ALTERNATIVES TO METHYL BROMIDE FUMIGATION FOR INSECT CONTROL IN RICE AND WHEAT PROCESSING FACILITIES: AN ECONOMIC OPTIMIZATION

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ALTERNATIVES TO METHYL BROMIDE FUMIGATION FOR INSECT CONTROL IN RICE AND WHEAT PROCESSING FACILITIES: AN ECONOMIC OPTIMIZATION

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Abstract: Insect control is very important in processing facilities for grain and grain-based products. Managers need economic information to choose appropriate insect control methods in their goal of profitably producing wholesome products. One approach to insect control is to fumigate at calendar-based intervals, perhaps determined by historical success or scheduled on holiday weekends to minimize shutdown costs. An alternative approach is to fumigate based on monitoring and evaluation of insect population dynamics. Monitoring-based fumigation may avoid unnecessary treatments, which would reduce costs, insecticide use, insect resistance to insecticides, and worker exposure to insecticides. However, little is known about the costs and efficacy of these strategies in food processing facilities.

Here, costs of several insect control strategies are evaluated and compared using an economic-engineering approach. The strategies include sanitation, calendar-based fumigation, and monitoring-based fumigation (an IPM approach). Components of treatment cost considered include sanitation cost, insect monitoring cost, fumigation cost, and the opportunity cost of shutdown time. An insect growth model is used to estimate the insect population under each treatment strategy. Lowest-cost strategies that achieve target insect population thresholds or below are selected.

The selected lowest-cost strategies under most scenarios are calendar-based fumigations. Under the range of weather conditions and insect population thresholds considered here, monitoring-based fumigation strategies result in more, rather than fewer, fumigations on average. Thus, this particular IPM approach raises costs and does not necessarily reduce insecticide use.

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INTRODUCTION

Background

Insect infestation during rice and wheat storage and processing can cause extensive damage. It has been estimated that at least one-third of the food supply potentially available to the population of the United States is lost on an annual basis due to pest infestations during production and post-harvest. In addition, more than 9 billion is spent annually on chemical pesticides applied in agriculture and industry as farmers and processors attempt to reduce losses (Benbrook, 1996). Insects and their fragments can cause direct product loss and market discounts to producers and annoyance or even health hazards to consumers. Also, product recalls resulting from insect infestation could cost millions of dollars, in addition to loss of reputation by producers and processors (although recalls due to insect infestation are probably much less likely than recalls due to food safety issues) (Marshall and Wordsworth, 1994; Arthur and Phillips, 2003; Batresmarquez, Jensen, and Upton, 2009).

In this article we will focus on wheat and rice processing facilities, especially rice. The need to maintain product quality is quite important to the US rice and wheat industries. But more concerns will fall on rice industry, since the predominant market for rice is for direct human consumption, unlike the markets for non-wheat grains, which are primarily used as livestock feed, and wheat, which is extensively processed before consumption by humans. Both domestic consumption and export of rice in the United States has been increasing in recent years. Some factors contributing to the increase include the growing Asian-American and Hispanic-American populations, new and expanded offerings of rice-based food products, and marketing efforts by the rice industry (Batresmarquez, Jensen, and Upton, 2009). As rice consumption increases, quality of the rice and wholesomeness (pest-free) are increasingly important in rice milling.

For many years, fumigants and residual insecticides have been used to control insects for rice and wheat products. Methyl bromide has been the most important component of insect control management in rice and wheat mills and other processing facilities. Because this fumigant was classified as an ozone-depleting substance in the Montreal Protocol, it is being phased out worldwide (Ristaino and Thomas, 1997; Bell et al. 1998). In the original plan, developed countries were scheduled to reduce it 100 percent by 2005 and developing countries by 2015. Under CUEs (critical use exemptions) program, though, methyl bromide has still been available to rice millers in the U.S. who are members of the USA Rice Millers Association in the year 2014 (http://www.epa.gov/ozone/mbr/cueuses.html). The loss of methyl bromide, together with increased concerns about worker safety and insects developing resistance to insecticides, has led to an intensive search for alternatives, including alternative fumigants and Integrated Pest Management (IPM).

Phosphine and sulfuryl fluoride are two registered fumigants which could potentially substitute for methyl bromide. Phosphine is used to fumigate bulk grains, but it is corrosive to metals, and will damage electrical equipment and wiring (Bond et al. 1984). Because of the corrosion issue, use of phosphine for fumigation of rice mills has been limited. Sulfuryl fluoride, under the trade name ProFume™ (Dow AgroSciences LLC), is a registered fumigant that is a viable alternative to methyl bromide. Small (2007) evaluated its efficacy against infestation of flour beetles (*Tribolium spp.*) and of Mediterranean flour moth (*Ephestia kuehniella*) between sulfuryl fluoride and methyl bromide in UK flour mills, finding no significant difference in initial insect mortality and recovery of insect population. More recently, US-EPA has proposed the revocation of all food tolerances associated with sulfuryl fluoride as a fumigant for the milling industry. Adam et al. (2010a) found that sulfuryl fluoride fumigation typically costs more than methyl bromide fumigation in food processing facilities and warehouses.

An alternative for methyl bromide, integrated pest management, has been defined by Kogan (1998, p. 249) as "a decision support system for the selection and use of pest control tactics, singly or harmoniously coordinated into a management strategy, based on cost/benefit analyses that take into account the interests of and impacts on producers, society, and the environment." IPM is a balanced use of multiple control tactics – biological, chemical, and cultural – as is most appropriate for a particular situation in light of careful study of all factors involved (Way, 1977). Monitoring-based decision making and multiple strategies of insect control techniques are two key factors for IPM. Available treatments can be more easily and effectively used if the insect population is monitored timely and precisely in rice and wheat processing facilities. Unnecessary fumigation could be reduced by insect population sampling, saving money and reducing potential for other fumigation-related problems, including worker safety. Using multiple strategies of insect control techniques can slow the development of insect resistance to the conventional insecticides. From the consumer side, Su et al. (2010) found that consumers were willing to pay an average of six cents per pound more for rice stored using IPM methods rather than using conventional fumigation methods to control the insects.

Although there are several potential advantages in using IPM for insect control in food processing facilities, it is not clear if the benefits are more than the costs. In the case of stored wheat, the simulation analysis by Adam et al. (2010) found that sampling-based fumigation was an economically attractive alternative to conventional calendar-based fumigation only under certain conditions, such as a minimum percentage of storage bins in a wheat elevator having a low rate of insect immigration.

In the case of rough rice storage, IPM methods may identify fumigation dates more optimally, but may not reduce the number of fumigations needed, and as a result may not reduce costs. Monitoring insect populations requires significant expertise and more labor. Since special management expertise is needed for IPM, there is risk that a manager would fail to apply IPM methods correctly. Also risk exists in sampling itself, since it may fail to detect an insect problem.

There are few studies of economic feasibility of IPM in rice and wheat processing facilities. This study will provide helpful economic information to rice and wheat processors searching for economical insect control alternatives to conventional methyl bromide fumigation.

Objectives

The purpose of this thesis is to determine the least cost combination of insect control methods that will achieve the desired level of target insect control in rice and wheat processing facilities. Specifically, this study will generate an optimization model to find the most cost-effective insect control approach, comparing calendar-based and monitoring-based fumigation strategies as well as two levels of sanitation.

Outline of Methods

To determine the best insect control strategy, the cost and effectiveness of each insect control method must be known. In a previous study of economics of insect control in stored grain by Adam et al. (2010), the expected total cost of each pest control strategy was estimated by adding the cost of treatments and the cost of failure to control insects.

Following Adam et al. (2010), an economic-engineering approach is used here to estimate the cost of every treatment component, and an insect growth model is used to predict the effect of each treatment on adult insect population. However, whereas the cost of failing to control insects in stored grain can be estimated using market-based grade and quality discounts, the cost of failing to control insects in rice and wheat processing facilities is difficult to estimate. There is little information about discounts due to insect-damaged kernels and from the live insects in the rice and wheat processing facilities, and the relationship between insect population and economic loss is much less predictable.

Therefore, an alternative approach is used here. Due to the special characteristics of rice and wheat processing facilities, this cost minimization model will select the least-cost insect control strategy from among several reasonably available treatment strategies, with a constraint that the strategy achieves a target level of insect control.

The reasoning is as follows. The relationship between insect population in any given location within a processing facility and the resulting economic loss is highly variable. For example, insects in a warehouse portion of the facility where sealed packages of the processed product are ready for shipment are less likely to cause economic loss than they would if they were in the room where the processed product is put into packaging. Little, if any, information is available relating insect population to economic loss in processing facilities. Therefore, it is assumed here that processing facility managers have at least an intuitive knowledge of the level of insect population that each location in their facilities can tolerate before the insects cause significant economic loss. With this assumption, we can assume that the manager has sufficient insight to be able to select a desired target level of insect population, above which economic loss would be greater than treatment cost. However, it should be noted that additional research is needed on the relationship between insect population and economic loss; the results of this thesis provide an initial approximation of optimal strategies.

CHAPTER II

REVIEW OF LITERATURE

Target Insect and Rice and Wheat Milling

According to McKay et al. (2010, p.1) , “Red flour beetle (*Tribolium castaneum*) is the most frequently targeted pest for methyl bromide fumigations under the continuing use exemption (CUE) program for rice mills.” As an important worldwide pest of post-harvest products, *T. castaneum* challenges the efficacy of control tactics since it can adapt well to heterogeneous landscapes and successfully disperse among several resource patches over its lifetime (Romero et al. 2010). The survival and reproduction rates of red flour beetle are higher on wheat flour than on whole grain. They lay eggs in the grain bulk and spend their entire life cycle outside the grain kernel (Karunakaran et al. 2004). The red flour beetle is more difficult to eliminate with insecticides compared to other stored product beetles (Arthur 2008). Hence it can be used as a model insect to develop management plans for rice and wheat mills.

Rice milling converts rough rice into polished white rice. First, removing the husk from rough rice gives brown rice, which is classified by FDA as whole grain. Then, removing the bran layer of brown rice produces milled rice. After several additional processing steps, the milled rice becomes polished white rice. During rice milling, two types of waste material – husks and bran – are produced, both of which could be used by red flour beetles to oviposit, or lay eggs (Campbell and Runnion, 2003). After processing, polished white rice is packed into bags.

Marshall and Wordsworth (1994) mention in their book that during all these processes, if insects are controlled to below a certain level in the facility, little damage will be done by the pests. But if the population is not controlled, rice and wheat may be damaged, and insects and their fragments may be found in the packaged rice or the package wheat flour. Serious economic loss can occur, including rejection by buyers, recalls, and damage to the processor's brand reputation.

Within a processing facility, insects will be present in varying numbers in different locations, depending on factors such as temperature and humidity, presence of food sources (such as particles of the husks and bran removed in processing), and ease of insect immigration from outside and other areas of the facility (Troller, 2012). The costs of insect infestation may also vary across locations. For example, insects in processing stages and locations near the final product may cause greater damage and economic costs than insects in earlier stages of processing which are away from the final product.

A Geographic Information Systems (GIS) model that considers the proximity of insects to sensitive areas and the damage of the infestation in those areas could be used to set the desired level of insect population. For example, darker areas in the contour map below taken from Campbell et al. (2004) show increased levels of insect activity. The darkest area is just near to the rice processing machine, which is the "zero-tolerance zone", and means the desired level of the insect numbers of this area is very low. This contour map is generated from monitoring traps data which show the insect population at each trap location.

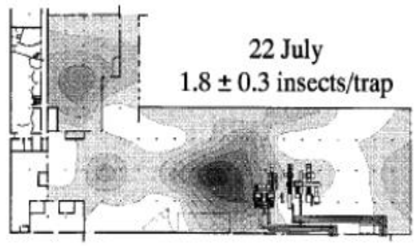

Figure 1. Contour map of Insect population density
Source: Campbell et al. 2004

<u>Conventional Insect Control Management</u>

Conventional fumigation management in processing facilities may frequently be implemented based on the calendar. Fumigants fill an entire facility with the insecticide, and since workers and food material must be removed from the facility during fumigation, plant operations are shut down for several days. The opportunity costs of this are high, so managers typically schedule fumigations over holiday weekends, such as Memorial Day and Independence Day weekends, when the facility would be shut down anyway. These fumigations have historically relied on methyl bromide. For more than 50 years, methyl bromide has been the most cost-efficient fumigant to control insects, nematodes, pathogens, and weeds (Bell et al. 1998). Methyl bromide is more effective than alternative fumigants at killing all life stages of insects. However, methyl bromide has been designated as an "ozone depleter," and will soon be, for typical fumigations, unavailable (Ristaino and Thomas, 1997).

Alternatives

The alternatives to methyl bromide fumigation have strengths and weaknesses. The ease of use and residue-safe nature of phosphine (PH_3) gas has made it a common fumigant used for controlling insect infestation in stored commodities in most places around the world (Benhalima et al. 2004; Rajandran and Sriranjini, 2008). As an alternative fumigant, phosphine's severe limitation for use in processing facilities is that it is corrosive to metals, including electrical and electronic components.

Bell and Savvidou (1999) found that ProFume® (trade name for sulfuryl fluoride) was effective as a fumigant, but that higher doses or longer exposure times were required to kill eggs of some species compared to methyl bromide. Adam, Bonjour, and Criswell (2010) compared the cost of methyl bromide and sulfuryl fluoride for fumigating food processing facilities. They found that the amount of ProFume required for insect control is about two thirds more than the amount of methyl bromide required, so that using sulfuryl fluoride is 28% to 55% more expensive than using methyl bromide in fumigating a 28,317 m^3 warehouse.

Boina et al. (2008) have tested physical control methods such as heat treatment. Extremely high temperatures (50ºC or above) in the grain mill can effectively kill insects within the mill and facilities, but the costs of electricity and equipment are much higher than for methyl bromide. Mortality of *T. castaneum* life stages was 100% in most mill locations, except in areas where the temperature was below 50ºC. However, the pupae stage mortality still need to be studied (Mahroof et al. 2003).

Recently, some entomologists (Arthur, 2008; Arthur and Campbell, 2008; Jenson et al., 2010a) have been working on distribution and efficacy of aerosol treatment on insect control programs in food storage and processing facilities. Aerosol insecticides (also known as ultra-low-volume or fogging treatments) are often delivered through an ultra-low-volume application system. Jenson et al. (2010b) noted that a possible treatment combination is to use synergized pyrethrins (1%) combined with the insect growth regulator (IGR) methoprene. Result shows that aerosols are efficient methods to control pest. However, the drawback of aerosols is that they are only effective with exposed insects. Arthur (2012) suggests that refugial areas within a rice mill could be considered obstructed to aerosol penetration, thus allowing insect populations to persist and develop.

McKay et al. (2010) note that one of the most common residual insecticides used as a surface treatment for stored product insects is the pyrethrin cyfluthrin. The new formulation of cyfluthrin is marketed as B-cyfluthrin, trade name Tempo SC Ultra, but there are no published studies that examine the effects from rice mills on residual efficacy.

Sanitation programs have been considered as the initial step in stored pest control methods (Phillips and Thorne, 2009; Campbell et al., 2004). Sanitation can remarkably reduce the food source which insects can exploit, and helps ensure that insect control treatments remain effective for extended periods of time (Arthur, 2000). Sanitation is an important part of pest management programs, but it is difficult to quantify its impact on pest population levels. A recent study by Scott et al. (2015) compared the annual costs in pest control of two food processing facilities whose managers had different attitude towards sanitation. Facility A treated sanitation as the foundation for insect control program, while Facility B emphasized fumigation in controlling insect infestations. They found Facility A spent less overall on both pest control and sanitation than Facility B, and concluded that sanitation is important, but that a larger study sample is required to confirm this.

Integrated Pest Management

"Integrated Pest Management (IPM) is the implementation of diverse methods of pest controls, paired with monitoring to reduce unnecessary pesticide applications." (USDA ERS, 2011). Way (1977) pointed out that IPM is a balanced use of multiple control tactics – biological, chemical, and cultural – as it is most appropriate for a particular situation in light of careful study of all factors involved. Food industry IPM goals are to prevent insects from entering the facility and to keep populations from increasing or becoming established in the production stream. IPM programs must focus on prevention, detection, and early elimination of insect problems. IPM approaches offer the potential to either completely eliminate the need to fumigate or to reduce the frequency of fumigation.

McKay et al. (2010) noted that an integrated approach to insect pest management that has been advocated for the wheat milling industry, combining the use of insect population sampling, sanitation, aerosol insecticides, and residual surface treatments, can also be applied to rice mills. Among all the treatments, sampling (monitoring) the insect population is essential.

One way to sample red flour beetle populations uses pitfall traps baited with food oil along with aggregation pheromone for the species (Arthur and Phillips, 2003). While the relationship between trap catch and pest population is not always clear (Toews et al., 2005, 2009; Campbell, 2006), data are available to describe the seasonal patterns and response to treatment. According to Campbell et al. (2010ab), trap catch data show how red flour beetle populations rebound after fumigation, and threshold of two adults 14 days has been used to estimate population rebound after fumigation with methyl bromide and sulfuryl fluoride. Evidences proved that insect population in the facilities can be well evaluated by the approaches the entomologist provided.

Insect Growth Model

The red flour beetle growth model used in this study is described by Flinn et al. (2010). The model was developed by the authors for wheat flour mills, and considers the survivorship, and pesticide-induced mortality for individual life stages. The model predicts mean insect density for each floor of a flour mill based on historical inside air temperature. This mathematical model incorporates the impact of structural fumigations and aerosol insecticide applications, as well as the impact of sanitation. Although the parameters were calibrated using data from wheat mills, this model also can be modified and applied to rice milling.

Figure 2 below shows the input and results interface of the insect growth model for predictions of daily insect population for each floor using temperature data from 01/11/2005 to 01/11/2007, zero immigration per ten days, two fumigations with sulfuryl fluoride at 07/04/2005 and 07/04/2006, using good sanitation procedures, and the model's default starting number of insects. The results show the prediction number of daily insect population (four life stage eggs, pupae, larvae, and adults) during that period.

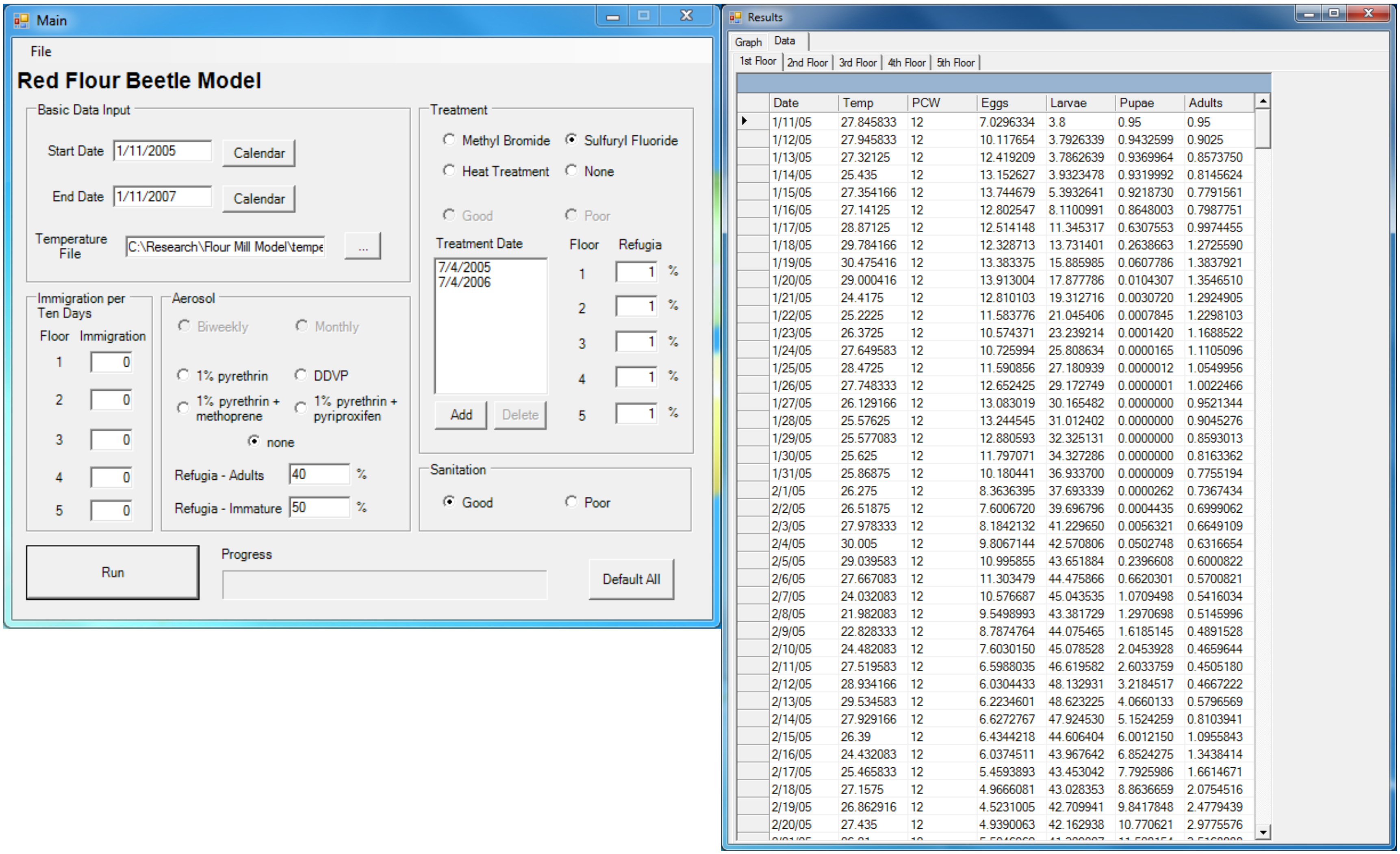

Figure 2. Interface of the insect population growth model

Cost Calculation of Insect Control Management

Mah (2004) showed in her thesis the economic-engineering approach to calculate the cost of integrated pest management in controlling insects on stored grain. The results in her simulation scenarios shows that the IPM strategy sampling twice a month during the year and fumigating only when needed was not economically feasible, because it only changed the timing but not the frequency of fumigation. Thus, a sampling-based strategy increased the costs by the extra sampling costs, without increasing benefits.

Adam et al. (2010b) compared the economic costs and benefits of conventional calendar-based fumigation and a sampling-based integrated pest management approach in Oklahoma. A sampling-based IPM approach would have been profitable for elevators in this climatic region only if a minimum percentage of their storage bins had a low insect immigration rate. Although the studies by Mah (2004) and Adam et al. (2010b) apply directly to wheat storage, the cost calculation approach can be applied to rice and wheat processing facilities.

CHAPTER III

METHODOLOGY

Conceptual Framework

It is assumed that the manager of a processing facility seeks to choose the strategy – combination of treatments – that minimizes the combined treatment cost and cost of failure to control insects. Treatment cost (*TCj*) includes the labor, material, training, equipment and chemical costs of each treatment in the strategy and the opportunity cost of shutdown time. The expected cost of failing to control insects (E(FC_j)) includes losses due to market discounts, weight loss, buyer rejections, recalls, and loss of brand value.

(1) $$\min_j E(C_j) = TC_j + E(FC_j),$$

where $E(C_j)$ is the expected cost of insect control strategy *j*, TC_j is the treatment cost associated with the *j*th insect control strategy, and $E(FC_j)$ is the expected cost of failure to control insects using the *j*th strategy. Adam et al. (2010) estimated this failure-to-control cost for stored wheat by summing the discounts due to damaged grain (IDK insect-damaged kernels) and presence of live insects in a sample.

In processing facilities, it is very difficult to estimate the damage caused by uncontrolled insects and how much the damage will cost. Also, damage estimates are likely to vary widely across facilities and be highly sensitive to basic assumptions. Thus, the model specified above is modified so that its objective is to minimize strategy cost subject to achieving a target insect population. It is assumed that managers at each facility have sufficient prior information based on their operating experience to determine at least implicitly the insect population that can be sustained without causing excessive costs or risk. The general conceptual model is specified as

(2) $$\min_{Q_{i,l,t}} E(TC_j) = \sum_i \sum_l \sum_t Q_{i,l,t} * TRC_{i,l,t} + SC_j$$

$$\text{s.t.} \;\; I_{l,t}(j) < K_{l,t},$$

where TC_j is the treatment cost associated with the *j*th insect control strategy, the choice variable $Q_{i,l,t}$ is quantity of treatment *i* implemented at location *l* in time *t* in the *j*th insect control strategy. $TRC_{i,l,t}$ is the unit costs of treatment combination $Q_{i,l,t}$, so the treatment cost of strategy *j* can be calculated as $Q_{i,l,t} * TRC_{i,l,t}$. SC_j is the estimated shutdown cost of conducting the *j*th treatment, essentially an opportunity cost resulting from not being able to use the facility. The constraint $I_{l,t}(j)$ is the insect population at location *l* and time *t* using strategy *j* with $K_{l,t}$ the maximum allowed insect population at location *l* and time *t*.

Table 1 lists the types of treatments considered for use in a rice processing facility.

Table 1. Summary of possible insect control treatment in rice processing facility

i	type of treatments
1	Sanitation
2	Target Aerosols
3	Space spray
4	Structure modification
5	Aeration
6	extreme temperature treatment
7	Surface pesticide treatment
8	Fumigation with Sulfuryl Fluoride

Location *l* indicates the location of the trap, each of which includes a surrounding area, so that the set of locations cover the entire processing facility. Time *t* stands for each day during the insect control period. It is assumed that if monitoring at time *t* indicates treatment is necessary, treatment also occurs at time *t*.

In the constraint of insect population level, $I_{l,t}(j)$, the insect population achieved using strategy *j*, is estimated using an entomological growth model specifically developed for red flour beetles in processing facilities (Flinn et al. 2010). This prediction is based on the initial insect population, immigration rate, temperature, and other environmental factors, as well as the effect of the treatments administered. $K_{l,t}$ is the threshold level of insect control. The threshold $K_{l,t}$ can be selected by each rice mill manager to match the mill's situation.

This cost minimization model selects the lowest cost insect control strategy among all the available treatment strategies while satisfying the threshold insect population constraint. (Without the constraint, the minimum cost would be achieved by doing nothing.)

Procedures

The purpose of this research is to find the lowest-cost treatments that achieve the threshold insect population or below in the rice processing facilities. Following Adam, Bonjour and Criswell (2010), a 28,317 m^3 (approx. 1,000,000 ft^3) rice processing facility is assumed, so that that paper's cost of ProFume fumigation can be directly applied here.

The first step is to identify the strategies to be considered in the analysis. The thirty-two treatment strategies simulated (table 2) include combinations of: two levels of sanitation, good sanitation and poor sanitation; calendar-based fumigations; and monitoring-based fumigations. Two strategies without either monitoring or fumigation – one with good sanitation and one with poor sanitation – provide a baseline for insect population to compare with the other strategies. Following industry practice for strategies involving fumigations, since shutdown time is needed for fumigation volatilization and worker safety, calendar-based fumigations are scheduled here on Memorial Day, Independence Day and Thanksgiving which are the holidays during which processing facilities would normally be shut down for fumigation. Thus, for the first part of the analysis, shut-down costs can be reasonably ignored as part of fumigation costs. The assumption of treatment on holiday weekends is then relaxed to assess the effect of shut-down costs on choice of treatment strategy.

Timing and frequency of monitoring is important for the strategies based on monitoring-based fumigation. Three monitoring frequencies used here are: monthly monitoring (every month's first day is the monitoring date), biweekly monitoring (every month's first day and 15th day are the monitoring dates), and a seasonal monitoring frequency (monitoring biweekly in June, July, August and September while monitoring monthly in the other months). Since summer temperatures are most conducive for insects to reproduce, unchecked populations rapidly increase during those months. Seasonal monitoring frequency is more likely to detect quickly-expanding summer populations with more frequent monitoring, while saving cost with less frequent monitoring during months when insect populations typically grow less rapidly.

Under monitoring-based fumigation, the “trigger” to fumigate is when insect population on a floor of the processing facility measured by trap-based monitoring is beyond a specified threshold number. Here, 100, 150, 200 and 250 are set for the triggers. Though these numbers are selected arbitrarily in some degree, they result in a reasonable fumigation frequency (one to three times per year). If the trigger were less than 100, the model would prescribe a large number of fumigations; if a trigger greater than 250 were selected, it is possible that no fumigation would be prescribed during a year, which is an unrealistic result for most situations.

To illustrate the decision rules, the 9th strategy, for example, a monitoring-based strategy with poor sanitation, monitors the adult insect population every 1st day of the month and prescribes fumigation if the insect population is greater than 100. The 24th strategy, a monitoring-based strategy with good sanitation, monitors the adult insect population every 1st and 15th day of the month and prescribes fumigation if the insect populations is greater than 250. The 30th strategy, a monitoring-based strategy with good sanitation, monitors the adult insect population every 1st and 15th day for June, July, August and September and every 1st day for the other months, and prescribes fumigation if the insect populations is greater than 150.

Table 2. Simulated Strategies

ID		Treatments
1		Poor sanitation
2		Good sanitation
3	Calendar Based Strategies	Fumigation [a] once a year; poor sanitation
4		Fumigation once a year; good sanitation
5		Fumigation twice a year; poor sanitation (Independence Day, Memorial Day)
6		Fumigation twice a year; good sanitation
7		Fumigation 3 times a year; poor sanitation (Independence Day, Memorial Day and Thanksgiving)
8		Fumigation 3 times a year; good sanitation
9	Monitoring Based Strategies	Poor Sanitation; Monitoring monthly; If monitoring observation >100 then Fumigate
10		Poor Sanitation; Monitoring monthly; If monitoring observation >150 then Fumigate
11		Poor Sanitation; Monitoring monthly; If monitoring observation >200 then Fumigate
12		Poor Sanitation; Monitoring monthly; If monitoring observation >250 then Fumigate
13		Poor Sanitation; Monitoring Biweekly; If monitoring observation >100 then Fumigate
14		Poor Sanitation; Monitoring Biweekly; If monitoring observation >150 then Fumigate
15		Poor Sanitation; Monitoring Biweekly; If monitoring observation >200 then Fumigate
16		Poor Sanitation; Monitoring Biweekly; If monitoring observation >250 then Fumigate
17		Good Sanitation; Monitoring monthly; If monitoring observation >100 then Fumigate
18		Good Sanitation; Monitoring monthly; If monitoring observation >150 then Fumigate
19		Good Sanitation; Monitoring monthly; If monitoring observation >200 then Fumigate
20		Good Sanitation; Monitoring monthly; If monitoring observation >250 then Fumigate
21		Good Sanitation; Monitoring Biweekly; If monitoring observation >100 then Fumigate
22		Good Sanitation; Monitoring Biweekly; If monitoring observation >150 then Fumigate
23		Good Sanitation; Monitoring Biweekly; If monitoring observation >200 then Fumigate
24		Good Sanitation; Monitoring Biweekly; If monitoring observation >250 then Fumigate
25		Poor Sanitation; Seasonal Monitoring; If monitoring observation >100 then Fumigate
26		Poor Sanitation; Seasonal Monitoring; If monitoring observation >150 then Fumigate
27		Poor Sanitation; Seasonal Monitoring; If monitoring observation >200 then Fumigate
28		Poor Sanitation; Seasonal Monitoring; If monitoring observation >250 then Fumigate
29		Good Sanitation; Seasonal Monitoring; If monitoring observation >100 then Fumigate
30		Good Sanitation; Seasonal Monitoring; If monitoring observation >150 then Fumigate
31		Good Sanitation; Seasonal Monitoring; If monitoring observation >200 then Fumigate
32		Good Sanitation; Seasonal Monitoring; If monitoring observation >250 then Fumigate

[a] All fumigations assume that sulfuryl fluoride (tradename ProFume®) is the fumigant.

The second step is to get the insect population prediction results from the insect growth model for these 32 strategies. The model's default starting numbers of red flour beetle's four life stages (eggs 3.6, pupae 1.0, larvae 4.1 and adults 1.4) and default of zero immigration rate were used for all the simulated scenarios. Three periods of two years of historical temperature (inside the facility) data were used in the growth model to predict insect population under thirty-two simulated insect management strategies (Table 2):

1) 01/11/2005 to 01/10/2007 (Period I, t = 1 - 730), and
2) 01/11/2007 to 01/10/2009 (Period II, t = 731 – 1,461), and
3) 01/11/2009 to 01/11/2011 (Period III, t = (1,462 – 2,191).

The three two-year periods all start in winter, which is consistent with the relative low starting number of the insect, since the insect population are usually small during the winter. As shown in Figure 2, the results are series of insect populations for each day during the periods for each strategy considered. Here, an assumption is made that the facility for which the insect growth model is calibrated is the same size as the 28,317 m^3 facility assumed for the treatment cost calculations. We have to assume that the insect growth model is calibrated for the 28,317 m^3 rice processing facility.

The third step is to estimate the treatment costs for the 32 given strategies. Treatment costs considered in this study include sanitation cost, insect monitoring cost, fumigation cost, and the opportunity cost of shutdown time.

The final step is the selection of the least cost strategy that will achieve specified insect population targets. Using the insect population predictions, combined with the cost estimates of the strategies that yielded those insect population predictions, the model selects the lowest cost strategy given a specified target, or threshold, insect population.

The insect population threshold can be expressed as either the maximum number of insects permitted on any day of the period, or the mean daily number over all the days of the period. Using the average daily number of insects over the time period may better represent ongoing insect pressure, ignoring population spikes if they are temporary, while using the maximum number as a threshold may better represent acute situations that could easily spiral out of control. In addition, since the number of strategies considered is limited to a set of 32, rather than all possible combinations of i, k, and l, the model expressed in (2) above can be expressed as

$$(3) \qquad \min_{j} E\left(TC_{j,T}\right)$$

$$\text{s.t.} \quad \text{Mean}\left(I_{j,T}\right) < K_{\text{mean}} \text{ or } \text{Max}\left(I_{j,T}\right) < K_{\text{max}} \;;$$

$$j \epsilon [1,2,\ldots,32];$$

$$T \epsilon [1,2,3] \text{ (as defined above) } \begin{cases} T = 1, \text{stand for period I} & t = 1 - 730, \\ T = 2, \text{stand for period II} & t = 730 - 1461, \\ T = 3, \text{stand for period III} & t = 1461 - 2191, \end{cases}$$

for each period I, II, and III, where $\text{Mean}\left(I_{j,T}\right)$ is the mean value of $I_{j,T}$, $\text{Max}\left(I_{j,T}\right)$ is the maximum value of $I_{j,T}$, and K_{mean} and K_{max} are the corresponding insect population thresholds. Since the insect population results estimated by Flinn's insect growth model are the whole insect population of the first floor, there is no need to include the subscript *l* which stand for specific location in this optimization model (3). For both of these models, it is assumed that the monitoring results for insect population from using a monitoring-based fumigation approach are consistent with the true insect population, as predicted by the insect growth model.

Data and Sources

Together with the optimization model which predicts insect population for each floor of the facility under alternative insect control treatments using daily temperature data for the specified time periods, and an assumed insect immigration rate, the following data are needed: cost of each component of the treatment for each strategy, and the annual revenue for this assumed 28,317 m^3 rice processing facility (for estimating the opportunity cost of shutdown time).

We are using the cost data for conducting a fumigation with ProFume® fumigation from Adam, Bonjour, and Criswell (2010).

Table 3. Cost of Hypothetical 24-hr Fumigations of a 28,317 m^3 Food Processing Facility for ProFume per job.

Cost Component	**USD**
Equipment	$58
Labor	$4,134
Training	$19
Fumigant	$15,000
Total Cost	$19,211

Source: Adam, Bonjour, and Criswell (2010). (ProFume dosage is assumed to be the Dow-reported average density of 40 g/m^3).

The cost data of monitoring the insect population comes from McKay (2014). The data include the cost of lures and traps, and the time needed for workers to collect, identify, and count the insects collected from the traps.

Table 4. Parameters Used to Calculate Costs of Monitoring a 28,317 m^3 Food Processing Facility Using Lure Traps

Parameter	values
Equipment (per trap)	$0.89
Price of lures per trap per monitoring	$10.72
Labor rate ($/h)	$20.00
Hours/trap/monitoring	0.17
Number of traps in a 28,317 m^3 Food Processing Facility	96
Costs of monitoring per job	$1,444.56

The insect growth model developed by Flinn et al. (2010) is used to predict red flour beetle population. By considering the survivorship and the insecticide-induced mortality for each of four insect growth stages, this mathematical model incorporates the impact of structural fumigations and predicts mean insect population for each floor of the facility based on historical inside air temperature. The authors calibrated their model using data from wheat mills, but it is assumed that those parameters are also appropriate for rice processing facilities. The model is used to predict daily adult insect population over the three two-year periods.

After application of fumigant, the processing facility must be shut down and ventilated for 12 hours, which will be counted as one day (Adam, Bonjour, and Criswell, 2010). The opportunity cost of shutdown time is assumed to be three fourths of the facility's daily revenue. However, because the shutdown cost estimated here could vary widely across facilities, the model is re-estimated for alternative shutdown costs: zero ($0) shutdown time cost (as indicated above, this would be appropriate if a firm can schedule a fumigation on a holiday weekend), 50% shutdown time cost ($15,000) and 100% shutdown time cost ($30,000) are used in selecting the minimum cost strategy that can achieve specified insect populations.

Table 5. Parameters Used to Estimate the Opportunity Cost of Shutdown

Parameter	values
Annual Revenue	$10,000,000
# of workdays per year	250
75% revenue per day	$30,000

Costs for the treatments used in this study – sanitation, insect monitoring, and fumigation with sulfuryl fluoride, and the opportunity cost of shutdown time – are summarized in table 5. In the insect growth model, poor sanitation is defined as achieving 0% mortality for red flour beetle while good sanitation achieves 5% mortality (Flinn et al. 2010). Sanitation costs are calculated by multiplying the labor rate by the number of hours workers have to spend for poor and good sanitation. It is assumed arbitrarily that the amount of labor required to achieve good sanitation is three worker-hours per week, and the amount required to achieve poor sanitation is one worker-hour per week.

Table 6. Costs for Treatments Used in the Applicable Strategies

	Poor Sanitation	Good Sanitation	Fumigation with Sulfuryl Fluoride	Monitoring	Shutdown cost
Equipment			$58	$85	
labor	$1,040	$3,120	$4,134	$330	
Chemicals (lures)			$19	$1,029	
training			$15,000		
Total cost per year	$1,040	$3,120			
Total cost per job			$19,211	$1,445	$0; $15,000; $30,000

CHAPTER IV

RESULTS

Insect Population Results

Figures 3-8 show insect population generated from Flinn et al. (2010) for the periods 2005-2007, 2007-2009 and 2009-2011 under three types of strategies: no treatment, calendar-based fumigation and monitoring-based fumigation.

Figure 3 shows the effect of sanitation on adult insect population over the period 01/11/2005 to 01/11/2007. The simulated numbers show that insect population increases rapidly from June to October both years, with the maximum value over the two years occurring in summer 2006. (In the year 2006, a small population spike occurred in February, suggesting that temperatures at that time were especially suitable for red flour beetles to reproduce.) The simulation showed that using good sanitation would have reduced the insect population by almost 55% compared to using poor sanitation, with the maximum number decreased from 869 to 402 and the average number decreased from 431 to 199.

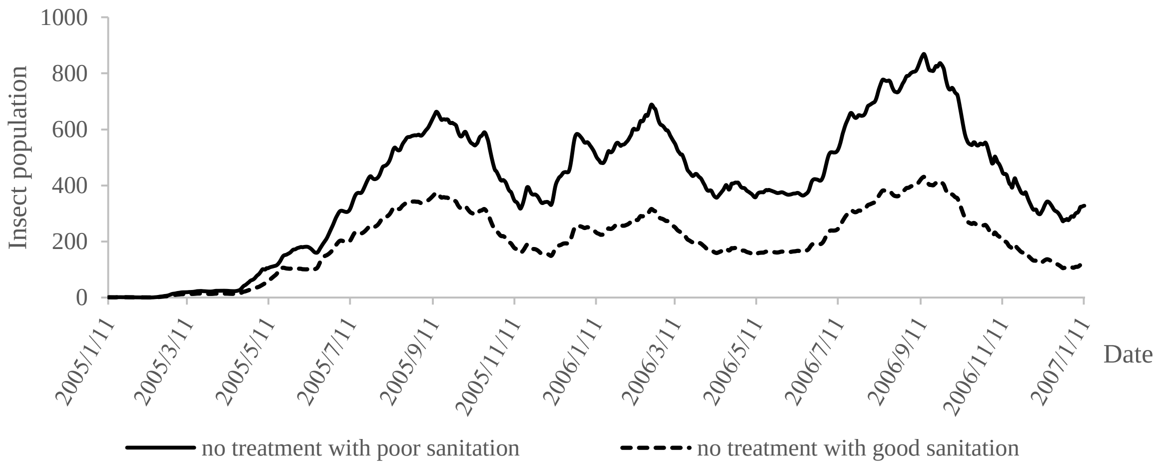

Figure 3: Adult insect population, 2005-2007.

Figures 4 and 5 show insect population for the periods 2007-2009 and 2009-2011. The insect population increased rapidly in the summer time from June to October, but increases in the winter were much smaller. Good sanitation would have reduced insect population during these two periods about 40% compared to poor sanitation. For all three time periods, insect population was lowest in January.

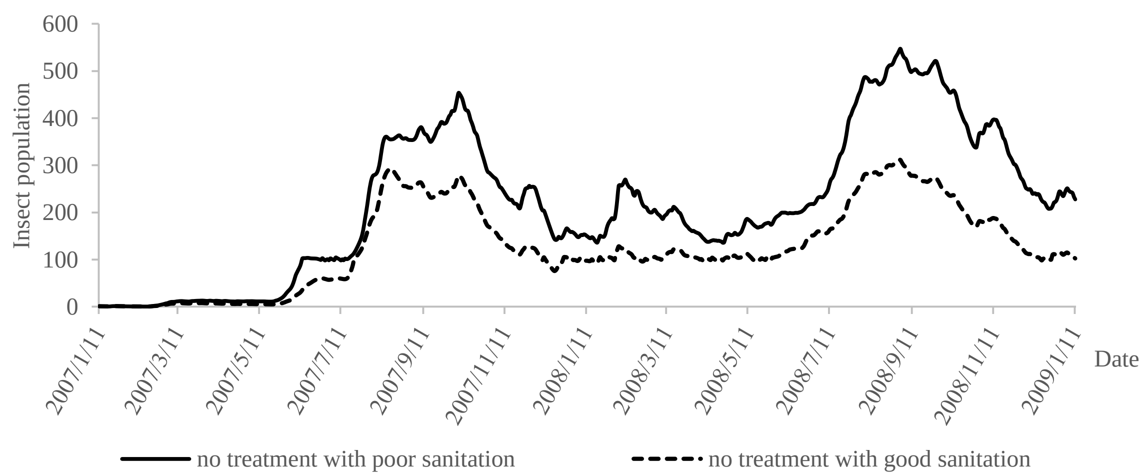

Figure 4: Adult insect population, 2007-2009.

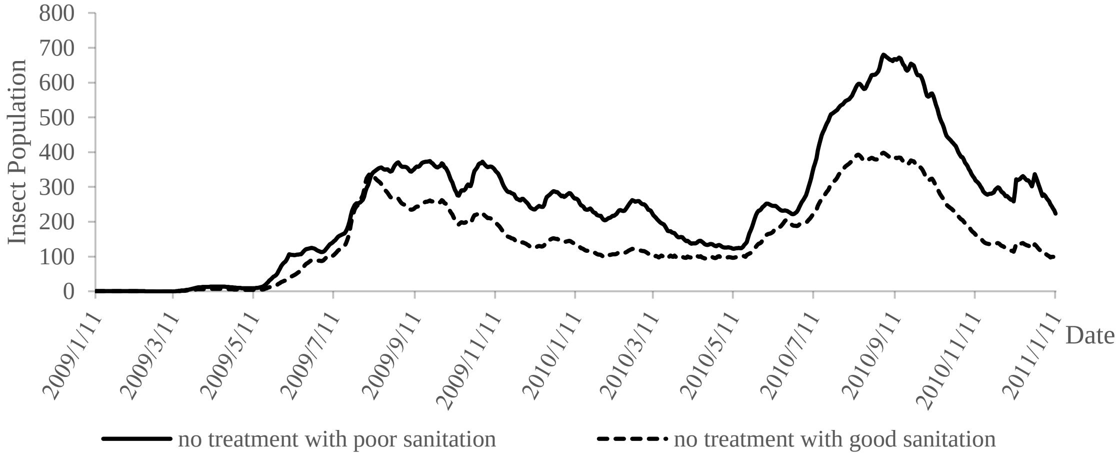

Figure 5: Adult insect population, 2009-2011.

Figure 6 shows simulated adult insect population for the period 2007-2009 under a calendar-based fumigation strategy of fumigating with sulfuryl fluoride twice a year (every Memorial Day & Independence Day), under poor sanitation. During this two-year period, four fumigations would have been conducted. The arrows show the timing of the fumigations. Comparing figures 4 and 6, the first of these fumigations may not have been necessary, since insect population without fumigation (figure 4) stabilized around the time of Memorial Day. The second fumigation, at Independence Day 2007, kept insect population from rising to the high levels seen in figure 4 (the scales of the vertical axes of the graphs are different).

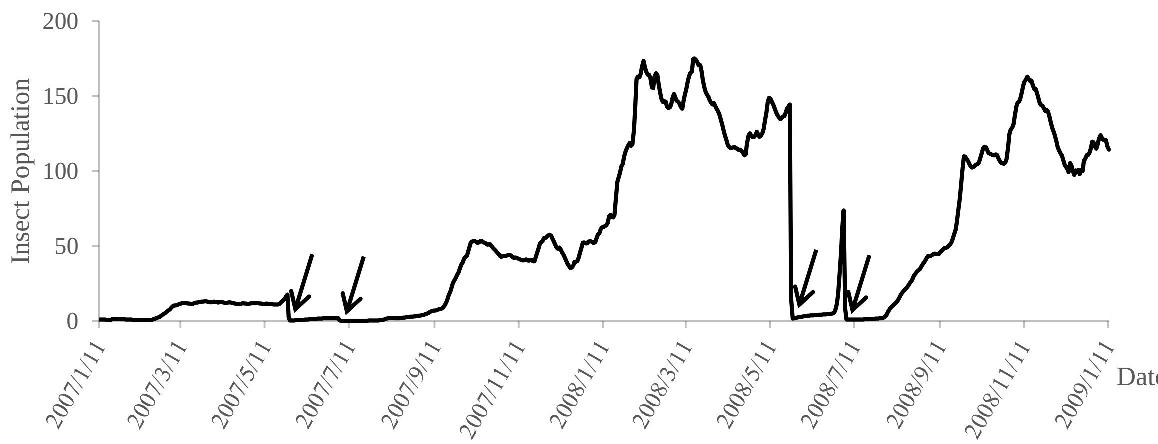

Figure 6. Adult insect population under strategy #5, calendar-based fumigation (2007-2009)

Figure 7 shows simulated adult insect population under a calendar-based fumigation strategy of fumigating with sulfuryl fluoride three times a year (every Memorial Day, Independence Day and Thanksgiving holiday) for the period 2009-2011, under good sanitation. During this two-year period, six fumigations would have been conducted. Figure 8 shows adult insect population under a monitoring-based fumigation strategy that uses seasonal monitoring frequency for the period 2009-2011, under good sanitation. Five fumigations would have occurred, at times in which the scheduled monitoring would have revealed that the insect population was greater than 100, the chosen threshold ("trigger") for this strategy. Comparing figures 7 and 8, insect population under the calendar-based strategy resulted in almost the same maximum value as, and a somewhat higher mean than, using the monitoring-based IPM method (although the number of times insect population reached the maximum was higher with the IPM method), but the monitoring-based strategy would have reduced the number of fumigations by one. This suggests that an IPM method may potentially save costs compared with a calendar-based fumigation approach for controlling insects in a grain processing facility. To determine whether a monitoring-based fumigation strategy does in fact save costs, treatment costs, including the opportunity cost of shutdown time, must be calculated and compared for these two approaches.

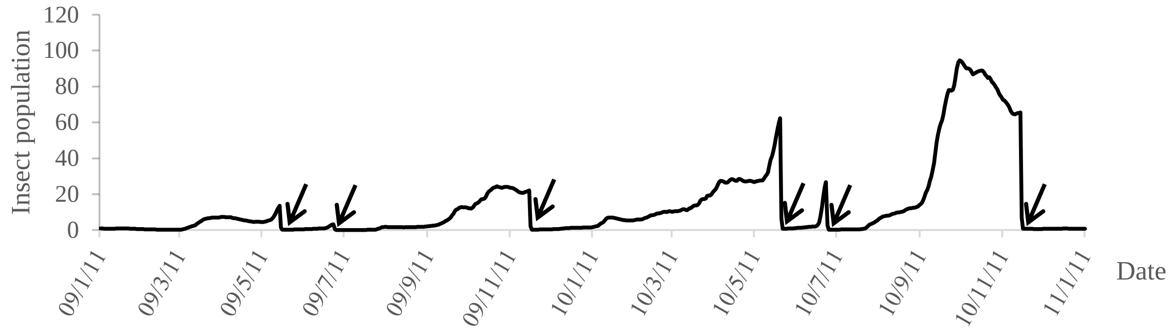

Figure 7. Adult insect population under the calendar-based fumigation #8 (2009-2011)

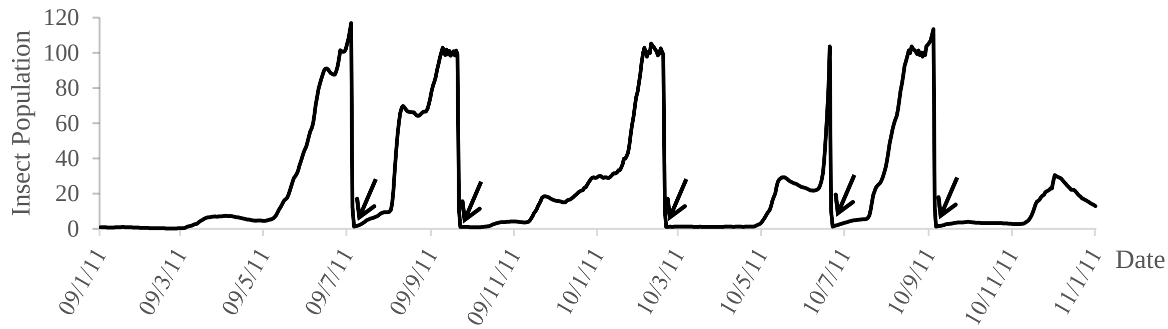

Figure 8. Insect population under the monitoring based fumigation strategy #24 (2009-2011).

Fumigation Implementation Frequency

Table 7 shows the dates fumigations occurred for each of the thirty-two strategies during the three two-year periods. It also shows the total times of fumigations and shutdown times for each strategy during each period in columns named "# of F" and "# of S". For the calendar-based fumigation strategies (strategies #3 through #8), since fumigations are always done on a holiday weekend, the fumigation dates change very little from year to year and there is no opportunity cost for shutdown time. The number of fumigations conducted is fixed for each time period for the calendar-based fumigation strategies, but the number varies for monitoring-based fumigation strategies (Strategies #9 to #32). Due to the relatively higher temperatures, there are more fumigations conducted under monitoring-based fumigation strategies in the period 2005-2007 (average 5.4 times) than in the period 2007-2009 (average 3.2 times) and 2009-2011 (average 3.5 times).

For monitoring-based fumigation strategies, the simulated fumigations occur immediately after the monitoring date that has determined fumigation is necessary. In order to reduce opportunity cost of shutdown time, fumigations that would otherwise be conducted on Jan 1st (New Year's Day), Feb 15th (George Washington's Birthday), Jun 1st (Memorial Day), Jul 1st (Independence Day), Sep 1st (Labor Day) and Nov 1st (Thanksgiving Day) are instead conducted on the nearby Federal Holidays. Table 8, a simplified version of the simulated strategies table (Table 2), is provided below the fumigation frequency table to remind what treatments are conducted in the simulated strategies.

Table 7. Dates and Frequencies of Fumigations under Each Strategy.

Strategy #	Period I 2005—2007		# of F[a]	# of S[b]	Strategy #	Period II 2007—2009		# of F	# of S	Strategy #	Period III 2009—2011		# of F	# of S
	05—06	06—07				07—08	08—09				09—10	10—11		
1	-	-	-	-	1	-	-	-	-	1	-	-	-	-
2	-	-	-	-	2	-	-	-	-	2	-	-	-	-
3	7/4	7/4	2	-	3	7/4	7/4	2	-	3	7/4	7/4	2	-
4	7/4	7/4	2	-	4	7/4	7/4	2	-	4	7/4	7/4	2	-
5	5/30 7/4	5/29 7/4	4	-	5	5/28 7/4	5/26 7/4	4	-	5	5/25 7/4	5/31 7/4	4	-
6	5/30 7/4	5/29 7/4	4	-	6	5/28 7/4	5/26 7/4	4	-	6	5/25 7/4	5/31 7/4	4	-
7	5/30 7/4 11/24	5/29 7/4 11/23	6	-	7	5/28 7/4 11/22	5/26 7/4 11/27	6	-	7	5/25 7/4 11/26	5/31 7/4 11/25	6	-
8	5/30 7/4 11/24	5/29 7/4 11/23	6	-	8	5/28 7/4 11/22	5/26 7/4 11/27	6	-	8	5/25 7/4 11/26	5/31 7/4 11/25	6	-
9	3/1 7/1 9/1	1/1 3/1 7/1 8/1 1/1	8	3	9	7/1 10/1	5/1 8/1 10/1	5	4	9	7/1 9/1	1/1 6/1 8/1 10/1	6	2
10	6/1 9/1	1/1 5/1 8/1	5	2	10	8/1	3/1 8/1 1/1	4	3	10	8/1 12/1	6/1 9/1	4	1
11	6/1 9/1	1/1 6/1 9/1	5	-	11	8/1	7/1 10/1	3	2	11	8/1	3/1 7/1 10/1	4	3
12	6/1 9/1	1/1 7/1 10/1	5	1	12	8/1	8/1	2	2	12	8/1	7/1	2	1
13	3/1 6/15 8/15 12/15	2/15 6/1 8/1 11/15	8	6	13	6/15 9/1	2/15 7/1 9/1	5	1	13	6/15 8/15 12/1	4/15 7/15 9/15	6	5
14	6/1 8/15 12/15	3/15 7/1 9/15	6	4	14	8/1 12/1	6/15 9/1	4	3	14	7/15 11/1	6/1 8/15	4	3
15	6/1 9/1	1/1 5/15 8/15	5	2	15	8/1	2/15 7/1 10/1	4	2	15	8/1	3/1 7/1 9/15	4	3
16	6/1 9/1	1/1 6/15 9/1	5	1	16	8/1	7/15	2	2	16	8/1	7/15	2	2
17	3/1 7/1 10/1	2/1 6/1 8/1 1/1	7	4	17	8/1 12/1	7/1 9/1	4	1	17	8/1 12/1	6/1 8/1	4	2
18	6/1 9/1	1/1 6/1 9/1	5	-	18	8/1	7/1 10/1	3	2	18	8/1	1/1 8/1	3	2
19	6/1 9/1	1/1 7/1 10/1	5	1	19	9/1	8/1	2	1	19	8/1	8/1	2	2
20	6/1 9/1	8/1	3	1	20	9/1	8/1	2	1	20	8/1	8/1	2	2
21	3/1 7/1 9/15	1/1 4/15 7/15 9/15	7	5	21	8/1 12/1	7/1 9/1	4	1	21	7/15 10/1	2/15 7/1 9/15	5	3
22	6/1 8/15	1/1 5/1 8/1	5	3	22	8/1	7/1 10/1	3	2	22	8/1	1/1 7/15 10/1	4	3

23	6/1 9/1	1/1 7/1 10/1	5	1	23	8/15	8/1	2	2	23	8/1	7/15	2	2
24	6/1 9/1	7/15	3	1	24	8/15	8/1	2	2	24	8/1	8/1	2	2
25	3/1 6/15 8/15	1/1 3/1 6/15 8/15	8	6	25	6/15 9/1	3/1 7/1 9/1	5	2	25	6/15 8/15 12/1	5/1 7/15 9/15	6	5
26	6/1 8/15	1/1 5/1 8/1	5	3	26	8/1 12/1	6/15 9/1	4	2	26	7/15 11/1	6/1 8/15	4	3
27	6/1 9/1	1/1 6/1 8/15	5	1	27	8/1	3/1 7/15 11/1	4	4	27	8/1	3/1 7/1 9/15	4	3
28	6/1 9/1	1/1 6/15 9/1	5	1	28	8/1	7/15	2	2	28	8/1	7/15	2	2
29	3/1 7/1 9/15	1/1 5/1 8/1 12/1	7	4	29	8/1 12/1	7/1 9/1	4	1	29	7/15 10/1	3/1 7/1 9/15	5	4
30	6/1 8/15	1/1 5/1 8/1	5	3	30	8/1	7/1 10/1	3	2	30	8/1	1/1 7/15 10/1	4	3
31	6/1 9/1	1/1 7/1 10/1	5	-	31	8/15	8/1	2	2	31	8/1	7/15	2	2
32	6/1 9/1	7/15	3	1	32	8/15	8/1	2	2	32	8/1	8/1	2	2

[a] # of F here refer to the numbers of fumigation conducted during that period; [b] # of S here refer to the numbers of shutdown time during that period; [c] "-" means nothing there.

Table 8. Simulated Strategies

ID		Treatments
1		Poor sanitation
2		Good sanitation
3		Fumigation once a year; poor sanitation
4		Fumigation once a year; good sanitation
5	Calendar-Based Strategies	Fumigation twice a year; poor sanitation (Independence Day, Memorial Day)
6		Fumigation twice a year; good sanitation
7		Fumigation 3 times a year; poor sanitation (Independence Day, Memorial Day and Thanksgiving)
8		Fumigation 3 times a year; good sanitation
9		Poor Sanitation; Monitoring monthly; If monitoring observation>100 then Fumigate
10		Poor Sanitation; Monitoring monthly; If monitoring observation >150 then Fumigate
11		Poor Sanitation; Monitoring monthly; If monitoring observation >200 then Fumigate
12		Poor Sanitation; Monitoring monthly; If monitoring observation >250 then Fumigate
13		Poor Sanitation; Monitoring Biweekly; If monitoring observation >100 then Fumigate
14		Poor Sanitation; Monitoring Biweekly; If monitoring observation >150 then Fumigate
15		Poor Sanitation; Monitoring Biweekly; If monitoring observation >200 then Fumigate
16		Poor Sanitation; Monitoring Biweekly; If monitoring observation >250 then Fumigate
17		Good Sanitation; Monitoring monthly; If monitoring observation >100 then Fumigate
18	Monitoring-Based Strategies	Good Sanitation; Monitoring monthly; If monitoring observation >150 then Fumigate
19		Good Sanitation; Monitoring monthly; If monitoring observation >200 then Fumigate
20		Good Sanitation; Monitoring monthly; If monitoring observation >250 then Fumigate
21		Good Sanitation; Monitoring Biweekly; If monitoring observation >100 then Fumigate
22		Good Sanitation; Monitoring Biweekly; If monitoring observation >150 then Fumigate
23		Good Sanitation; Monitoring Biweekly; If monitoring observation >200 then Fumigate
24		Good Sanitation; Monitoring Biweekly; If monitoring observation >250 then Fumigate
25		Poor Sanitation; Rational Monitoring; If monitoring observation >100 then Fumigate
26		Poor Sanitation; Rational Monitoring; If monitoring observation >150 then Fumigate
27		Poor Sanitation; Rational Monitoring; If monitoring observation >200 then Fumigate
28		Poor Sanitation; Rational Monitoring; If monitoring observation >250 then Fumigate
29		Good Sanitation; Rational Monitoring; If monitoring observation >100 then Fumigate
30		Good Sanitation; Rational Monitoring; If monitoring observation >150 then Fumigate
31		Good Sanitation; Rational Monitoring; If monitoring observation >200 then Fumigate
32		Good Sanitation; Rational Monitoring; If monitoring observation >250 then Fumigate

<u>Least Cost Strategies</u>

Tables 9, 10 and 11 calculate the annual treatment cost, including an assumed opportunity cost of $30,000), of shutdown time of the thirty-two strategies considered during the three two-year period (2005-2007, 2007-2009, 2009-2011). From these, an optimization routine selects the lowest cost strategy that satisfies alternative specified insect population thresholds. The annual cost of each strategy is calculated using the cost data in table 5, including the sanitation, fumigation, monitoring, and shutdown time costs. For example, in table 9 (2005-2007) the annual treatment cost ($41,542) of #6 strategy, a calendar-based strategy, is calculated by adding the annual cost conducting good sanitation ($3,120) and the annual fumigation cost (twice a year, $38,422 = $19,211×2). The annual cost ($87,180) of #27 strategy, a monitoring-based strategy, is calculated by adding the annual cost of conducting poor sanitation ($1,040), the annual monitoring cost (rational monitoring frequency, resulting in 16 monitoring jobs per year) $23,113 = $1,445×16), the annual fumigation cost (5 fumigations carried out in year 2005-2007 in table 6, $48,028 = $19,211× $\frac{5}{2}$), and the opportunity cost of shutdown time (1 out of 5 fumigations required shutting down the processing facility during the two-year period, $15,000 = $30,000 × $\frac{1}{2}$).

The average number and maximum value are listed in the column “Insect Control Results.” In the columns “Ranking by Mean” and “Ranking by Maximum,” least cost strategies are identified under alternative desired levels of insect population. The strategies with an “F” in this column are the strategies which satisfy the corresponding threshold *K*, while the strategies with a “LC” in this column are the least cost strategies under the corresponding threshold *K*.

Table 9. Selection of Least Cost Strategies under Alternative Adult Insect Population Thresholds (2005-2007, Opportunity Cost of Shutdown Time = $30,000)

		Insect Control Result		Ranking by Mean			Ranking by Maximum		
Strategy #	Annual Cost	Mean	Max	*K*=60	*K*=80	*K*=100	*K*=200	*K*=270	*K*=340
1	$ 1,040	402.50	869.31						
2	$ 3,120	198.59	430.57						
3	$ 20,251	184.06	496.10						
4	$ 22,331	119.07	276.21						LC
5	$ 39,462	135.81	453.50						
6	$ 41,542	76.84	260.29		LC	LC		LC	F
7	$ 58,673	86.36	292.66			F			F
8	$ 60,753	48.02	164.75	LC	F	F	LC	F	F
9	$ 140,219	44.11	272.07	F	F	F			F
10	$ 96,402	88.55	347.26			F			
11	$ 66,402	91.24	327.27			F			F
12	$ 81,402	93.20	327.27			F			F
13	$ 202,553	43.58	171.88	F	F	F	F	F	F
14	$ 153,342	64.38	254.00		F	F		F	F
15	$ 113,737	89.76	350.16			F			
16	$ 98,737	88.34	327.27			F			F
17	$ 147,693	45.37	266.71	F	F	F		F	F
18	$ 68,482	76.97	372.68		F	F			
19	$ 83,482	74.80	337.42		F	F			F
20	$ 64,271	115.81	337.42						F
21	$ 180,028	28.01	144.24	F	F	F	F	F	F
22	$ 130,817	73.64	237.78		F	F		F	F
23	$ 100,817	74.80	337.42		F	F			F
24	$ 81,606	114.92	337.42						F
25	$ 190,997	49.76	393.45	F	F	F			
26	$ 117,180	87.17	357.28			F			
27	$ 87,180	89.69	327.27			F			F
28	$ 87,180	88.34	327.27			F			F
29	$ 153,471	40.81	201.33	F	F	F		F	F
30	$ 119,260	73.64	237.78		F	F		F	F
31	$ 74,260	74.80	337.42		F	F			F
32	$ 70,049	114.92	337.42						F

K is the threshold insect population, to be chosen by a facility's manager.
F (feasible) indicates the strategy satisfies the constraint, and LC indicates that the strategy is both feasible and lowest cost.

In Table 9, the least cost strategies are selected in the period 2005-2007 under alternative threshold levels *K* in the cost minimization model (3). The mean value of the insect population is used to evaluate the constraint K_{mean}. For K_{mean} equal to 60, seven strategies satisfy the constraint. Among them, the 8th strategy, calendar-based fumigation three times a year (every Memorial Day, Independence Day and Thanksgiving) with good sanitation, is the least cost strategy. For K_{mean} equal to 80, eight additional strategies satisfy the constraint. Of the 15 strategies that satisfy this constraint, strategy #6, calendar-based fumigation twice a year (every Memorial Day and Independence Day) with good sanitation, has the lowest cost. For K_{mean} equal to 100, an additional eight strategies satisfy the constraint. Still, of the feasible 24 strategies, strategy #6, calendar-based fumigation twice a year with good sanitation, has the lowest cost.

Table 9 also shows the results when the maximum adult insect population, rather than the mean, is used to evaluate the constraint. For K_{max} equal to 200, three strategies satisfy the constraint. Strategy #8, calendar-based fumigation three times a year (every Memorial Day, Independence Day and Thanksgiving) with good sanitation has the lowest cost. For K_{max} equal to 270, six additional strategies satisfy the constraint, with strategy #6, calendar-based fumigation twice a year (every Memorial Day and Independence Day) with good sanitation, achieving the lowest cost. For K_{max} equal to 340, fourteen additional strategies satisfy the constraint. Of the 23 feasible strategies, strategy #4, calendar-based fumigation once a year (every Independence Day) with good sanitation, has the lowest cost. These threshold values were selected somewhat arbitrarily, but the increments between them are large enough that increasing from a lower threshold to a higher one adds several meaningful strategies to the feasible set.

Table 10. Selection of Least Cost Strategies under Alternative Adult Insect Population Thresholds (2007-2009, Opportunity Cost of Shutdown Time = $30,000)

		Insect Control Result		Ranking by Mean			Ranking by Maximum		
Strategy #	Annual Cost	Mean	Max	*K*=50	*K*=70	*K*=90	*K*=180	*K*=240	*K*=300
1	$ 1,040	219.33	547.16						
2	$ 3,120	126.69	311.58						
3	$ 20,251	108.64	309.02						
4	$ 22,331	76.05	223.91			LC		LC	LC
5	$ 39,462	54.68	175.08		LC	F	LC	F	F
6	$ 41,542	24.31	118.05	LC	F	F	F	F	F
7	$ 58,673	19.33	114.25	F	F	F	F	F	F
8	$ 60,753	2.42	9.40	F	F	F	F	F	F
9	$ 126,402	40.42	318.05	F	F	F			
10	$ 101,797	77.35	428.64			F			
11	$ 77,191	80.40	242.02						F
12	$ 67,586	100.83	415.06						
13	$ 98,737	32.28	150.43	F	F	F	F	F	F
14	$ 119,131	46.86	222.66	F	F	F		F	F
15	$ 104,131	57.38	240.46		F	F			F
16	$ 84,920	98.24	263.79						F
17	$ 73,877	27.78	160.51	F	F	F	F	F	F
18	$ 79,271	58.27	213.87		F	F		F	F
19	$ 54,666	71.91	293.01			F			F
20	$ 54,666	71.91	293.01			F			F
21	$ 91,211	27.78	160.51	F	F	F	F	F	F
22	$ 96,606	58.27	213.87		F	F		F	F
23	$ 87,000	70.55	283.93			F			F
24	$ 87,000	70.55	283.93			F			F
25	$ 102,180	32.46	144.72	F	F	F	F	F	F
26	$ 92,575	46.86	222.66	F	F	F		F	F
27	$ 122,575	63.22	251.57		F	F			F
28	$ 73,364	98.24	263.79						F
29	$ 79,655	27.78	160.51	F	F	F	F	F	F
30	$ 85,049	58.27	213.87		F	F		F	F
31	$ 75,444	70.55	283.93			F			F
32	$ 75,444	70.55	283.93			F			F

K is the threshold insect population, to be chosen by a facility's manager.
F (feasible) indicates the strategy satisfies the constraint, and LC indicates that the strategy is both feasible and lowest cost.

Table 10 shows the same kind of analysis for the years 2007-2009. For K_{mean} equal to 50, eleven strategies satisfy the constraint. Of these, strategy #6, calendar-based fumigation two times a year (every Memorial Day and Independence Day) with good sanitation, has the lowest cost. For K_{mean} equal to 70, six additional strategies satisfy the constraint. Of the 17 strategies that satisfy this constraint, strategy #5, calendar-based fumigation twice a year (every Memorial Day and Independence Day) with poor sanitation, has the lowest cost. For K_{mean} equal to 90, an additional three strategies satisfy the constraint. Of the feasible 25 strategies, strategy #4, calendar-based fumigation once a year (every Independence Day) with good sanitation, has the lowest cost.

Table 10 also shows the results for 2007-2009 when the maximum adult insect population, rather than the mean, is used to evaluate the constraint. For $K_{\max}$ equal to 180, nine strategies satisfy the constraint. Strategy #5, calendar-based fumigation twice a year (every Memorial Day and Independence Day) with poor sanitation, has the lowest cost. For $K_{\max}$ equal to 240, six additional strategies satisfy the constraint, and strategy #4, calendar-based fumigation twice a year (every Memorial Day and Independence Day) with good sanitation, has the lowest cost. For $K_{\max}$ equal to 300, eleven additional strategies satisfy the constraint. Of the 26 feasible strategies, strategy #4 still has the lowest cost.

Table 11. Selection of Least Cost Strategies under Alternative Adult Insect Population Thresholds (2009-2011, Opportunity Cost of Shutdown Time = $30,000)

		Insect Control Result		Ranking by Mean			Ranking by Maximum		
Strategy #	Annual Cost	Mean	Max	*K*=50	*K*=70	*K*=90	*K*=160	*K*=260	*K*=340
1	$ 1,040	249.91	679.95						
2	$ 3,120	152.27	398.63						
3	$ 20,251	125.54	299.61						LC
4	$ 22,331	86.18	213.72			LC		LC	F
5	$ 39,462	74.70	233.62			F		F	F
6	$ 41,542	43.88	126.28	LC	LC	F	LC	F	F
7	$ 58,673	43.22	220.43	F	F	F		F	F
8	$ 60,753	13.50	94.51	F	F	F	F	F	F
9	$ 106,008	31.75	153.23	F	F	F	F	F	F
10	$ 71,797	66.64	319.30		F	F			F
11	$ 101,797	70.65	256.16			F		F	F
12	$ 52,586	108.83	256.16					F	F
13	$ 168,342	29.82	111.71	F	F	F	F	F	F
14	$ 119,131	65.47	302.60		F	F			F
15	$ 119,131	69.65	256.16		F	F		F	F
16	$ 84,920	109.58	378.92						
17	$ 88,877	46.89	259.58	F	F	F		F	F
18	$ 79,271	63.30	329.40		F	F			F
19	$ 69,666	85.84	332.50			F			F
20	$ 69,666	85.84	332.50			F			F
21	$ 130,817	23.30	134.79	F	F	F	F	F	F
22	$ 121,211	45.53	259.58	F	F	F		F	F
23	$ 87,000	85.97	259.58			F		F	F
24	$ 87,000	85.84	332.50			F			F
25	$ 156,786	32.00	115.12	F	F	F	F	F	F
26	$ 107,575	65.47	302.60		F	F			F
27	$ 107,575	69.65	256.16		F	F		F	F
28	$ 73,364	109.58	378.92						
29	$ 134,260	24.47	116.95	F	F	F	F	F	F
30	$ 109,655	45.53	259.58	F	F	F		F	F
31	$ 75,444	85.97	259.58			F		F	F
32	$ 75,444	85.84	332.50			F			F

K is the threshold insect population, to be chosen by a facility's manager.
F (feasible) indicates the strategy satisfies the constraint, and LC indicates that the strategy is both feasible and lowest cost.

Table 11 shows the same kind of analysis for the years 2009-2011. For K_{mean} equal to 50, eleven strategies satisfy the constraint. Of these, strategy #6, calendar-based fumigation twice a year (every Memorial Day and Independence Day) with good sanitation, has the lowest cost. For K_{mean} equal to 70, six additional strategies satisfy the constraint. Of the 17 strategies, strategy #6 still has the lowest cost. For K_{mean} equal to 90, an additional nine strategies satisfy the constraint. Of the feasible 26 strategies, strategy #4, calendar-based fumigation once a year (every Independence Day) with good sanitation, has the lowest cost.

Table 11 also shows the results for 2009-2011 when the maximum adult insect population, rather than the mean, is used to evaluate the constraint. For K_{max} equal to 160, seven strategies satisfy the constraint. Strategy #6, calendar-based fumigation twice a year (every Memorial Day and Independence Day) with good sanitation, has the lowest cost. For K_{max} equal to 260, 12 additional strategies satisfy the constraint, and strategy #4, calendar-based fumigation twice a year (every Memorial Day and Independence Day) with good sanitation, has the lowest cost. For K_{max} equal to 340, nine additional strategies satisfy the constraint. Of the 28 feasible strategies, strategy #3, calendar-based fumigation twice a year (every Memorial Day and Independence Day) with poor sanitation, has the lowest cost.

Because the average temperatures during 2005-2007 were relatively high, and there was an unusually warm winter in early 2006 compared to the temperatures in 2007-2009 and 2009-2011, the selected thresholds K_{mean} and K_{max} in 2005-2007 (K_{mean}= 60, 80, and 100 and K_{max} = 200, 270, and 340) are bigger than those for 2007-2009 (K_{mean}= 50, 70, and 90 and K_{max} = 180, 240, and 300) and 2009-2011 (K_{mean}= 50, 70, and 90 and K_{max} = 160, 260, and 340). The thresholds were expanded for 2005-2007, permitting higher insect populations, because no strategies can achieve the lower thresholds. This illustrates that environmental conditions are important determinants of managers' insect control choices.

Table 12. Least Cost Strategies for Simulated Scenarios

	K_{mean}			K_{max}		
2005-2007	60	80	100	200	270	340
LC Strategy #	8	6	6	8	6	4
2007-2009	50	70	90	180	240	300
LC Strategy #	6	5	4	5	4	4
2009-2011	50	70	90	160	260	340
LC Strategy #	6	6	4	6	4	3

Opportunity Cost of Shutdown Time = $30,000

Table 12 shows that all of the least cost strategies selected from the simulated scenarios are calendar-based fumigations, for all three time periods. Two strategies, strategies #6 and #4, are robust to alternative weather conditions (strategy #6 was identified in the analysis as optimal seven times, while strategy #4 was identified in the analysis as optimal six times). Although monitoring the insect population provides very useful knowledge for decision makers in food processing facilities, with assumptions used here a monitoring-based strategy is not the lowest-cost choice.

To determine if monitoring-based strategies would become optimal if shutdown time cost were reduced, sensitivity analysis was conducted varying shutdown time cost to half of the cost assumed above, and then to zero. The results are shown in the following tables. Even with shutdown costs of zero, the optimal strategies are all calendar-based fumigations with good sanitation: one fumigation per year (#4), two fumigations per year (#6), or three fumigations per year (#8). Thus, higher shutdown costs (opportunity costs) are not the entire reason monitoring-based fumigation strategies are higher cost than calendar-based fumigation strategies.

Table 13. Selection of Least Cost Strategies under Alternative Adult Insect Population Thresholds (2005-2007, Opportunity Cost of Shutdown Time = $15,000)

		Insect Control Result		Ranking by Mean			Ranking by Maximum		
Strategy #	Annual Cost	Mean	Max	*K*=60	*K*=80	*K*=100	*K*=200	*K*=270	*K*=340
1	$ 1,040	402.50	869.31						
2	$ 3,120	198.59	430.57						
3	$ 20,251	184.06	496.10						
4	$ 22,331	119.07	276.21						LC
5	$ 39,462	135.81	453.50						
6	$ 41,542	76.84	260.29		LC	LC		LC	F
7	$ 58,673	86.36	292.66			F			F
8	$ 60,753	48.02	164.75	LC	F	F	LC	F	F
9	$ 117,719	44.11	272.07	F	F	F			F
10	$ 81,402	88.55	347.26			F			
11	$ 66,402	91.24	327.27			F			F
12	$ 73,902	93.20	327.27			F			F
13	$ 157,553	43.58	171.88	F	F	F	F	F	F
14	$ 123,342	64.38	254.00		F	F		F	F
15	$ 98,737	89.76	350.16			F			
16	$ 91,237	88.34	327.27			F			F
17	$ 117,693	45.37	266.71	F	F	F		F	F
18	$ 68,482	76.97	372.68		F	F			
19	$ 75,982	74.80	337.42		F	F			F
20	$ 56,771	115.81	337.42						F
21	$ 142,528	28.01	144.24	F	F	F	F	F	F
22	$ 108,317	73.64	237.78		F	F		F	F
23	$ 93,317	74.80	337.42		F	F			F
24	$ 74,106	114.92	337.42						F
25	$ 145,997	49.76	393.45	F	F	F			
26	$ 94,680	87.17	357.28			F			
27	$ 79,680	89.69	327.27			F			F
28	$ 79,680	88.34	327.27			F			F
29	$ 123,471	40.81	201.33	F	F	F		F	F
30	$ 96,760	73.64	237.78		F	F		F	F
31	$ 74,260	74.80	337.42		F	F			F
32	$ 62,549	114.92	337.42						F

K is the threshold insect population, to be chosen by a facility's manager.
F (feasible) indicates the strategy satisfies the constraint, and LC indicates that the strategy is both feasible and lowest cost.

Table 14. Selection of Least Cost Strategies under Alternative Adult Insect Population Thresholds (2005-2007, Opportunity Cost of Shutdown Time = $0)

		Insect Control Result		Ranking by Mean			Ranking by Maximum		
Strategy #	Annual Cost	Mean	Max	*K*=60	*K*=80	*K*=100	*K*=200	*K*=270	*K*=340
1	$ 1,040	402.50	869.31						
2	$ 3,120	198.59	430.57						
3	$ 20,251	184.06	496.10						
4	$ 22,331	119.07	276.21						LC
5	$ 39,462	135.81	453.50						
6	$ 41,542	76.84	260.29		LC	LC		LC	F
7	$ 58,673	86.36	292.66			F			F
8	$ 60,753	48.02	164.75	LC	F	F	LC	F	F
9	$ 95,219	44.11	272.07	F	F	F			F
10	$ 66,402	88.55	347.26			F			
11	$ 66,402	91.24	327.27			F			F
12	$ 66,402	93.20	327.27			F			F
13	$ 112,553	43.58	171.88	F	F	F	F	F	F
14	$ 93,342	64.38	254.00		F	F		F	F
15	$ 83,737	89.76	350.16			F			
16	$ 83,737	88.34	327.27			F			F
17	$ 87,693	45.37	266.71	F	F	F		F	F
18	$ 68,482	76.97	372.68		F	F			
19	$ 68,482	74.80	337.42		F	F			F
20	$ 49,271	115.81	337.42						F
21	$ 105,028	28.01	144.24	F	F	F	F	F	F
22	$ 85,817	73.64	237.78		F	F		F	F
23	$ 85,817	74.80	337.42		F	F			F
24	$ 66,606	114.92	337.42						F
25	$ 100,997	49.76	393.45	F	F	F			
26	$ 72,180	87.17	357.28			F			
27	$ 72,180	89.69	327.27			F			F
28	$ 72,180	88.34	327.27			F			F
29	$ 93,471	40.81	201.33	F	F	F		F	F
30	$ 74,260	73.64	237.78		F	F		F	F
31	$ 74,260	74.80	337.42		F	F			F
32	$ 55,049	114.92	337.42						F

K is the threshold insect population, to be chosen by a facility's manager.
F (feasible) indicates the strategy satisfies the constraint, and LC indicates that the strategy is both feasible and lowest cost.

Table 15. Selection of Least Cost Strategies under Alternative Adult Insect Population Thresholds (2007-2009, Opportunity Cost of Shutdown Time = $15,000)

		Insect Control Result		Ranking by Mean			Ranking by Maximum		
Strategy #	Annual Cost	Mean	Max	*K*=50	*K*=70	*K*=*90*	*K*=180	*K*=240	*K*=300
1	$ 1,040	219.33	547.16						
2	$ 3,120	126.69	311.58						
3	$ 20,251	108.64	309.02						
4	$ 22,331	76.05	223.91			LC		LC	LC
5	$ 39,462	54.68	175.08		LC	F	LC	F	F
6	$ 41,542	24.31	118.05	LC	F	F	F	F	F
7	$ 58,673	19.33	114.25	F	F	F	F	F	F
8	$ 60,753	2.42	9.40	F	F	F	F	F	F
9	$ 96,402	40.42	318.05	F	F	F			
10	$ 79,297	77.35	428.64			F			
11	$ 62,191	80.40	242.02						F
12	$ 52,586	100.83	415.06						
13	$ 91,237	32.28	150.43	F	F	F	F	F	F
14	$ 96,631	46.86	222.66	F	F	F		F	F
15	$ 89,131	57.38	240.46		F	F			F
16	$ 69,920	98.24	263.79						F
17	$ 66,377	27.78	160.51	F	F	F	F	F	F
18	$ 64,271	58.27	213.87		F	F		F	F
19	$ 47,166	71.91	293.01			F			F
20	$ 47,166	71.91	293.01			F			F
21	$ 83,711	27.78	160.51	F	F	F	F	F	F
22	$ 81,606	58.27	213.87		F	F		F	F
23	$ 72,000	70.55	283.93			F			F
24	$ 72,000	70.55	283.93			F			F
25	$ 87,180	32.46	144.72	F	F	F	F	F	F
26	$ 77,575	46.86	222.66	F	F	F		F	F
27	$ 92,575	63.22	251.57		F	F			F
28	$ 58,364	98.24	263.79						F
29	$ 72,155	27.78	160.51	F	F	F	F	F	F
30	$ 70,049	58.27	213.87		F	F		F	F
31	$ 60,444	70.55	283.93			F			F
32	$ 60,444	70.55	283.93			F			F

K is the threshold insect population, to be chosen by a facility's manager.
F (feasible) indicates the strategy satisfies the constraint, and LC indicates that the strategy is both feasible and lowest cost.

Table 16. Selection of Least Cost Strategies under Alternative Adult Insect Population Thresholds (2007-2009, Opportunity Cost of Shutdown Time = $0)

		Insect Control Result		Ranking by Mean			Ranking by Maximum		
Strategy #	Annual Cost	Mean	Max	*K*=50	*K*=75	*K=100*	*K*=180	*K*=240	*K*=300
1	$ 1,040	219.33	547.16						
2	$ 3,120	126.69	311.58						
3	$ 20,251	108.64	309.02						
4	$ 22,331	76.05	223.91			LC		LC	LC
5	$ 39,462	54.68	175.08		LC	F	LC	F	F
6	$ 41,542	24.31	118.05	LC	F	F	F	F	F
7	$ 58,673	19.33	114.25	F	F	F	F	F	F
8	$ 60,753	2.42	9.40	F	F	F	F	F	F
9	$ 66,402	40.42	318.05	F	F	F			
10	$ 56,797	77.35	428.64			F			
11	$ 47,191	80.40	242.02						F
12	$ 37,586	100.83	415.06						
13	$ 83,737	32.28	150.43	F	F	F	F	F	F
14	$ 74,131	46.86	222.66	F	F	F		F	F
15	$ 74,131	57.38	240.46		F	F			F
16	$ 54,920	98.24	263.79						F
17	$ 58,877	27.78	160.51	F	F	F	F	F	F
18	$ 49,271	58.27	213.87		F	F		F	F
19	$ 39,666	71.91	293.01			F			F
20	$ 39,666	71.91	293.01			F			F
21	$ 76,211	27.78	160.51	F	F	F	F	F	F
22	$ 66,606	58.27	213.87		F	F		F	F
23	$ 57,000	70.55	283.93			F			F
24	$ 57,000	70.55	283.93			F			F
25	$ 72,180	32.46	144.72	F	F	F	F	F	F
26	$ 62,575	46.86	222.66	F	F	F		F	F
27	$ 62,575	63.22	251.57		F	F			F
28	$ 43,364	98.24	263.79						F
29	$ 64,655	27.78	160.51	F	F	F	F	F	F
30	$ 55,049	58.27	213.87		F	F		F	F
31	$ 45,444	70.55	283.93			F			F
32	$ 45,444	70.55	283.93			F			F

K is the threshold insect population, to be chosen by a facility's manager.
F (feasible) indicates the strategy satisfies the constraint, and LC indicates that the strategy is both feasible and lowest cost.

Table 17. Selection of Least Cost Strategies under Alternative Adult Insect Population Thresholds (2009-2011, Opportunity Cost of Shutdown Time = $15,000)

		Insect Control Result		Ranking by Mean			Ranking by Maximum		
Strategy #	Annual Cost	Mean	Max	*K*=50	*K*=70	*K*=90	*K*=160	*K*=260	*K*=340
1	$ 1,040	249.91	679.95						
2	$ 3,120	152.27	398.63						
3	$ 20,251	125.54	299.61						LC
4	$ 22,331	86.18	213.72			LC		LC	F
5	$ 39,462	74.70	233.62			F		F	F
6	$ 41,542	43.88	126.28	LC	LC	F	LC	F	F
7	$ 58,673	43.22	220.43	F	F	F		F	F
8	$ 60,753	13.50	94.51	F	F	F	F	F	F
9	$ 91,008	31.75	153.23	F	F	F	F	F	F
10	$ 64,297	66.64	319.30		F	F			F
11	$ 79,297	70.65	256.16			F		F	F
12	$ 45,086	108.83	256.16					F	F
13	$ 130,842	29.82	111.71	F	F	F	F	F	F
14	$ 96,631	65.47	302.60		F	F			F
15	$ 96,631	69.65	256.16		F	F		F	F
16	$ 69,920	109.58	378.92						
17	$ 73,877	46.89	259.58	F	F	F		F	F
18	$ 64,271	63.30	329.40		F	F			F
19	$ 54,666	85.84	332.50			F			F
20	$ 54,666	85.84	332.50			F			F
21	$ 108,317	23.30	134.79	F	F	F	F	F	F
22	$ 98,711	45.53	259.58	F	F	F		F	F
23	$ 72,000	85.97	259.58			F		F	F
24	$ 72,000	85.84	332.50			F			F
25	$ 119,286	32.00	115.12	F	F	F	F	F	F
26	$ 85,075	65.47	302.60		F	F			F
27	$ 85,075	69.65	256.16		F	F		F	F
28	$ 58,364	109.58	378.92						
29	$ 104,260	24.47	116.95	F	F	F	F	F	F
30	$ 87,155	45.53	259.58	F	F	F		F	F
31	$ 60,444	85.97	259.58			F		F	F
32	$ 60,444	85.84	332.50			F			F

K is the threshold insect population, to be chosen by a facility's manager.
F (feasible) indicates the strategy satisfies the constraint, and LC indicates that the strategy is both feasible and lowest cost.

Table 18. Selection of Least Cost Strategies under Alternative Adult Insect Population Thresholds (2009-2011, Opportunity Cost of Shutdown Time = $ 0)

		Insect Control Result		Ranking by Mean			Ranking by Maximum		
Strategy #	Annual Cost	Mean	Max	*K*=50	*K*=70	*K*=90	*K*=160	*K*=260	*K*=340
1	$ 1,040	249.91	679.95						
2	$ 3,120	152.27	398.63						
3	$ 20,251	125.54	299.61						LC
4	$ 22,331	86.18	213.72			LC		LC	F
5	$ 39,462	74.70	233.62			F		F	F
6	$ 41,542	43.88	126.28	LC	LC	F	LC	F	F
7	$ 58,673	43.22	220.43	F	F	F		F	F
8	$ 60,753	13.50	94.51	F	F	F	F	F	F
9	$ 76,008	31.75	153.23	F	F	F	F	F	F
10	$ 56,797	66.64	319.30		F	F			F
11	$ 56,797	70.65	256.16			F		F	F
12	$ 37,586	108.83	256.16					F	F
13	$ 93,342	29.82	111.71	F	F	F	F	F	F
14	$ 74,131	65.47	302.60		F	F			F
15	$ 74,131	69.65	256.16		F	F		F	F
16	$ 54,920	109.58	378.92						
17	$ 58,877	46.89	259.58	F	F	F		F	F
18	$ 49,271	63.30	329.40		F	F			F
19	$ 39,666	85.84	332.50			F			F
20	$ 39,666	85.84	332.50			F			F
21	$ 85,817	23.30	134.79	F	F	F	F	F	F
22	$ 76,211	45.53	259.58	F	F	F		F	F
23	$ 57,000	85.97	259.58			F		F	F
24	$ 57,000	85.84	332.50			F			F
25	$ 81,786	32.00	115.12	F	F	F	F	F	F
26	$ 62,575	65.47	302.60		F	F			F
27	$ 62,575	69.65	256.16		F	F		F	F
28	$ 43,364	109.58	378.92						
29	$ 74,260	24.47	116.95	F	F	F	F	F	F
30	$ 64,655	45.53	259.58	F	F	F		F	F
31	$ 45,444	85.97	259.58			F		F	F
32	$ 45,444	85.84	332.50			F			F

K is the threshold insect population, to be chosen by a facility's manager.
F (feasible) indicates the strategy satisfies the constraint, and LC indicates that the strategy is both feasible and lowest cost.

Least Cost Strategy Selection – Graphical Presentation

Figures 9 - 17 illustrate the relationship between the insect population predicted to result from a particular strategy (x-axis) and the treatment cost of that strategy (y-axis). The no-treatment strategies (#1, poor sanitation only, and #2, good sanitation only) are presented in the figure as circular points, calendar-based strategies are presented as diamond shaped points, and monitoring-based strategies are presented as triangular points.

The solid curve in the figure that envelopes the data points represents a "cost frontier curve." At each point on the frontier curve, there is no strategy that achieves the same level of insect control at a lower cost. The smaller the distance from the strategy point to the curve, the more cost-efficient the strategy is. Threshold population levels K_{mean} and K_{max} are represented as vertical lines. The strategy points satisfy the insect population constraints if they are positioned to the left of the threshold lines.

Figures 9 and 10 show the annual treatment cost (including shutdown time cost of $30,000 per fumigation where appropriate) and the average and the maximum values of insect population for the 32 simulated strategies. The diamond-shaped points (calendar-based strategies) are all located below the triangular points (monitoring-based strategies). This reflects the higher cost of monitoring-based strategies than calendar-based strategies for the same level of insect control. However, for situations requiring that insect population be controlled to a very low threshold, feasible strategies are more likely to be monitoring-based strategies. For example, in figure 9, when the K_{mean} threshold is less than or equal to 48, there are five monitoring-based strategies that satisfy the constraint, but no calendar-based strategies. Also, in figure 10, when the K_{max} threshold is less than or equal to 150, the only strategy that satisfies the constraint is a monitoring-based strategy.

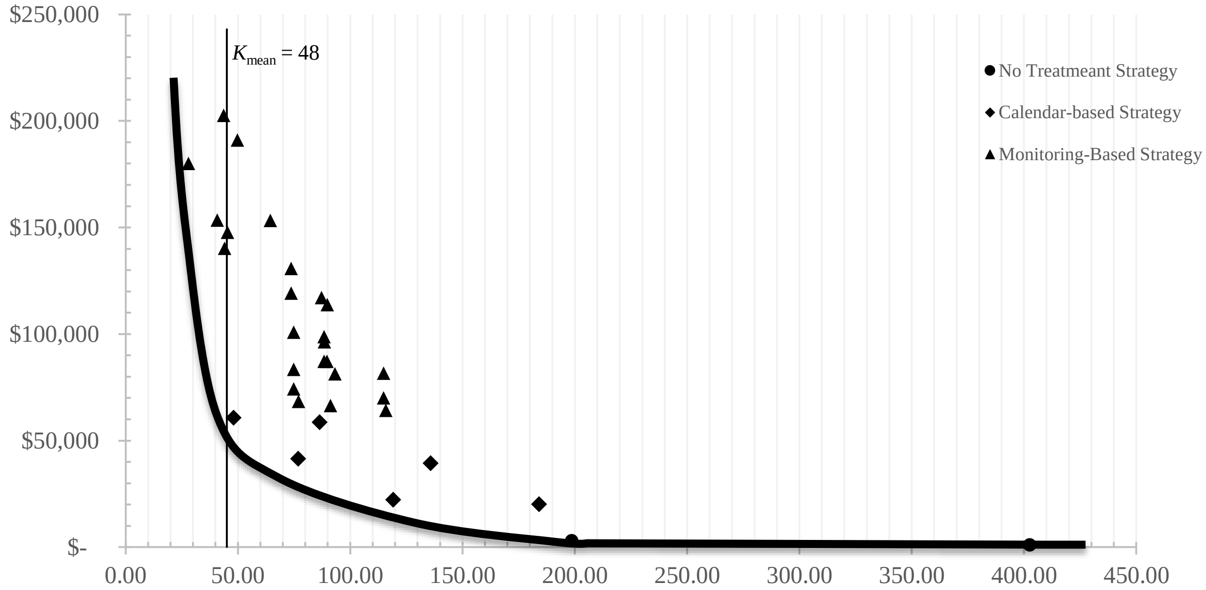

Figure 9. Cost frontier graph for strategies using mean insect population thresholds (2005-2007)

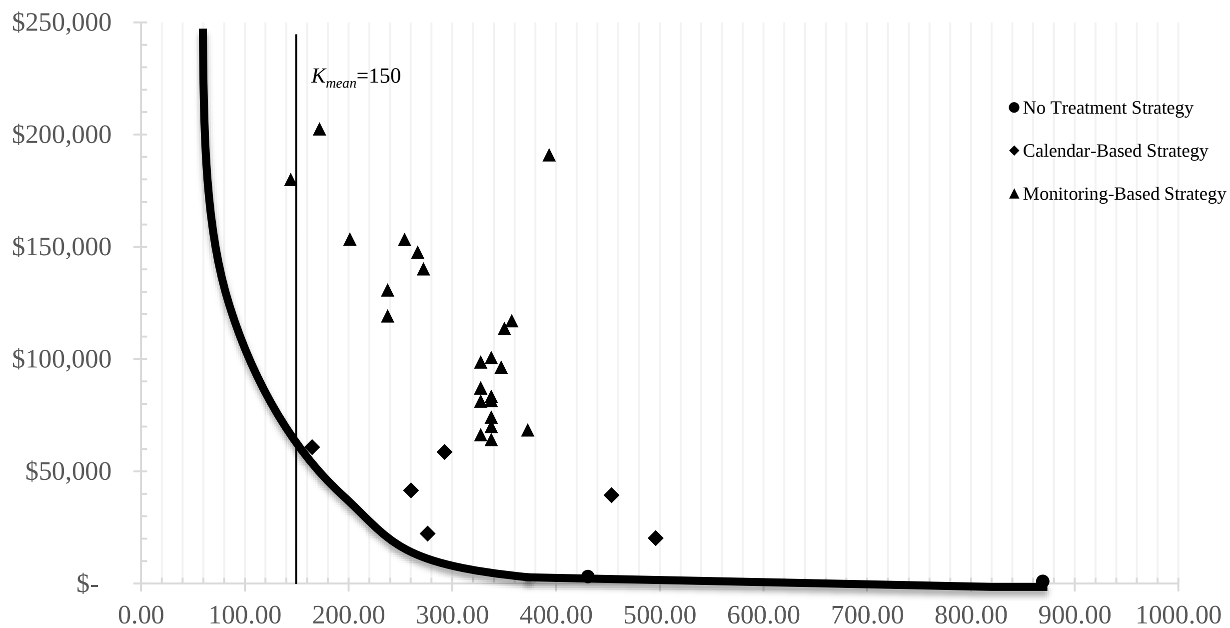

Figure 10. Cost frontier graph for strategies using maximum insect population thresholds (2005-2007)

Figure 11 shows the effect of reducing shutdown time cost from $30,000 per fumigation, to $15,000 per fumigation, to $0 per fumigation. As the cost is reduced, attractiveness of monitoring-based strategies increases relative to calendar-based strategies. But even at a shutdown cost of $0, calendar-based strategies are still lower cost than monitoring-based strategies, except at the lowest insect population thresholds. Thus, shutdown time cost is not the only reason calendar-based strategies are less expensive than monitoring-based strategies at most population thresholds. Similar figures using maximum insect population as threshold are not presented here, but show similar qualitative results to those presented for mean insect population thresholds.

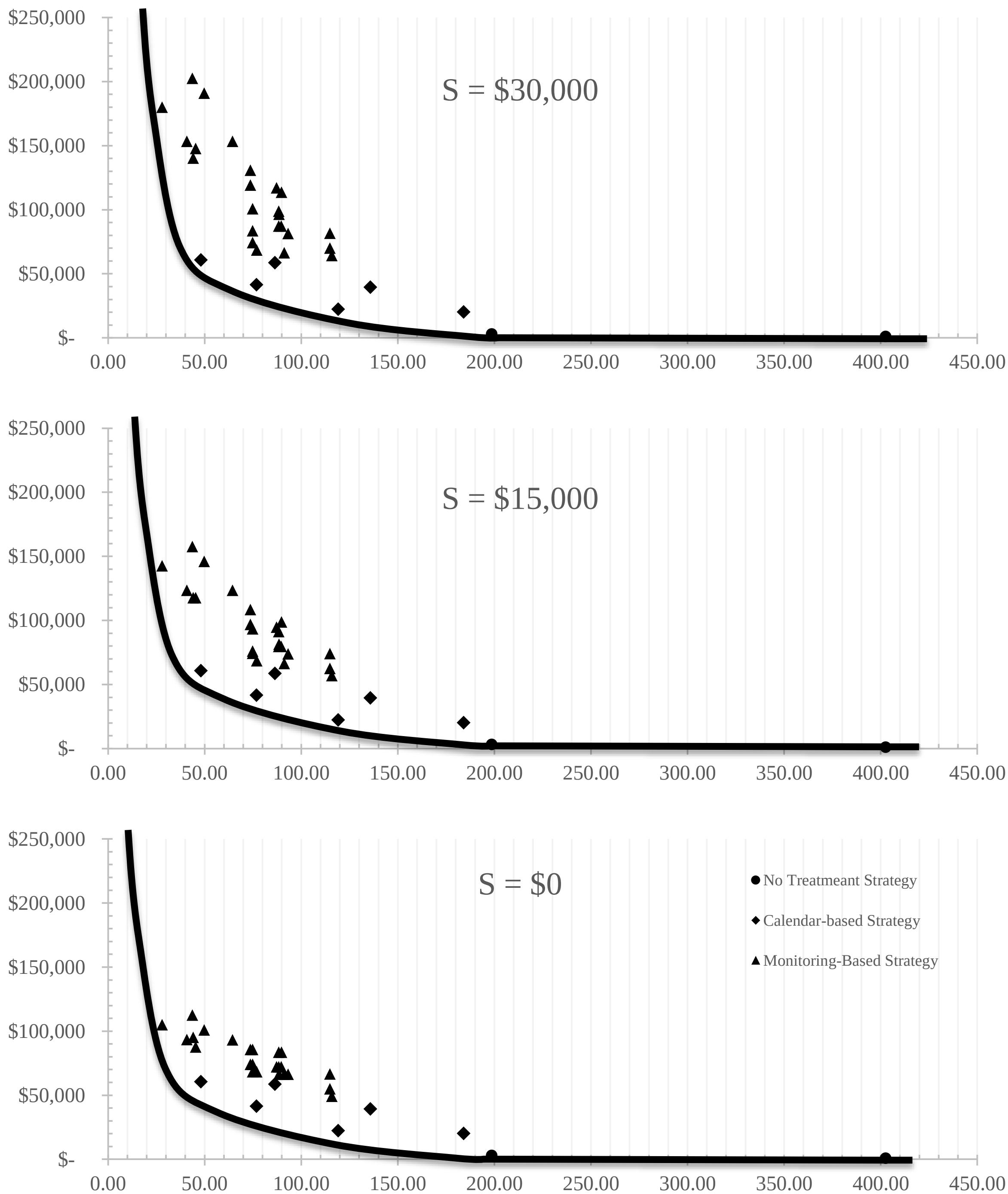

Figure 11. Annual Treatment Cost for Each Strategy across Different Shutdown Time Opportunity Cost Using Mean Insect Population Threshold (2005-2007)

Figures 12 through 17 show the same situation for the periods 2007-2009 and 2009-2011.

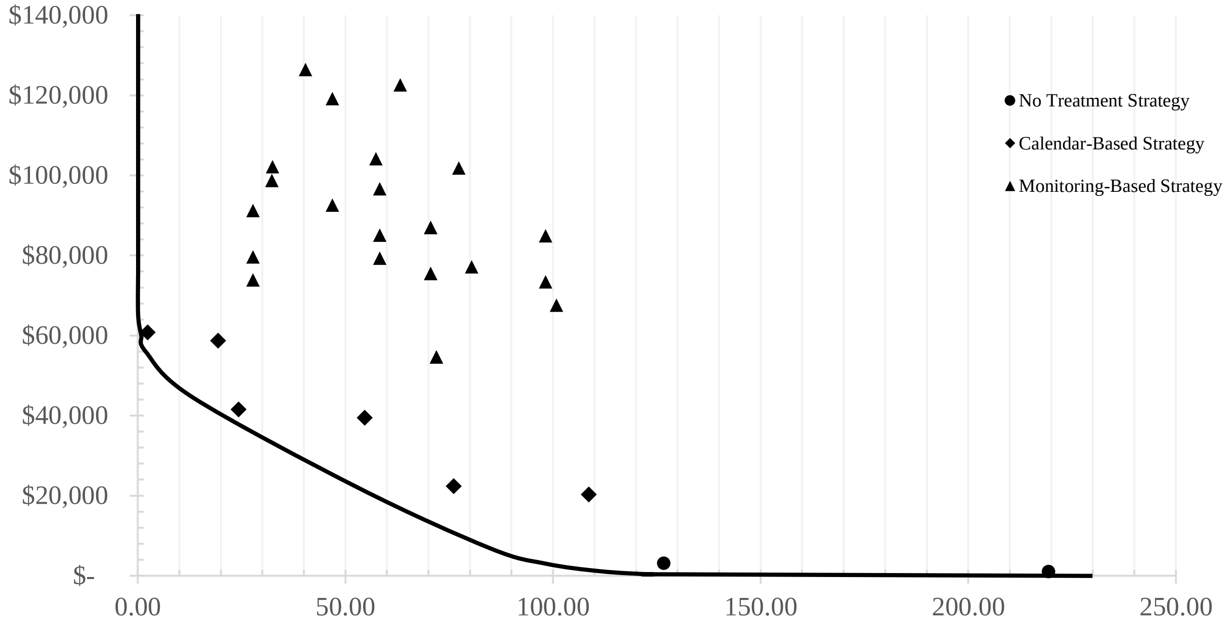

Figure 12. Cost Frontier for Strategies Using Mean Insect Population Thresholds (2007-2009)

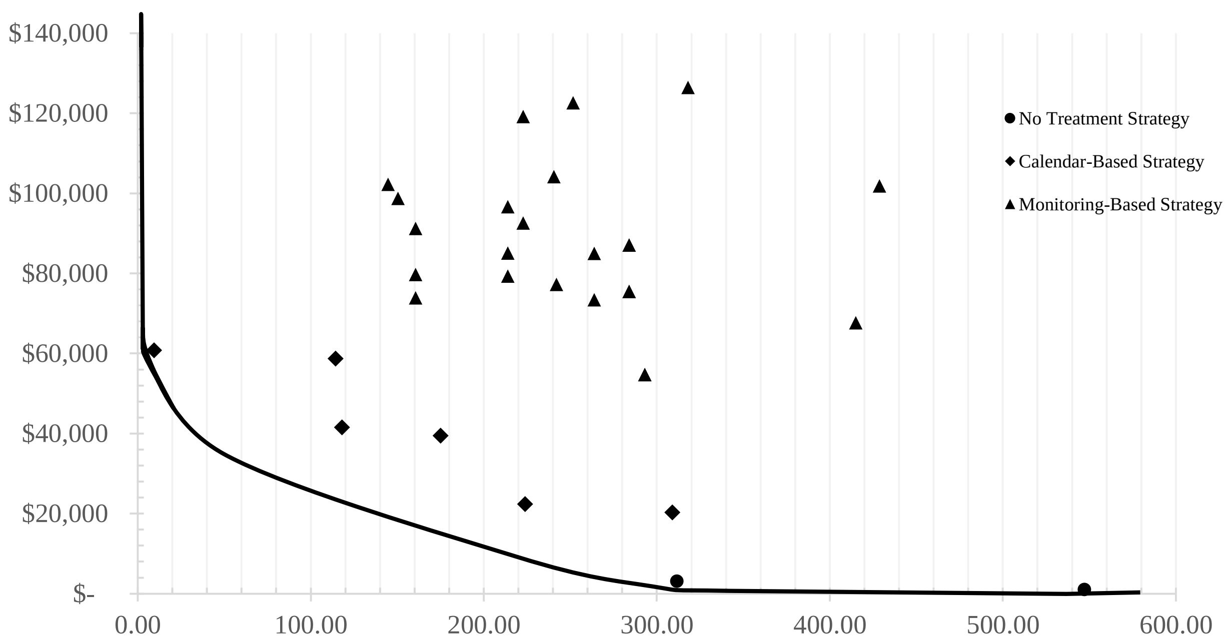

Figure 13. Cost Frontier for Strategies Using Maximum Insect Population Thresholds (2007-2009)

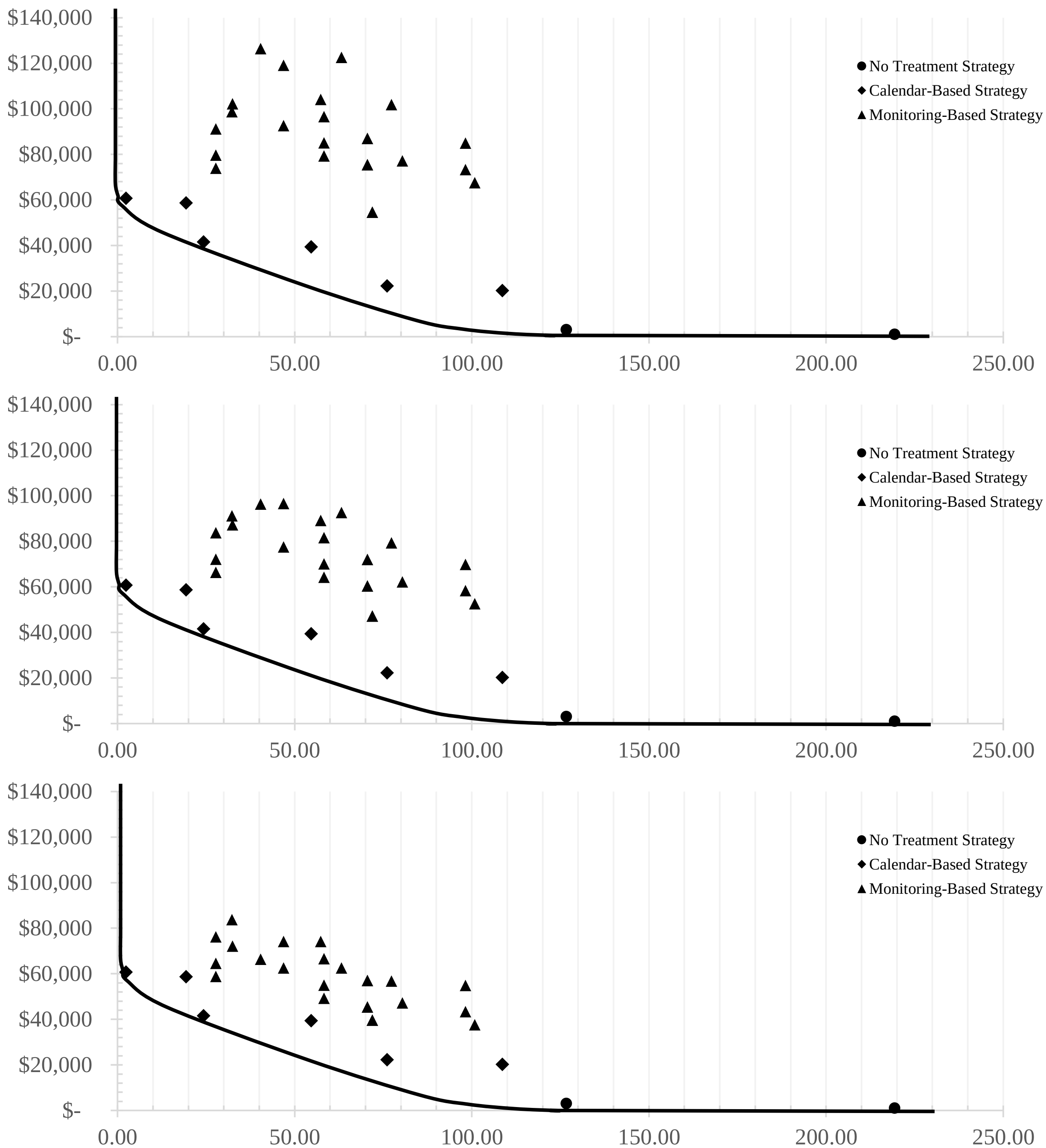

Figure 14. Annual Treatment Cost for Each Strategy across Alternate Shutdown Time Opportunity Costs Using Mean Insect Population Threshold (2007-2009)

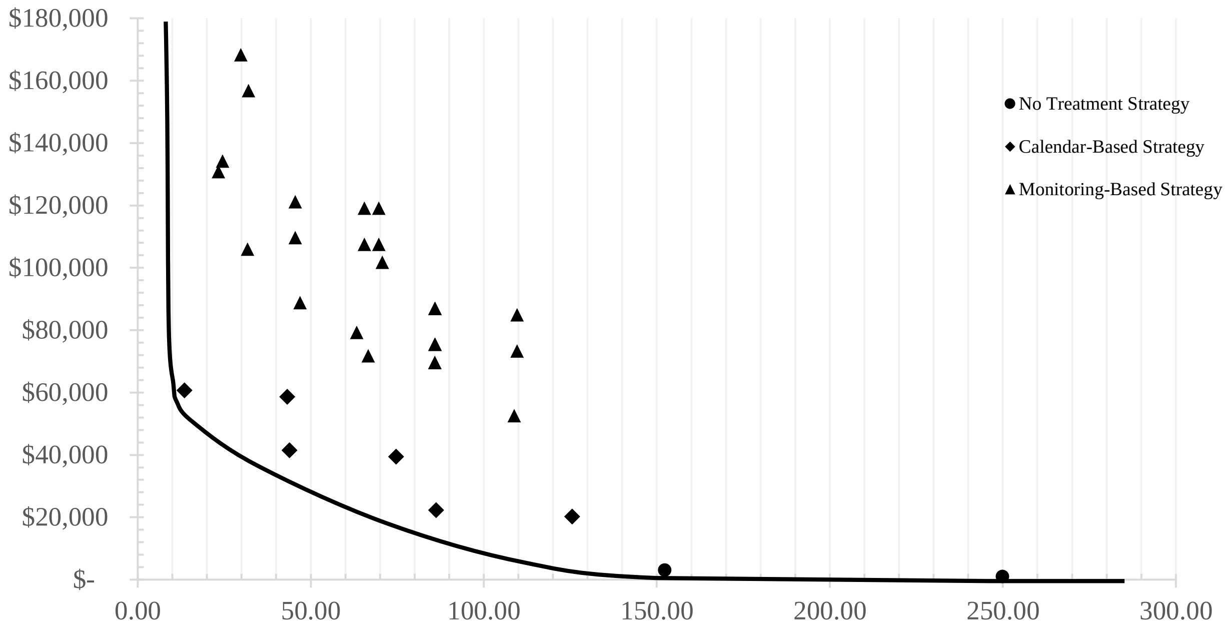

Figure 15. Cost Frontier for Strategies Using Mean Insect Population Thresholds (2009-2011)

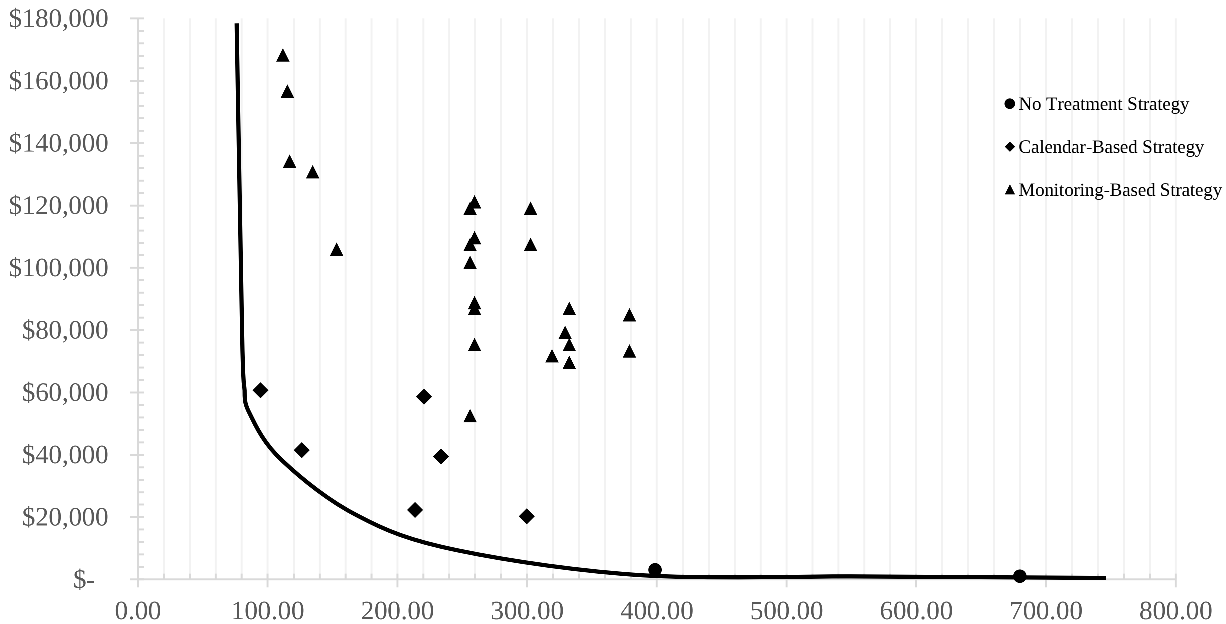

Figure 16. Cost Frontier for Strategies Using Maximum Insect Population Thresholds (2009-2011)

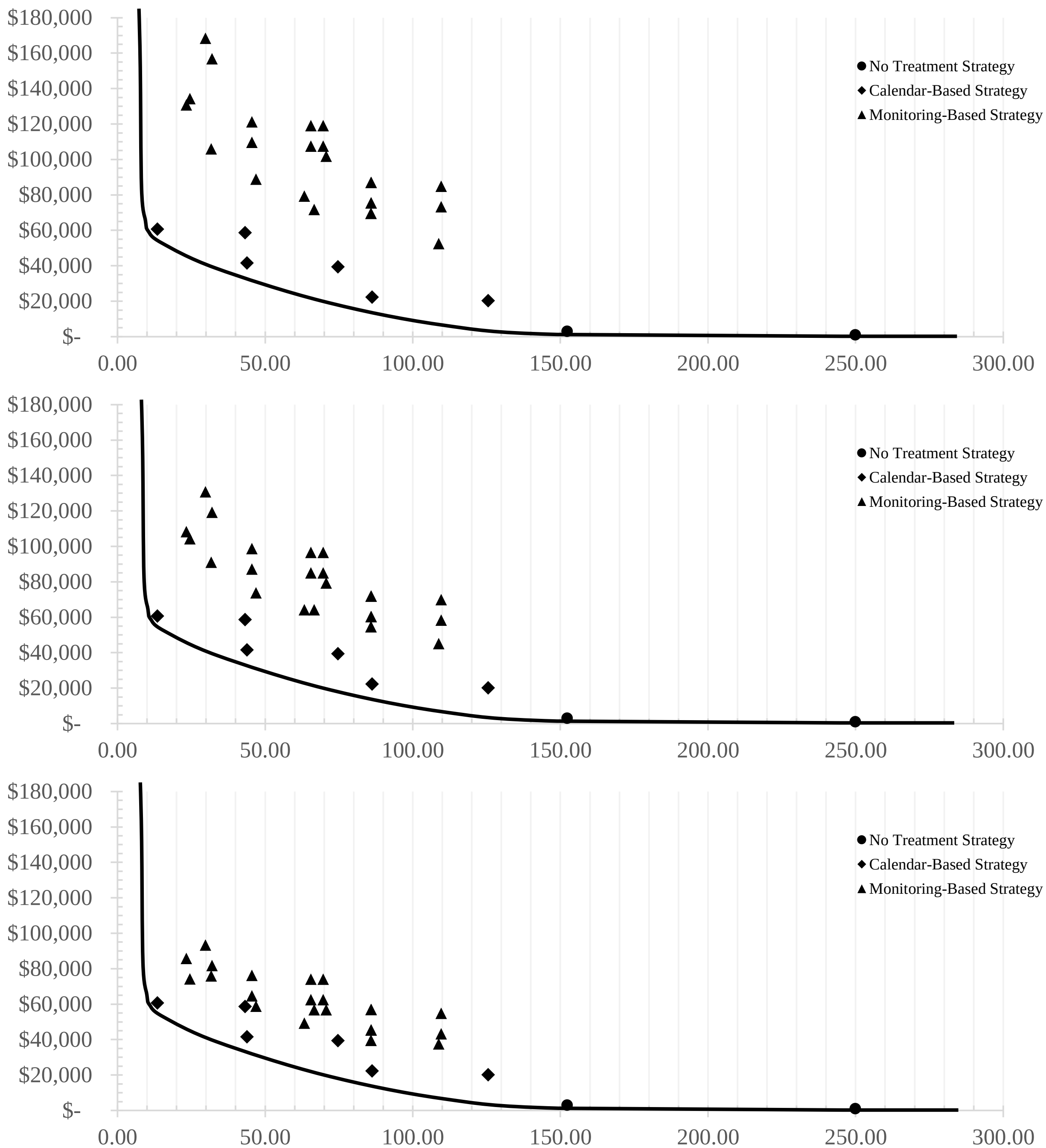

Figure 17. Annual Treatment Cost for Each Strategy across Different Shutdown Time Opportunity Costs Using Mean Insect Population Threshold (2009-2011)

Least Cost Monitoring-based Fumigation Strategy

Table 19 highlights the reasons that the best calendar-based fumigation strategies are economically preferred in this analysis to the best monitoring-based fumigation strategies, even taking into account the higher cost of shutdown with monitoring-based strategies. Table 19 shows the annual cost and number of fumigations conducted using the overall lowest cost strategies, along with the same measures for the lowest cost monitoring-based fumigation strategies. For example, during period 2005-2007, strategy #8 is the lowest cost overall strategy that achieves a target of K_{mean} = 60, with 6 fumigations conducted at an annual average cost of $60,753 (strategy #8 is a calendar-based strategy with good sanitation). Strategy #17 is the lowest cost monitoring-based fumigation strategy that achieves the same target insect population. Using strategy #17 results in one more fumigation than strategy #8, and has an annual average cost of $87,693, 44.3% higher than the cost of strategy #8.

Under all 18 scenarios in Table 19, using monitoring-based fumigation strategy results in an additional ½ fumigation on average compared to the best calendar-based strategy. Thus, in addition to the extra monitoring costs, monitoring-based fumigation strategies using the fumigation rules (fumigation frequency: monthly monitoring, biweekly monitoring and seasonal monitoring) specified in this analysis incur higher fumigation costs as well. Averaging across all 18 scenarios, the annual cost of the least cost monitoring-based strategy is 78.2% higher than the least cost calendar-based strategy. Thus, even though a reason for using monitoring-based strategies is the potential to reduce number of fumigations, these results suggest that monitoring-based strategies may not reduce number of fumigations, and may even increase the number. This is true over a range of possible “triggers” for the fumigation decision: 100, 150, 200, and 250 insects counted on the sampling day as the fumigation criterion.

Table 19. Least Cost Strategies Compared with Least Cost Monitoring-based Fumigation Strategies for Simulated Scenarios (Opportunity Cost of Shutdown = $ 0)

	K_{mean}			K_{max}		
2005-2007	60	80	100	200	270	340
LC Strategy #	8	6	6	8	6	4
Fumigation #	6	4	4	6	4	2
Annual cost $	60,753	41,542	41,542	60,753	41,542	22,331
LCM Strategy #	17	19	10	21	30	20
Fumigation #	7 (+1)	5 (+1)	6 (+2)	7 (+1)	5 (+1)	3 (+1)
Annual cost $	87,693 (+44.3%)	68,482 (+64.9%)	66,402 (+59.8%)	105,028 (+72.9%)	74,260 (+78.8%)	49,271 (+120.6%)
2007-2009	50	70	90	180	240	300
LC Strategy #	6	5	4	5	4	4
Fumigation #	4	3	2	3	2	2
Annual cost $	41,542	20,251	22,331	20,251	22,331	22,331
LCM Strategy #	17	19	12	17	18	19
Fumigation #	4 (_)	2 (-1)	2 (_)	4 (+1)	3 (+1)	2 (_)
Annual cost $	58,877 (+41.7%)	39,666 (+95.9%)	37,586 (+68.3%)	58,877 (+190.7%)	49,271 (+120.6%)	39,666 (+77.6%)
2009-2011	50	70	90	160	260	340
LC Strategy #	6	6	4	6	4	3
Fumigation #	4	4	2	4	2	1
Annual cost $	41,542	41,542	22,331	41,542	22,331	20,251
LCM Strategy #	17	18	19	29	12	12
Fumigation #	4 (_)	3 (-1)	2 (_)	5 (+1)	2 (_)	2 (+1)
Annual cost $	58,877 (+41.7%)	49,271 (+18.6%)	39,666 (+77.6%)	74,260 (+78.8%)	37,586 (+68.3%)	37,586 (+85.6%)

LCM refer to the least cost monitoring-based fumigation strategies

Limitations

The insect growth model used here is a significant tool in the research, because it is used to model not only insect growth but also the effectiveness of alternative treatments used to reduce insect population and/or limit insect population growth. Three potential problems caused by the model's limitations are:

(1) Humidity has a significant effect on insect population growth, but it is not included as a variable in the insect growth model. The implicit assumption by the modelers apparently is that humidity within a processing environment is relatively constant. To the extent that humidity is variable, the insect population could be over- or under-estimated.

(2) The insect growth model only allows 10 fumigations per time period. Since some strategies considered here need four fumigations per year, the maximum length of time period that can be fully evaluated is two years. This limits a researcher's ability to consider robustness of strategies across time, limiting the possibility of identifying strategies that might be effective yet require less intensive management because they take into account weather variability across more years.

(3) The insect growth model used here is calibrated for wheat flour mills while some of the cost data are collected from rice processing facilities. While flour mills are typically located in cooler climates within the U.S. than rice processing facilities, inside temperatures in flour mills may actually be warmer than inside temperatures in rice processing facilities because more heat is generated by machines used in wheat flour mills (Campbell et al, 2015). Thus, the insect growth model may overestimate insect growth when applied to rice processing facilities.

Another limitation of this research is that an assumption is made that the insect growth model corresponds with insect numbers that would be predicted from an effective monitoring program. However, monitoring is a sampling procedure, and the numbers of insects observed in monitoring insect traps may be more or less correlated with actual insect population. For example, if pheromones are used in traps, they may attract too many insects and thus overestimate insect population, or if pheromones are not used, or the insects are not mobile, a low number of insects might fall into the traps, thus underestimating the true insect population.

Further Research

As more insect population (monitoring) data are collected as part of the larger project of which this research is a part, GIS techniques can be used to model insect population pressure at specific locations on each floor within a processing facility, rather than just whole-floor analysis as conducted here. Such information could facilitate targeting treatments for more efficient use of those treatments, helping to reduce costs. While fumigation is a whole-facility treatment, other treatments, primarily aerosols, are capable of targeting specific locations within a facility. In this way, insect control resources can be more efficiently targeted to locations with high insect pressure, or to locations with high cost of insect infestation.

Further, a significant cost savings could result from not having to shut down the entire plant's operation while targeted treatments are occurring. Monitoring of the type assumed in this thesis for monitoring-based fumigation would be an especially important component of targeted treatments. Further research, probably using GIS techniques, is necessary to assess and measure the extent to which insects would migrate from a treated area to a non-treated area in response to treatment. The greater the extent of such migration, the less effective would be targeted treatments.

CHAPTER V

CONCLUSION

Conclusion

The objective of this study was to find least-cost strategies for controlling red flour beetles in rice and wheat processing facility. A cost-minimization model was used to determine the lowest-cost strategy that can achieve the desired insect population level. Insect population under 32 whole-plant treatment strategies was simulated for three two-year periods (2005-2007, 2007-2009 and 2009-2011), and treatment cost was calculated for each strategy. The strategies with lowest cost that met the threshold constraints were selected.

One result was that good sanitation is more economical than poor sanitation. It significantly reduced the mean and maximum value of simulated insect population with little cost. A second result was that the costs of monitoring-based strategies were higher than those for calendar-based strategies for the same target insect population. The exception to this was that only monitoring-based strategies were capable of achieving insect population targets that were set very low. A manager would have to pay 78.2% more if he chose to use the best monitoring-based strategies compared to the best calendar-based strategies. Another finding was that besides the additional opportunity cost of shutdown incurred when monitoring signals that a fumigation should be conducted on other than a holiday weekend, and the added monitoring costs, monitoring-based strategies do not necessarily reduce number of fumigations. ,In this study, monitoring-based strategies add an average of ½ fumigation over a two-year period compared to the calendar-based strategies.

The approach used here to determine the least cost strategy in rice and wheat milling can also be applied to other food processing facilities. The model minimizes the total cost of each strategy considering both the treatment cost and the damage cost caused by insects, but because of limited data the model was modified here to express the insect damage cost as a constraint on the average or maximum number of adult insects. This work provides useful information to rice and wheat millers about the relative costs and benefits of calendar-based and monitoring-based fumigation strategies

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