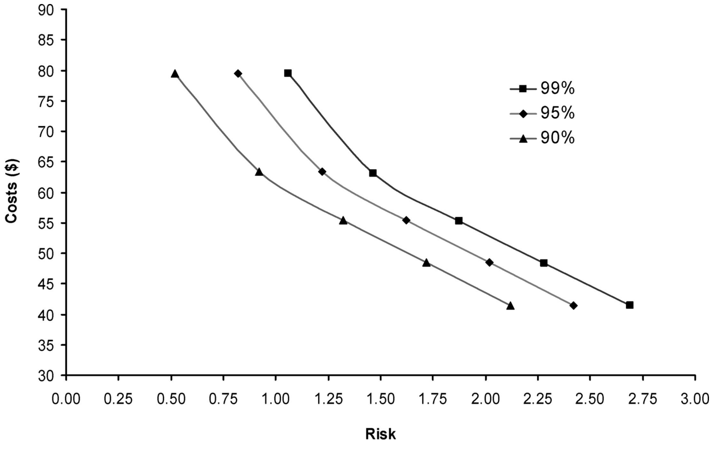

Fig. 2. Risk-cost graph of mortality-goal frontiers of 99, 95, and 90% for electric system 2. Each frontier was developed using an empirical model, with risk measured as the sum of deviations below a target at each respective variable cost.

Table 2. Heating and chemical system variable-cost summary

Variable cost	Electric systems								
	Electric system 1 (18-kW)			Electric system 2 (18-kW)			Electric system 3 (15-kW)		
	12 h	27 h	40 h	12 h	27 h	40 h	12 h	27 h	40 h
Labor ($12.56/h)	50.24	50.24	50.24	25.12	25.12	25.12	25.12	25.12	25.12
Energy ($/kW · h)	16.30	36.68	54.84	16.3	36.68	54.84	13.58	30.57	45.28
Total	66.54	86.92	105.08	41.42	61.80	79.96	38.70	55.69	70.40
	Propane systems								
	Propane system 1 (29-kW)			Propane system 2 (19-kW)					
	2 h	3 h	4 h	4 h	6 h	8 h			
Labor ($12.56/h)	25.12	25.12	25.12	25.12	25.12	25.12			
Energy ($/kW · h)	2.75	4.12	5.50	3.50	5.25	7.00			
Total	27.87	29.24	30.62	28.62	30.37	32.12			
	Chemical systems								
	Solution rate 1 (9.3 ml)			Solution rate 2 (18.6 ml)					
Labor ($12.56/h)	12.56			12.56					
Chemical solution	1.09			2.18					
Total	13.65			14.74					

Each solution set derived by the empirical model minimizes cost, subject to a given level of deviations below the mortality goal or target.

Table 1 provides an example of the components of the empirical model. This example uses a target mortality goal, or M from equation 4, of 95%. The observed data for each time interval activity was compared with the right-hand side (RHS) of each constraint. The time interval activities, in the example of Table 1, are 12, 27, and 40 h for electric systems. Constraints that had deviations below the target mortality goal were recorded. A deviation was computed for each row. To illustrate this computation from equation 2 with a numerical example from Table 1, the condensed deviation section for constraint number 8 with mortality observations of 0.44, 0.64, 0.80 was as follows:

$$[(0.95 - 0.44) * 0.345] + [(0.95 - 0.64) * 0.655] + [(0.95 - 0.80) * 0.00] = 0.38$$

This equation illustrates the interaction between target mortality goal and the calculated deviation of each constraint. The condensed deviation section of Table 1 was summed for each row (i.e., each constraint). Thus, the sum of deviations below the target mortality goal, or T from equation 2, is interrelated with the target mortality goal of M from equation 4. In this example, the sum of deviations was set equal to 1.66. Changing the allowable level of deviations in the sum of deviations row, or T in equation 2, allowed us to trace out the frontier (e.g., Fig. 2). Increasing T decreases cost. Conversely, decreasing T increases cost.

Lowest cost solutions often contain a mixture of treatment times. Trade-offs between objectives often have a mixture between the objectives, because no single feasible point simultaneously optimizes all of the objective functions (Ragsdale 2004). For example, Table 1 gives an activity proportion for each time activity in the optimal solution. Activity proportions are constrained to sum to 1. Minimum cost is computed using the optimal proportions. For the example in Table 1, minimum cost is $54.77 and is calculated as follows:

$$(41.42 * 0.345) + (61.80 * 0.655) + (79.46 * 0.000) = \$54.77$$

The sum product or left-hand side (LHS) of each constraint is computed by using each mortality observation and activity proportion and adding the corresponding deviation. The sum product is calculated as follows:

$$[(0.44 * 0.345) + (0.64 * 0.655) + (0.80 * 0.000)\} + 0.38 = 0.95$$

Using the activity proportions, weighted time is 21.83 and is calculated as follows:

$$(12 * 0.345) + (27 * 0.655) + (40 * 0.00) = 21.83 \text{ h}$$

Chemical application treatments used a similar empirical model. However, time-interval activities were replaced with the two chemical rates of formulated solution.

Results and Discussion

A high-output propane system 1 heating system had the lowest variable costs and greatest insect mortality success rate of the heating systems tested. Propane system 1 resulted in 100% mortality for all insects within 2 h and raising all test areas in the treated bin above 50°C (Tilley et al. 2007). Electric system 1 also produced 100% mortality for all insects after 40 h but at higher variable costs and using a complicated interior heat-distribution system. The other electrical and propane systems produced <100% mortality and had higher variable costs.

The empirical model of propane system 1 used three time-interval activities: 2, 3, and 4 h. The model se-

Table 3. Propane system 2 was evaluated using an empirical risk model at three different mortality goals

Mortality goal	Variable cost	Sum of deviations	Time (h) 4	6	8	Optimal time (h)
99%	31.94	1.45	0.00	0.10	0.90	7.80
	30.00	2.32	0.21	0.79	0.00	5.58
	29.54	3.19	0.47	0.53	0.00	5.06
	29.08	4.06	0.74	0.26	0.00	4.52
	28.62	4.93	1.00	0.00	0.00	4.00
95%	31.42	1.16	0.00	0.40	0.60	7.20
	29.93	1.98	0.25	0.75	0.00	5.50
	29.49	2.80	0.50	0.50	0.00	5.00
	29.06	3.62	0.75	0.25	0.00	4.50
	28.62	4.44	1.00	0.00	0.00	4.00
90%	31.24	0.80	0.00	0.50	0.50	7.00
	29.84	1.60	0.30	0.70	0.00	5.40
	29.39	2.40	0.56	0.44	0.00	4.88
	28.96	3.20	0.80	0.20	0.00	4.40
	28.62	4.00	1.00	0.00	0.00	4.00

The model minimized costs and measured risk as the sum of deviations below the mortality goal for each time interval. The matrix indicates a percentage of operating time for each time interval.

lected the lowest time interval of 2 h, with variable costs of $27.87 (Table 2) and zero deviations from a mortality goal of 100%. Each of the other time intervals had zero deviations from a mortality goal of 100% but higher variable costs. Propane system 1 proved to be the most cost-effective and best overall heating system of those tested to disinfest a grain bin. This heating system was relatively easy to setup (Tilley et al. 2007) and quickly disinfested the grain bin with no risk of insect survival, based on the arena data.

Propane system 2 had a small variation for variable costs, $3.32 or less, over a wide range of risk levels for each mortality goal (Table 3). The small variable-cost span indicates the operator would likely move toward the lowest level of risk and highest mortality-goal frontier of 0.99 (Fig. 2). Moving out to the highest frontier of 99% and then decreasing the risk level to a minimum of 1.45 will increase variable costs a minimal amount, while benefiting the operator with the maximum insect mortality rate for this system.

Electric system 1 had the greatest variation in variable costs, a maximum span of nearly $65, over a wide range of risk levels for each mortality goal (Table 4). The wide variable-cost span suggests that the operator would not likely accept the lowest risk level due to the high variable costs. The operator would likely accept some risk, while reducing variable costs. An individual would likely move outward to the highest mortality-goal frontier possible, while accepting a comfortable risk level to reduce variable costs to an acceptable level. Electric system 1 had 100% insect mortality at 40 h, but a high variable cost at this time-treatment level.

Electric system 1 matrices for each mortality goal of 99, 95, and 90% (Table 4) recorded a zero for every risk level in the 27-h time interval. The empirical model chose between the 12- and 40-h time intervals for each of the different risk levels. The reason the empirical model responded in this manner was due to the insect mortality rates between 12- and 27-h time intervals. A normal pattern of mortality would suggest an increase as time intervals increased; however, three arena test locations had higher mortality rates at the 12-h time interval than at the 27-h time interval. This phenomenon did not happen with any other heating system tested.

Table 4. Electric system 1 (ES1), electric system 2 (ES2), and electric system 3 (ES3) were evaluated within an empirical risk model at three different mortality goals

Heating system	Mortality goal	Variable cost	Sum of deviations	Time (h) 12	27	40	Optimal time (h)
ES1	99%	103.40	0.00	0.02	0.00	0.98	39.40
		85.63	1.09	0.27	0.00	0.73	32.44
		68.27	2.18	0.51	0.00	0.49	25.72
		50.91	3.28	0.76	0.00	0.24	18.72
		33.54	4.00	1.00	0.00	0.00	12.00
	95%	98.66	0.00	0.08	0.00	0.92	37.76
		81.12	1.00	0.33	0.00	0.67	30.76
		64.93	2.00	0.56	0.00	0.44	24.32
		48.96	3.00	0.78	0.00	0.22	18.16
		33.54	4.00	1.00	0.00	0.00	12.00
	90%	92.74	0.00	0.17	0.00	0.83	35.24
		73.83	1.00	0.43	0.00	0.57	27.96
		57.65	2.00	0.66	0.00	0.34	21.52
		41.47	3.00	0.89	0.00	0.11	15.08
		33.54	4.00	1.00	0.00	0.00	12.00
ES2	99%	79.46	1.06	0.00	0.00	1.00	40.00
		63.11	1.47	0.00	0.93	0.07	27.91
		55.27	1.87	0.32	0.68	0.00	22.20
		48.35	2.28	0.68	0.34	0.00	17.10
		41.42	2.69	1.00	0.00	0.00	12.00
	95%	79.46	0.82	0.00	0.00	1.00	40.00
		63.41	1.22	0.00	0.91	0.09	28.17
		55.48	1.62	0.31	0.69	0.00	22.35
		48.45	2.02	0.66	0.34	0.00	17.10
		41.42	2.42	1.00	0.00	0.00	12.00
	90%	79.46	0.52	0.00	0.00	1.00	40.00
		63.41	0.92	0.00	0.91	0.09	28.17
		55.48	1.32	0.31	0.69	0.00	22.35
		48.45	1.72	0.66	0.34	0.00	17.10
		41.42	2.12	1.00	0.00	0.00	12.00
ES3	99%	70.40	0.58	0.00	0.00	1.00	40.00
		53.48	1.42	0.13	0.87	0.00	25.05
		48.50	2.27	0.42	0.58	0.00	20.70
		43.51	3.11	0.72	0.28	0.00	16.20
		38.70	3.95	1.00	0.00	0.00	12.00
	95%	70.40	0.36	0.00	0.00	1.00	40.00
		53.11	1.15	0.15	0.85	0.00	24.75
		47.88	1.93	0.46	0.54	0.00	20.10
		43.23	2.72	0.73	0.27	0.00	16.05
		38.70	3.50	1.00	0.00	0.00	12.00
	90%	70.40	0.16	0.00	0.00	1.00	40.00
		53.28	0.87	0.14	0.86	0.00	24.90
		46.93	1.58	0.52	0.48	0.00	19.20
		42.49	2.29	0.78	0.22	0.00	15.30
		38.70	3.00	1.00	0.00	0.00	12.00

The model minimized variable costs and measured risk as the sum of deviations below the mortality goal for each time interval. The matrix indicates a percentage of operating hours for each time interval.

Electric system 2 had high variable costs over a narrow range of risk levels for each mortality goal (Table 4). To reach a high insect mortality goal, an operator's variable costs would have to increase substantially. Electric system 3 was much like electric system 2, with high variable costs and a narrow range of risk levels for each mortality goal. The mortality-goal frontiers were concave for this system when the data in Table 4 was plotted. An operator accepting a low mortality goal of 90% and a high level of risk at 3.00 can operate this system at a variable-cost amount of

Table 5. Propane system 1 (PS1), propane system 2 (PS2), electric system 1 (ES1), electric system 2 (ES2), electric system 3 (ES3) heating and chemical system fixed cost ($) summary

Fixed cost	Heating system					Chemical application
	PS1	PS2	ES1	ES2	ES3	
Equipment	189	189	1500	1500	1050	35
Miscellaneous	60	60	172	150	150	0
Total	249	249	1672	1650	1200	35

$38.70 (Table 4); however, the risk of live insects remaining in the grain bin is an unattractive feature of this system.

Propane system 2, and electric systems 1, 2, and 3 all had deviations below each mortality goal, with the exception of electric system 1 at a time interval 40 h. The empirical model of each heating system formed a matrix between risk and the three time intervals at each mortality goal of 99, 95, and 90% (Tables 3 and 4). The risk and time-interval relationship for each mortality goal indicates a longer time interval was needed to reduce risk. As the operator assumes more risk, the time-interval shifts to a smaller operating-hour treatment and lower variable costs.

The above-mentioned analysis excluded fixed costs because we compared trade-offs within each heating system. A comparison across heating systems would include fixed costs. Comparing across heating systems is possible because risk was measured consistently as the total cumulative percentage of all deviations from each inequality constraint. Fixed costs of the propane systems were much lower than the electrical systems (Table 5). Propane system 1 with low fixed cost, low variable costs, and 100% insect mortality was the most attractive nonchemical approach to disinfestation of empty grain bins.

Propane system 2 and the electric systems leave live insects in the grain bin, with the exception of electric system 1 at 40 h (Tables 3 and 4). The reader may question why an operation would accept the risk of using a heating system that leaves live insects in the grain bin upon completion of the treatment. An operator may want to move toward the highest frontier possible in Fig. 2 and strive for 100% mortality. Research, however, indicates that insects surviving sublethal temperatures of <50°C or exposure to lethal temperatures for less than the intended duration (sublethal exposure) may have their reproductive potential impaired (Proverbs and Newton 1962; Okasha et al. 1970; Gonen 1977; Arbogast 1981; Tikku and Saxena 1985, 1990; Kawamoto et al. 1989; Saxena et al. 1992; Lale and Vidal 2003). Sterile insects cannot reproduce and the population will eventually die out, causing no damage to the grain mass. Grain damage occurs as a result of multiple generations of stored-product insect reproduction. Exposure to a sublethal temperature (44°C) was effective in producing either partial or complete sterility of the confused flour beetle, *Tribolium confusum* Jacquelin du Val, exposed as larvae or pupae for an 8-h period (Oosthuizen 1935).

The two chemical application rates both had near 100% mortality for each insect species above the floor at the 4-h time interval. However, mortality data for insects exposed below the floor were highly variable, which could have resulted from the fact that the chemical runoff below the perforated flooring varied randomly in the containers. This in turn would have caused differential exposure due to these random effects, and the increased volume application of the high rate would have compounded these effects. Nevertheless, mortality variation below the floor was significant for application rate and exposure interval (Table 6). This was evident for each insect species and especially for *S. oryzae,* which had 100% mortality after 4 h of exposure at the higher rate. All *T. castaneum* were knocked down and on their backs after 2 h of exposure at the higher rate for each floor level. *T. castaneum* showed significantly different mortality

Table 6. Percentage mortality (mean ± SEM[1]) of adult *S. oryzae*, *T. castaneum*, and *R. dominica*, exposed for three time intervals to the low and high label rates of cyfluthrin, at positions above and below the false floor of the grain bin where tests were conducted

Chemical rate	Insect species	Floor location	Time 1 h	2 h	4 h
Low 40.8 ml/m^2	*S. oryzae* (L.)[a]	Above	62.0 ± 19.8aA	83.3 ± 8.4aA	94.3 ± 5.6aA
		Below	46.3 ± 23.3aA	51.0 ± 21.0aA	76.6 ± 11.7aA
	T. castaneum[a]	Above	63.6 ± 8.8aB	81.0 ± 6.1aAB	92.3 ± 6.2aA
		Below	28.0 ± 14.9aA	43.3 ± 12.5aA	63.3 ± 12.5aA
	R. dominica (F.)[b]	Above	76.6 ± 2.0aB	95.3 ± 2.3aA	100 ± 0.0aA
		Below	24.3 ± 2.9bC	48.6 ± 7.2bB	81.0 ± 1.0bA
High 81.6 ml/m^2	*S. oryzae* (L.)	Above	100 ± 0.0aA	100 ± 0.0aA	100 ± 0.0aA
		Below	63.3 ± 18.3aA	92.3 ± 6.2aA	100 ± 0.0aA
	T. castaneum	Above	85.6 ± 4.3aA	95.6 ± 1.3aA	92.0 ± 4.9aA
		Below	54.3 ± 12.7aA	73.3 ± 6.6bA	84.3 ± 8.6aA
	R. dominica (F.)	Above	98.0 ± 1.0aA	100 ± 0.0aA	100 ± 0.0aA
		Below	70.0 ± 1.7bC	78.0 ± 1.0bB	92.3 ± 2.3bA

Means between rows followed by different lowercase letters are significantly different ($P < 0.05$; Waller–Duncan *k*-ratio *t*-test); and means between columns followed by different uppercase letters are significantly different ($P < 0.05$; *t*-test).

[a] No difference in mortality of *S. oryzae* or *T. castaneum* exposed to low versus high application rate.

[b] Mortality of *R. dominica* at 1 h above and below the floor was significantly greater ($P < 0.05$) at the high than at the low rate; no difference above the floor at 2 and 4 h, and mortality below floor was greater at the high than at low rate at 2 and 4 h.

Table 7. Each chemical application was evaluated within an empirical risk model at three different mortality goals

Mortality goal	Variable cost	Risk	Formulated solution rate	
			1X (9.3 ml)	2X (18.6 ml)
99%	12.18	0.86	0.00	1.00
	11.89	1.31	0.26	0.74
	11.63	1.76	0.49	0.51
	11.36	2.21	0.75	0.25
	11.09	2.66	1.00	0.00
95%	12.18	0.56	0.00	1.00
	11.83	0.98	0.32	0.68
	11.58	1.40	0.55	0.45
	11.33	1.82	0.78	0.22
	11.09	2.25	1.00	0.00
90%	12.18	0.30	0.00	1.00
	11.74	0.66	0.41	0.59
	11.51	1.02	0.61	0.39
	11.30	1.38	0.81	0.19
	11.09	1.74	1.00	0.00

The model minimized variable costs and measured risk as the sum of deviations below the mortality goal for each formulated solution rate. The matrix indicates a formulated-solution percentage at each application rate in ml for a specific risk level.

between floor levels at the 2-h time interval at the higher rate of application. However, *T. castaneum* mortalities were only significantly different between the 2- and 4-h time intervals when using the low application rate. The *R. dominica* mortality showed significance between floor levels and time intervals below the floor for each application rate.

The successful control of *R. dominica* was surprising due to the species being less mobile compared with *T. castaneum* and *S. oryzae.* An insect species that is highly mobile seems more likely to come in contact with the random displacement of the chemical formulated solution. Random contact with the formulated solution would likely occur less frequently below the perforated floor using the low application rate. The *T. castaneum* mortality results were less than Arthur (1997) reported probably because of the random contact with the chemical after it dripped through to the surface below the perforated floor. The direct spraying described by Arthur (1997) may have produced greater contact between insect species and the chemical on the surface.

Chemical spray treatments produced excellent mortality for each insect species at low fixed and variable costs. Variable costs between each of the mortality goals of 99, 95, and 90% varied a minimum of $1.09 with low associated risk levels (Table 7). An operator choosing a chemical application treatment would apply at the low label rate, obtaining excellent mortality results at a low cost. However, total reliance on chemical treatments raises concerns about negative influences on the environment and worker safety and the danger of insects developing resistance to the chemical.

An empirical model for each heating and chemical system tested provided a wide range of risk levels and variable costs to obtain a specific insect mortality goal. The empirical model developed in this study could be easily adapted by other researchers interested in the trade-off between treatment cost and insect mortality. Specific conclusions based on the results of this study were as follows:

- Propane system one was the most cost effective and had the lowest risk level of the nonchemical systems, producing 100% mortality for all three insect species in 2 h.
- Electric system one had effective mortality results after 40 h of operation, but required high variable costs, making this system unattractive. All other electric systems were unattractive due to the high variable costs and lower mortality results.

Chemical treatments had extremely low costs and risk levels; however, chemical treatments have many negative influences on the environment, worker safety, and the danger of insects developing resistance to the chemical.

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