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Economic Feasibility of Methoprene Applied as a Surface Treatment and as an Aerosol Alone and in Combination With Two Other Insecticides

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ABSTRACT Economic evaluations of integrated pest management strategies are becoming increasingly important as restrictions on conventional insecticides continue to become more stringent and chemical control costs rise. Aerosol treatments with insect growth regulators alone and in combination with conventional contact insecticides may be a feasible alternative to expensive and highly toxic fumigants such as methyl bromide for control of the Indianmeal moth (*Plodia interpunctella* (Hübner)). Average calculated mortality of Indianmeal moth eggs exposed to surface applied methoprene, aerosol methoprene alone and in combination with esfenvalerate and synergized pyrethrins is 55.0, 69.0, and 94.6%, respectively. Temperature effects on development time makes frequency and timing of insecticide applications very important as evidenced by simulations of population levels in response to a variety of treatment dates by diet, and become critical in situations where survival of Indianmeal moth is high. Using a measurement of risk that is equal to deviations below a target mortality goal (99%), we are able to optimize cost and frequency of application using simulated mortality data for each of the treatment strategies. Optimal timing of each insecticide treatment depends heavily on the rate of development by diet. This type of analysis helps pest control operators and managers by showing consequences of treatment scenarios in time and cost.

KEY WORDS methoprene, esfenvalerate, *Plodia interpunctella* Hübner, economic analysis

Integrated pest management (IPM) in stored products relies on a variety of control strategies, but it may be difficult to quantify how much effect one particular treatment is having on the overall management effort. Traditional insect management practices such as neurotoxic insecticides and fumigants can be dangerous to workers and expensive to apply. One current, largely unexplored management option is aerosol applications of conventional insecticides and insect growth regulators (IGRs) to control insect pests in food storage and manufacturing facilities. IGRs are insecticides that mimic various hormones involved in the developmental processes in insects, and can be used in the control of various stored-product insects (Campbell et al. 2004, Mohandass et al. 2006, Athanassiou et al. 2011, Wijayaratne et al. 2012).

Aerosol space applications can be used to treat the interior surfaces and storage areas of warehouses and food processing facilities, as evidenced by recent studies (Arthur and Campbell 2007, Arthur 2008, Sutton et al. 2011) demonstrating effectiveness of aerosol pyrethrin for management of the red flour beetle, *Tribolium castaneum* (Herbst) (Arthur and Campbell 2007, Arthur 2008, Sutton et al. 2011). Systems for ultra-low volume (ULV) aerosol delivery have been designed for and installed in commercial milling and storage facilities. Currently, in facilities where aerosol fogging systems are installed, pest managers are using conventional insecticides alone and in combination with IGRs. One IGR, methoprene, which is a juvenile hormone analog, has been evaluated alone and in combination with esfenvalerate and 1% synergized pyrethrin for control of eggs of the Indianmeal moth (*Plodia interpunctella* Hübner) (Jenson et al. 2009, 2010a,b). Comparison can also be made between the use of methoprene as an aerosol and as a contact surface treatment in food storage and processing facilities.

Economic analysis for methyl bromide alternatives for specific field crops have been developed using enterprise budgets (Nelson 1996, Byrd et al. 2006). In this study, partial budget analysis is used to compute the cost of each management treatment or option (Boehlje and Eidman 1984). Model inputs include cost information from our partial budget analysis along

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Table 1. Empirical model with minimization of variable costs for treatments with methoprene as a surface treatment

	None	One time	6 wk	4 wk	3 wk	2 wk
T1 – wheat diet	0.00	0.550	0.926	0.982	0.995	0.999
T2 – wheat diet	0.00	0.508	0.928	0.984	0.995	0.999
T3 – wheat diet	0.00	0.212	0.901	0.934	0.993	0.999
T4 – wheat diet	0.00	0.468	0.919	0.981	0.993	0.999
T5 – wheat diet	0.00	0.598	0.984	0.984	0.989	0.999
T6 – wheat diet	0.00	0.464	0.907	0.975	0.989	0.999
T1 – raisins	0.00	0.551	0.951	0.988	0.996	1.000
T2 – raisins	0.00	0.550	0.957	0.982	0.997	1.000
T3 – raisins	0.00	0.550	0.939	0.989	0.997	1.000
T4 – raisins	0.00	0.550	0.949	0.989	0.997	1.000
T5 – raisins	0.00	0.550	0.927	0.989	0.997	1.000
T6 – raisins	0.00	0.550	0.926	0.982	0.995	0.999
Total deviations	−11.880	−5.779	−0.666	−0.121	−0.002	0.000
Cost by frequency of treatment in USD	0.00	1.56	6.24	9.36	12.48	17.16

Temperatures (T1–T6) correspond to the temperatures 21, 24, 27, 30, 32, and 35°C, respectively Treatments across the top row of this table correspond to; no treatment, one treatment at day 28, and reoccurring treatments every 2, 3, 4, and 6 wk beginning at day 28 (total deviations increase from right to left as explained in text). The wheat diet simulation represents an optimal diet, whereas the raisin diet reflects a sub-optimal diet. Columns are added to determine total deviations.

with data from a population growth model simulating development in response to multiple diet types (Fontenot et al. 2012a). Using this type of modified economic analysis could allow food production plant managers and warehouse managers to make decisions regarding control of a single pest species by comparing costs, efficacy of different treatments, and necessary frequency of application of those treatments. Using population growth models to simulate consequences of management decisions can provide even more insight. With extremely low thresholds for insects and insect fragments in finished stored product situations, a slightly different approach from traditional economic injury levels (EILs) is needed (Higley and Wintersteen 1992; Stejskal 2002, 2003).

Many types of economic analysis have already been applied to other systems including field crops, forests, and ornamentals (Headley and Hoy 1987, Olson et al. 1996, Jetter et al. 1997, Vannatta et al. 2012), and grain bins (Tilley et al. 2007); however, the warehouse environment is a novel use of these standard methodologies. These types of analyses could show how insecticide applications as a management strategy could be optimized in warehouse environments. The objectives of this study were to: 1) ascertain how to best use methoprene insecticide treatments by optimizing timing and frequency of applications, 2) examine the economic impact of environmental factors such as temperature and diet on these insecticide treatments, and 3) combine these parameters to determine which scenario and treatment methods would be optimal from a cost-risk standpoint.

Materials and Methods

Target Mortality Model and Optimization. Tilley et al. (2007) modified the Target MOTAD model (Tauer 1983) to examine risk and return for heat disinfestations of grain bins. The resulting empirical model is useful in analyzing trade-offs between risk and return, which are directly related (i.e., decreasing returns are associated with decreased risk levels). In this study, as in the Tilley et al. (2007) study, target return is defined to be the threshold mortality level associated with specific management options. Specifically, a mortality threshold level of 99% is used. The threshold for the model is set at such a high level to provide a realistic threshold for the infestation of food processed and stored for human consumption (virtually zero insects per unit). Risk, in this case, is defined as the situation in which insects remain alive. Cost is computed assuming that labor and equipment costs are fixed. Variable cost includes the chemical cost and associated application cost. Modification of Tilley's model allowed us to optimize treatment frequency and cost for the target threshold level for each management option.

Mortality indexes were obtained by simulating the mortality of Indianmeal moth eggs exposed to six scenarios; no treatment, one treatment at day 28, and reoccurring treatments every 2, 3, 4, and 6 wk beginning at day 28. These treatments were simulated across six temperatures (21, 24, 27, 30, 32, and 35°C) on wheat diet and raisins. Survivorship estimates for insecticide treatments were modeled based on results from studies by Jenson et al. (2009, 2010a,b); calculated for use in population simulations in Fontenot et al. (2012a,b); and this study. Mortality levels in this economic model are calculated by subtracting total population at 180 d for each treatment from total population survival at 180 d where there was no treatment.

Model solutions are obtained for various risk levels. Risk, as stated earlier is simply the probability that the insects will survive. The most restrictive risk level assumes that there are zero deviations of mortality below the threshold level. The other risk levels assume that the sum of the mortality deviations is equal to 1, 2, or 3. A risk level of one would indicate that there were a total of 100% in deviations below the 99% target mortality level for the six wheat diet and six raisin diet replications (Table 1). These deviations could be associated with 1–12 of the replications. As in the Tilley et al. (2007) model, interest is in the summation of the deviations (that is often referred to as downside risk)

Table 2. Cost summary by frequency of insecticide application

Number treatments in 180 d	0	1	4	6	8	11
No treatment	0.00	0.00	0.00	0.00	0.00	0.00
Methoprene-surface	0.00	1.56	6.24	9.36	12.48	17.16
Methoprene-aerosol	0.00	0.71	2.84	4.27	5.69	7.82
Methoprene plus esfenvalerate	0.00	1.17	4.68	7.01	9.35	12.86
Methoprene plus 1% pyrethrin	0.00	3.14	12.56	18.85	25.13	34.55

Costs are per 284 m^3 or 929 m^2 for surface treatments in US$.

rather than the deviations for a specific replication. In Table 1, total deviations increase as you move from right (treatment every 2 wk) to left (no treatment). Treating every 2 wk results in zero deviations below the 99% target mortality level (i.e., zero deviations below 0.99). Treating every 3 wk results in deviations of 0.002 (0.001 from the T5 – Wheat Diet line and 0.001 from the T6 – Wheat Diet line). As you move left to the one time treatment, total deviations are well above one indicating that, though this treatment has low cost, it is more risky in the sense that total deviations below the 99% target mortality level are relatively high.

Computer Simulations of Mortality. Simulations of the effect of timing and frequency of insecticide treatments were conducted using a population growth model modified for wheat diet and a model modified for raisins (Fontenot 2012a). These models were based on four main components; time required for the complete life cycle, male longevity, female longevity, and fecundity. Survivorship values for these models were calculated using data from Jenson et al. (2009), specifically for mortality when insecticides were applied to eggs. Adjustment of survivorship was only applied to immatures because there are no data to support the assertion that methoprene kills adult Lepidoptera and mortality was simulated to occur at noon on the day of insecticide treatment for all immatures that are in that stage at that time. Survivorship values were calculated using the mortality data for Indianmeal moth eggs exposed to the label rates for surface or aerosol application of each insecticide reared on the corresponding diet from Jenson et al. (2009, 2010a,b) as these are the most likely scenario for egg mortality in field situations. For a more detailed discussion of model components, please refer to Fontenot et al. (2012a,b).

The survivorship value calculated for methoprene at the label rate delivered as an aerosol was determined from the data presented in Jenson et al. 2010b, which evaluated a methoprene-only aerosol treatment. The mean survivorship averaged across all exposure types was 31.0%. Values for the aerosol insecticide treatment combination of methoprene and esfenvalerate were calculated from egg exposure data in Jenson et al. (2010a), where both chemicals were delivered at the label rate and survival was estimated as 17.7%. The final insecticide combination that was used for the simulations was the aerosol treatment of methoprene and 1% synergized pyrethrins (both at the label rate for aerosol application) from data in Jenson et al. (2010b). Survival was estimated as 5.4%, which was the lowest survivorship used in the simulations. Though there is no interaction or relationship between temperature and methoprene in survival or mortality of Indianmeal moth between 20 and 32°C, (Jenson et al. 2009), there is a strong relationship between temperature and total development time from egg to adult. Beginning populations were standardized to 100 eggs and no adult moths. Simulations were run at six temperatures (21, 24, 27, 30, 32, and 35°C) for insecticide treatment scenarios to use in this economic analysis. The simulation of a range of temperatures was necessary to evaluate the specific timing of insecticide applications because of the proportion of immatures present in the population on the day of treatment.

Frequency and timing of treatments scenarios were chosen to represent what might feasibly be done in a real world setting. In addition to mortality from treatment and response of population to temperature, timing, and frequency of insecticide applications had a large impact on population levels (Fontenot et al. 2012a,b).

Computation of Costs. For the purposes of the economic analysis, labor and equipment costs are assumed to be fixed. Variable costs include the cost of the chemical, the oil carrier for the chemical application, and the combination of carrier and insecticide. Costs associated with methoprene surface treatments were calculated using current industry costs for Dia-

Table 3. Empirical model solutions and optimization of frequency of treatments for treatments with surface treatments of methoprene

Model solution Cost ($) unit area	Overall risk level	Timing of application			4 wk	3 wk	2 wk
		None	One time	6 wk			
14.91	0	0.000	0.007	0.000	0.001	0.455	0.537
5.87	1	0.000	0.078	0.921	0.000	0.000	0.000
4.98	2	0.000	0.269	0.731	0.000	0.000	0.000
4.10	3	0.000	0.460	0.540	0.000	0.000	0.000

The first column displays calculated costs (in $US) per unit area. Treatments across the top row of this table correspond to; no treatment, one treatment at day 28, and reoccurring treatments every 2, 3, 4, and 6 wk beginning at day June.

Table 4. Empirical model with minimization of variable costs for treatments with aerosol methoprene alone

	None	One time	6 wk	4 wk	3 wk	2 wk
T1 – wheat diet	0.000	0.690	0.973	0.997	0.999	1.000
T2 – wheat diet	0.000	0.690	0.973	0.997	0.999	1.000
T3 – wheat diet	0.000	0.638	0.976	0.997	1.000	1.000
T4 – wheat diet	0.000	0.263	0.963	0.973	0.999	1.000
T5 – wheat diet	0.000	0.587	0.972	0.996	0.999	1.000
T6 – wheat diet	0.000	0.661	0.969	0.996	0.997	1.000
T1 – raisins	0.000	0.582	0.965	0.995	0.998	1.000
T2 – raisins	0.000	0.690	0.988	1.000	1.000	1.000
T3 – raisins	0.000	0.690	0.990	0.997	1.000	1.000
T4 – raisins	0.000	0.690	0.982	0.998	1.000	1.000
T5 – raisins	0.000	0.690	0.987	0.999	1.000	1.000
T6 – raisins	0.000	0.691	0.977	0.999	1.000	1.000
Total deviations	−11.880	−4.318	−0.165	−0.017	0.000	0.000
Cost by frequency of treatment in $US	0.00	0.71	2.84	4.27	5.69	7.82

Temperatures (T1–T6) correspond to the temperatures 21, 24, 27, 30, 32, and 35°C, respectively. Treatments across the top row of this table correspond to; no treatment, one treatment at day 28, and reoccurring treatments every 2, 3, 4, and 6 wk beginning at day 28. The wheat diet simulation represents an optimal diet, whereas the raisin diet reflects a sub-optimal diet. Columns are added to determine total deviations.

con II (Emulsifiable Concentrate, 288 mg active ingredient [AI]/ml, Central Sciences International, Schaumberg, IL), calculated per 929 m^2 (10,000 $feet^2$) at the label rate for surface applications (1 ml formulation in 3,784 ml to cover 94 m^2). Costs for aerosol methoprene treatments were calculated in the same way for per 284 m^3 at the label rate for aerosol space treatments (3 ml of formulation to cover 284 m^3) plus the cost of oil carrier. The costs of the oil carrier were fixed for the purposes of this analysis as to US$0.83 per liter (US$3.15 per gallon) or US$0.0008 per milliliter. However, the cost of oil carriers may fluctuate with the global petroleum market. Current prices for esfenvalerate (Conquer, Paragon Professional Products, Memphis, TN) and 1% synergized pyrethrin (1% AI, Entech Fog-10, Entech Systems, Kenner, LA) were calculated based on their labeled rates for aerosol delivery systems per 284 m^3 (10,000 $feet^3$). Costs for combination treatments were calculated by adding together the specific insecticide costs and adjusting the cost for carrier oil.

Results

Costs of each treatment and cumulative costs for each treatment scenario over the 6 mo interval are displayed in Table 2. Costs range from US$0.71 to US$3.14 for a single treatment to US$7.82 to US$34.55 for 6 mo of biweekly treatments per 284 m^3 of facility headspace. The individual costs of specific treatments are significantly different. Mortality levels (explained above) are not correlated with treatment cost, that is, the least expensive treatment does not always have the lowest survival. Optimization of the economic model shows that there is a 99% or more reduction in some of the treatment scenarios. However, because of unequal survivorship on wheat diet and raisins (88 and 11% from Fontenot et al. 2012a) respectively, there are often considerably more surviving individuals on wheat diet, though insecticide treatments reduce survival proportionally for both diets.

Tables 2–9 illustrate the mortality levels and model results. Although all four risk levels are pertinent, for discussion purposes we will focus on risk level 1. As risk levels increase; for example, going from 0 to 1, 1 to 2, and so forth; so does the probability that the insects survive. The mortality levels for each treatment frequency of methoprene as a surface treatment plus the allowable deviations below the target threshold mortality level for each diet row have to be greater than or equal to the threshold mortality level of 99% in Table 2. The total allowable deviations, computed by adding up the deviations for each diet row, cannot exceed the risk level (i.e., 0, 1, 2, or 3). The cost of each treatment frequency is also illustrated in Table 2. The total cost for each risk level is computed by multiplying the solution percentage for each treatment frequency by the respective treatment frequency cost. Four risk levels, including the solution with no deviations below the threshold, are illustrated in Table 3. For risk level 1, the optimal mix is between the one time treatment at day 28 and treating every 6 wk

Table 5. Empirical model solutions and optimization of frequency of treatments for treatments with methoprene aerosol

Model solution Cost ($) unit area	Overall risk level	Timing of application				3 wk	2 wk
		None	One time	6 wk	4 wk		
4.98	0	0.000	0.000	0.238	0.020	0.742	0.000
2.40	1	0.000	0.209	0.791	0.000	0.000	0.000
1.36	2	0.000	0.450	0.550	0.000	0.000	0.000
1.36	3	0.694	0.306	0.000	0.000	0.000	0.000

The first column displays calculated costs (in $US) per unit area. Treatments across the top row of this table correspond to; no treatment, one treatment at day 28, and reoccurring treatments every 2, 3, 4, and 6 wk beginning at day 28.

Table 6. Empirical model with minimization of variable costs for treatments with methoprene plus esfenvalerate

	None	One time	6 wk	4 wk	3 wk	2 wk
T1 – wheat diet	0.000	0.823	0.992	1.000	1.000	1.000
T2 – wheat diet	0.000	0.761	0.761	1.000	1.000	1.000
T3 – wheat diet	0.000	0.314	0.990	0.989	1.000	1.000
T4 – wheat diet	0.000	0.700	0.994	0.999	1.000	1.000
T5 – wheat diet	0.000	0.788	0.989	1.000	0.999	1.000
T6 – wheat diet	0.000	0.694	0.990	0.999	1.000	1.000
T1 – raisins	0.000	0.824	1.000	0.996	1.000	1.000
T2 – raisins	0.000	0.823	0.999	1.000	1.000	1.000
T3 – raisins	0.000	0.823	0.997	1.000	1.000	1.000
T4 – raisins	0.000	0.823	0.998	1.000	1.000	1.000
T5 – raisins	0.000	0.823	0.994	1.000	1.000	1.000
T6 – raisins	0.000	0.750	1.000	1.000	1.000	1.000
Total deviations	−11.88	−5.268	−2.971	−2.971	−2.970	−2.970
Cost by frequency of treatment in $US	0.00	1.17	4.68	7.01	9.35	12.86

Temperatures (T1–T6) correspond to the temperatures 21, 24, 27, 30, 32, and 35°C, respectively. Treatments across the top row of this table correspond to; no treatment, one treatment at day 28, and reoccurring treatments every 2, 3, 4, and 6 wk beginning at day 28. The wheat diet simulation represents an optimal diet, whereas the raisin diet reflects a sub-optimal diet. Columns are added to determine total deviations.

starting from day 28 in an environment where both diets are present. The cost of this optimal mix is US$5.87. As the risk level increases, cost is reduced, but there are also more deviations from the target mortality level (i.e., more risk) for the higher levels of risk.

The mortality rates and costs for each treatment frequency for the methoprene aerosol option are presented in Tables 4 and 5. Cost per treatment frequency ranges from US$0.71 for a single treatment to US$7.82 for bi-weekly treatments. For risk level 1, cost is US$2.40 (Table 5). The optimal mix is between one time treatment at day 28 and treating every 6 wk starting from day 28.

Tables 6 and 7 illustrate the mortality levels, costs, and model results for the methoprene plus esfenvalerate option. Cost per treatment frequency ranges from US$1.17 for a single treatment to US$12.86 for bi-weekly treatments. For risk level 1, the cost is US$3.63 and the optimal mix is between one time treatment at day 28 and treating every 6 wk starting from day 28 (Table 7). The results for methoprene plus 1% synergized pyrethrin are presented in Tables 8 and 9. Cost per treatment frequency ranges from US$3.14 for a single treatment to US$34.55 for bi-weekly treatments. For risk level 1, cost is US$5.98 (Table 9). The optimal mix is between one time treatment at day 28 and treating every 6 wk starting from day 28.

The results for each option indicate that it is possible to meet the target threshold level of 99% mortality. The cost of the methoprene plus esfenvalerate option is lower than that of the other options for each risk level considered. For each option, the cost of achieving the risk level with zero mortality deviations is substantially higher than the costs for the other risk levels.

Discussion

All simulated treatments based on industry practices and chemical applications were within the allowed application frequencies. Temperature and quality of diet affected the feasibility of methoprene treatments examined. As in prior research (Fontenot et al. 2012 a,b), temperature not only affects the speed of development, but also overall survival and timing of insecticide treatments. For example, in a sub-optimal environment for Indianmeal moth, only one treatment of methoprene plus synergized pyrethrin at 1% is adequate to suppress the population feeding on raisins according to our simulations. Conversely, for the same chemical combination on wheat diet, an application every 4–6 wk is necessary for the same risk level. Models and simulations such as those presented in this study allow warehouse managers to see what the trade-off between risk and cost is and make decisions based on these comparisons.

Treatments in our economic model are based on the combination of two diets (wheat-based and raisins only), on which Indianmeal moth survives very well and very poorly, respectively. These types of simula-

Table 7. Empirical model solutions and optimization of frequency of treatments for treatments with methoprene plus esfenvalerate

Model solution Cost ($) unit area	Overall risk level	Timing of application				3 wk	2 wk
		None	One time	6 wk	4 wk		
9.24	0	0.005	0.000	0.019	0.393	0.312	0.271
3.63	1	0.000	0.299	0.701	0.000	0.000	0.000
2.36	2	0.000	0.662	0.33	0.000	0.000	0.000
1.16	3	0.007	0.993	0.000	0.000	0.000	0.000

The first column displays calculated costs (in $US) per unit area. Treatments across the top row of this table correspond to; no treatment, one treatment at day 28, and reoccurring treatments every 2, 3, 4, and 6 wk beginning at day 28.

Table 8. Empirical model with minimization of variable costs for treatments with methoprene plus 1% synergized pyrethrin

	None	One time	6 wk	4 wk	3 wk	2 wk
T1 – wheat diet	0.000	0.946	0.999	1.000	1.000	1.000
T2 – wheat diet	0.000	0.874	0.999	1.000	1.000	1.000
T3 – wheat diet	0.000	0.360	0.999	0.995	1.000	1.000
T4 – wheat diet	0.000	0.804	1.000	1.000	1.000	1.000
T5 – wheat diet	0.000	0.906	0.996	1.000	1.000	1.000
T6 – wheat diet	0.000	0.798	0.999	1.000	1.000	1.000
T1 – raisins	0.000	0.947	1.000	1.000	1.000	1.000
T2 – raisins	0.000	0.945	1.000	1.000	1.000	1.000
T3 – raisins	0.000	0.945	1.000	1.000	1.000	1.000
T4 – raisins	0.000	0.946	1.000	1.000	1.000	1.000
T5 – raisins	0.000	0.945	1.000	1.000	1.000	1.000
T6 – raisins	0.000	1.000	1.000	1.000	1.000	1.000
Total deviations	−11.88	−1.474	0.000	0.000	0.000	0.000
Cost by frequency of treatment in $US	0.00	3.14	12.56	18.85	25.13	34.55

Temperatures (T1–T6) correspond to the temperatures 21, 24, 27, 30, 32, and 35°C, respectively. Treatments across the top row of this table correspond to; no treatment, one treatment at day 28, and reoccurring treatments every 2, 3, 4, and 6 wk beginning at day 28. The wheat diet simulation represents an optimal diet, whereas the raisin diet reflects a sub-optimal diet. Columns are added to determine total deviations.

tions are realistic given that warehouse environments may have many different food types stored in close proximity to one another. Possibilities for simulations are limited only by available pest population growth models and variable cost information. While our simulations and economic models do not include every possible treatment scenario, we have presented a range at which decisions about insecticide type, application type, and frequency could be made under our model conditions. It may be possible to compare and optimize for nonchemical pest management options such as chilled air aeration, ambient air aeration fumigation and heat treatments of facilities (Maier et al. 1997, Mason et al. 1997, Rulon et al. 1999, Tilley et al. 2007), which may be used to control the Indianmeal moth and other stored product insects. Our results are especially useful when comparing management strategies such as those listed, with costs of low risk insecticides.

The warehouse environment is a new and novel environment for economic simulation. IPM practices have long used the concepts of economic and esthetic injury levels in field crop systems and in biological control programs (Stejskal 2002, 2003). IPM in a finished stored products situation presents unique opportunities and challenges because of the low tolerance for insects and the tangible and intangible costs associated with insect infestation. IPM in field crops has a successful history of using EILs and economic thresholds to determine timing of control strategies. In fact, there are many recent studies involving economic analysis of novel control strategies where economic thresholds are applied to field crops where it is possible to relate the number of insects with a damage estimate (Crowder et al. 2006, Antwi et al. 2007, Beres et al. 2007). Indianmeal moth infestations of finished stored products present a unique challenge in that the products typically have high value and are stored for variable periods of time in multiple locations. In these instances, the desired insect threshold is essentially zero. The Indianmeal moth is a cosmopolitan pest known to infest a great number of commodities, including many different grains, dried fruits, and nuts (Mohandass et al. 2007). Damage caused by Indianmeal moth can involve direct feeding, product contamination, package holes and ruptures, and creation of favorable conditions for mold and bacterial growth. In addition, losses from these moths can occur anywhere along the process from manufacturer to the home of the consumer (Mowery et al. 2004). It has been shown by several studies that Indianmeal moth infests facilities ranging from feed mills (Larson et al. 2008) to flour mills and pet food storage facilities (Ryne et al. 2007), so frequency and timing of treatments as well as materials infested could be crucial in making management decisions.

There are many recent practices used to monitor insect pests in food storage facilities such as pheromone traps, sticky traps, and pitfall traps. However, because of the various biological and environmental factors that can affect trap catch, it is often difficult to relate the numbers of insects caught in traps to the

Table 9. Empirical model solutions and optimization for treatments methoprene plus 1% synergized pyrethrin

Model solution Cost ($) unit area	Overall risk level	Timing of application				3 wk	2 wk
		None	One time	6 wk	4 wk		
17.68	0	0.007	0.002	0.605	0.129	0.130	0.127
5.98	1	0.000	0.699	0.301	0.000	0.000	0.000
2.98	2	0.051	0.949	0.000	0.000	0.000	0.000
2.68	3	0.147	0.853	0.000	0.000	0.000	0.000

The first column displays calculated costs (in $US) per unit area. Treatments across the top row of this table correspond to; no treatment, one treatment at day 28, and reoccurring treatments every 2, 3, 4, and 6 wk beginning at day 28.

actual populations using monitoring alone. Using an economic approach to estimate the need for insecticide applications in food storage sites may be a useful addition to IPM programs. Using target mortality models to analyze economic risks and benefits may enable pest managers to optimize multiple control methods and improve their pest management programs.

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