COST OF CONTROLLING (OR FAILING TO CONTROL) INSECTS IN STORED GRAIN: A COMPARISON OF CHEMICAL-BASED AND INTEGRATED PEST MANAGEMENT STRATEGIES

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COST OF CONTROLLING (OR FAILING TO CONTROL) INSECTS IN STORED GRAIN: A COMPARISON OF CHEMICAL-BASED AND INTEGRATED PEST MANAGEMENT STRATEGIES

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CHAPTER I

INTRODUCTION

Insects cause millions of dollars of damage to stored grain and other stored products each year in the United States (Flinn, Hagstrum, Reed, and Phillips). Losses that caused by insects and other problems in stored grain are estimated to be greater than one billion dollars annually in the United States (Cuperus and Krischik). In many years, residual insecticides have been used to control insects in stored grain. However, the evolution of insects' resistances, regulatory restrictions on use of insecticides and consumer desire for a pesticide-free product have made insecticides less desirable (Arthur).

One possible solution is to use integrated pest management (IPM) on stored grain. "Better timing of pest suppression using monitoring and decision-making tools can improve the cost-effectiveness of pest management as much as developing better methods for suppressing insect populations" (Hagstrum and Subramanyam, p.1).

Kogan defines IPM 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 (p. 249)". Stored-grain insects cause losses due to price discounts from grain damage and the presence of insects. IPM can not only reduce insects in the stored grain but also reduce environmental impacts from pesticides, insect resistance, and pesticide residuals in grain.

The cost of using IPM for stored grains has been previously analyzed by Lukens. However, that study did not measure the costs of grain damage caused from incompletely controlling insects. Managers face uncertain costs due to grain damage because the level of effectiveness of a particular insect control strategy may be uncertain. Even if a manager is risk neutral, the uncertain level of insect control may change the expected cost of a strategy.

If the insect population in stored grains is not controlled effectively, the insect population will damage grain, which in turn triggers large discounts and loss of income. If the number of insect-damaged kernels exceeds 31 IDK/100g, the grain is automatically designated “sample grade” and is not permitted to be sold for human consumption, a significant discount results. Also, if two or more live grain-damaging insects are detected in a grain sample, the grain must be fumigated to kill the insects, increasing cost.

There are several reasons why a particular (IPM or chemical-based) strategy may not be effective. Insects may not be detected early enough for effective control; insects may have developed resistance to a particular chemical; temperature and moisture conditions may be favorable to insect growth so that control is difficult; a particular treatment may be effective only for a certain part of the insect growth cycle, leaving insects at different stages free to grow and reproduce; or a particular treatment may be incorrectly applied, reducing its effectiveness. Several studies have shown that non-chemical IPM methods such as aeration can be very effective in controlling insects (Arthur and Flinn; Hagstrum and Throne). However, less information is available about the relative effectiveness of IPM and non-IPM strategies. Moreover, little information exists about treatment costs and costs of failing to control insects when using IPM and non-IPM strategies.

A possible reason for few elevator managers adopting IPM methods may result from the abnormally large costs they face if they fail to control insects effectively. The cost is potentially large because insect populations grow exponentially. Since insect damage increases at least proportionally with insect population, given favorable conditions for insect growth the cost of failing to control insects can become very large. The rate at which insect populations grow depends on random weather conditions, as well as on treatments applied to the insects. Because weather conditions are random, the cost of failing to control insects is itself randomly distributed.

Applying treatments when they are not needed (i.e., when insect populations are not growing rapidly enough to cause future problems) adds unnecessary, though typically small costs. However, not applying treatments when they are needed results in large costs. Of course, total costs will be minimized if treatments are applied only when they are needed. However, since weather conditions, and thus insect growth, are random, the need for treatment is random and difficult to predict. To the extent that these variables are expected on random variable, the model outcomes are random. For example, in the simulations, several locations with different weather patterns are used. A different pattern of insect growth results from each location.

Complicating the analysis, some IPM practices such as sampling and monitoring, intended to more accurately assess the need for treatment, are themselves costly. In general, the major cost of conventional chemical-based insect control is the cost of chemicals and their application, whereas the major cost of IPM strategies are labor and management costs, primarily costs of sampling and monitoring, in addition to costs of treatments when necessary.

There is a need to assess the costs of failing to control insects in order to compare them with the more predictable, smaller costs of routine treatments. By considering costs of failing to control insects as well as costs of treatment, costs of both IPM and non-IPM practices can more accurately be evaluated.

Outline of Methods

To calculate costs due to failure to control insects, insect population will be predicted using an insect growth model developed by Hagstrum, Flinn Reed and Phillips. Predicted insect population will be used to estimate discounts due to grain damage and live insects.

Several IPM and chemical-based insect control strategies will be simulated, and daily populations of larvae, pupae and adult insects will be used to calculate number of IDK that result. Number of live adults at the end of the storage period will be used to estimate discounts due to an “infested” designation. The simulations will be conducted using weather data from five locations for the year 1989, for each insect control strategy.

Estimates of economic damage from insects for each treatment will be combined with costs of each treatment strategy to estimate total costs of insects in stored grain. Costs for IPM and chemical-based strategies will be compared.

Objectives

General objective: Help grain elevator managers increase returns to storing grain.

Specific objective: Estimate the cost of both grain damage and insect treatments for both IPM and chemical-based strategies in wheat.

CHAPTER II

LITERATURE REVIEW

The Negative Impact of Pesticide use

Buyers are focusing more on the quality of grain they buy (Schultz). Pest control is important in order to maintain grain quality. However, the public has become more concerned about pesticide use. Concerns include negative health effects through groundwater and surface water contamination, negative environmental impacts, reduced farm worker safety, and increased pest resistance (Teague and Brorsen). Zilberman and Millock state that there are three major side effects associated with pesticide use: the negative impact on workers (worker safety problems); the negative impact on consumers (food safety problems); and the negative impact on the environment.

Arguments over pesticide policy depend critically on productivity matters. The extent to which pesticide use should be restricted and reduced to protect human health and the environment depends in part on the degree to which food and fiber production would fall (Chambers and Lichtenberg). The concern about the adverse effects of pesticide use on human, wildlife, and livestock health, pest resistance and the growth of secondary pests prompted the development of integrated pest management. (Greene et al). Sunding and Zivin argued that “It is important for economists to pay attention to insect population dynamics when assessing pesticide productivity and the impact of pesticide regulations.”

Insects in Stored Grain

Stored wheat can be infested by several different species of insects, causing millions of dollars in losses annually in the U.S. Examples of stored grain insects are the lesser grain borer, the rice weevil, the sawtoothed grain beetle, the rusty grain beetle and the red flour beetle. (Arthur and Flinn). The costs due to the insects are an “infested” discount, IDK discount and a sample grade designation. Wheat is said to be infested on the grain inspection certificate if two or more live insects/kg of wheat are found. Insect damaged kernels (IDK) happens when insects feed inside wheat kernels (FGIS). If wheat carries more than 32 IDK/100g, it is designated as sample grade, which is not allowed to be sold for human consumption (Flinn, Hagstrum, Reed and Phillips 2004).

Insect Growth Model

By using insect monitoring and decision making tools like economic thresholds, predictive models and expert systems to decide the timing of pest control, economic losses due to insects and unneeded pest management can be reduced (Hagstrum and Subramanyam). Population growth models are able to provide information about stored-grain insect populations in order to help to make pest management decisions (Hagstrum 1994). To know when pest control is needed, it is important to forecast insect population. Population growth models also can be used to analyze the effectiveness of different pest management programs so that the most effective one will be chosen (Flinn and Hagstrum, Hagstrum and Flinn 1990).

Computer models to predict the changes of temperature and moisture in grain bins (Metzger and Muir) and insect population growth in farm-stored wheat (Flinn and Hagstrum; Flinn, Hagstrum and Muir) have been developed.

Flinn et al have developed an insect growth model which is a modification from the farm bin simulation model. Their insect growth model is based on a distributed-delay model (Manetsch) which was used to predict the population growth of lesser grain borer as a function of grain temperature and moisture (Flinn and Hagstrum). The four major parts of the insect component are: "(1) an equation describing the relationship between the daily rate of insect development and grain temperature and grain moisture; (2) a delay process for moving the immature insects through the stages and simulating variation in developmental rate; (3) a 70-element array for keeping track of adult age; and (4) an equation describing the relationship between temperature, female age, and daily egg production". The model assumes that insect immigration into a bin stops when the temperature is cooler in October 1 (Flinn, Hagstrum, Reed and Phillips 2004).

The model was validated by simulating one storage season that ran from July to December using hourly weather data for Topeka, Kansas, and comparing with data from bins in central Kansas. Grain in these bins was neither fumigated nor moved. A vacuum-probe sampler was used to sample insect populations in concrete bins fill with wheat. About nine bins were sampled every two months. Means and standard errors of the simulation results were computed using SAS (Flinn, Hagstrum, Reed and Phillips 2004).

Integrated Pest Management

The introduction of integrated pest management (IPM) in the late 1960s is a solution to the negative impacts of pesticide use. “Integrated Pest Management (IPM) is a sustainable approach to managing pests by combining biological, cultural, physical and chemical tools in a way that minimizes economic, health and environmental risks” (USDA ERS). It should be noted though that while the IPM approach attempts to reduce use of chemicals, it does not necessary eliminate them.

Insect monitoring plays an important role in pest management. Insect control treatments will be used only when expected pest damage costs exceeds the cost of treatment (Hagstrum and Subramanyam). Hagstrum and Subramanyam also stated that pest management may be done unnecessarily if the economic threshold is not well defined. Therefore, appropriate economic thresholds and insect monitoring programs are essential to IPM.

Zilberman and Millock argued that the impact of new technologies and enforcement of pesticide regulations play a big role in reducing the three major negative effects of pesticide use: on workers, on consumers, and on the environment. They argued that the technologies available to farmers affect their responses to pesticide regulation. As a result, pesticide management strategies and pesticide regulation should change over time as new technologies became available.

Hillebrandt stated that the economics of decision making in pest management is not only concerned with the cost of pest damage and control but also with the goals and behavior of those who make the decision of pest management. Mumford and Norton note that the economic threshold model, the marginal analysis (optimization) model, the decision theory model and the behavioral decision model are the four major economic models that have been used in dealing with decision making in pest management over the past 25 years.

Stern et al. introduced the concept of economic threshold in 1959, defining the economic threshold as the density of pest population where the benefit of treatment just exceeds its costs or the loss associated with pests exceeds the cost of control.

The marginal analysis or optimization model was explained by Hillebrandt who was the first to apply marginal analysis to pest control by showing how various doses of pesticide affect crop yield and illustrated how regular pesticide use will in time lead to diminishing returns. This simply means that there will be some point beyond which additional dosage of pesticides result in a decrease in returns.

The decision theory model implies that a decision maker decides what kind of pesticides to use, and when and how to use them by referring to variables that might influence its outcome (Mumford and Norton). The behavioral model consists of two parts: a static model and a dynamic model. The static model has to do with the decision maker's personal objectives and his own evaluation and other outcomes, so the outcome will depend heavily on the decision maker's ability to make judgments. The dynamic decision model is about how current decisions can be influenced by previous experiences (Mumford and Norton).

They note that in approaches that are based on assumptions of certainty, two questions are asked: "At what pest population level should a particular control action be taken?" (the economic threshold model); "What level of control is most profitable for that particular pest density?" (the marginal analysis model).

However, when determining pest control actions in real life, the decision maker is more likely to face uncertainty. A decision maker may be able to estimate the probability of pesticide problems and choose available control strategies (the decision model) based on past experience.

Feder notes that since a decision maker's utility of an outcome is reduced by uncertainty, a decision maker should be willing to pay for information that reduces uncertainty and pesticide use. Since pesticide use tends to reduce uncertainty, information could be substituted for pesticides, so that the same level of utility could be achieved depending on relative costs and availability (Feder). The decision maker's objectives and risk aversion level will affect the choice of how to use pest control (the behavioral decision model). Mumford and Norton suggested that developers of research and extension programs in pest control should obtain characteristics of decision makers, such as their objectives, perceptions and constraints, that might affect choice of strategies.

Hagstrum and Flinn have conducted numerous studies on IPM for stored grains, noting that IPM uses cost-benefit analysis for decision-making (Hagstrum and Flinn 1996). In a Philippine case study measuring the impacts of pesticide use on farmer health and the impacts of farmer health on productivity, reducing pesticides had a small effect on productivity. This is because the loss in productivity from reducing pesticide use was offset by the productivity gain from improved farmer health. The study suggested that the estimated rates of return on technologies that reduce pesticide use, such as development of pest-resistant varieties and integrated pest management methods, are likely to be understated because they do not include the health and productivity benefits associated with reductions in pesticide use (Antle and Pingali).

Perceived economic benefits such as changes in net revenue and the variability of net revenue associated with alternative pest control strategies influence farmers to adopt IPM. Also, when producers using traditional, chemical-based insect control do not use insecticides when they should, they suffer more insect-related yield losses than do producers using IPM (Greene et al.).

Rationale of This Study

The risk associated with IPM may be an important factor influencing its adoption. (Norgaard; Cochran et al.). The cost of IPM strategies compared to chemical-based methods in stored wheat has been examined by Lukens. Even though the cost of IPM for stored grains can be similar to that of chemical-based strategies, grain managers have been reluctant to adopt IPM strategies, possibly because they lack knowledge about the effectiveness of IPM and are thus uncertain about its true cost due to unknown risk possibilities (Lukens). Lukens' study did not measure the costs due to grain damage arising from incompletely controlling insects. Managers face uncertain costs due to grain damage if the level of effectiveness of a particular insect control strategy is uncertain. Even risk neutral managers may be affected because the uncertain level of insect control may change the expected cost of a strategy. For IPM or any strategy to be effective, the cost of control has to be less than the reduction in market value due to pests (Lukens).

Estimates of costs due to both grain damage and insect treatment for both IPM and chemical-based strategies are needed in order to help grain elevator managers understand the complete costs of adopting IPM.

CHAPTER III

MODEL AND PROCEDURES

Conceptual Framework

The purpose of this research is to measure the costs of alternative insect management strategies. The specific focus is to compare the costs of IPM approaches with those of traditional non-IPM approaches. Two components of cost are considered. The first is treatment cost, which has been examined by Lukens. The second is costs of insect damage resulting from failing to control insects. If insects reach a certain population, they can cause grain damage which triggers large discounts, or at least increase the need for additional insect treatments.

An elevator's profit is reduced by insect costs, both cost of treatment and cost due to insect damage. The elevator manager wants to find a treatment strategy that will eliminate these costs. For each insect management strategy, this cost can be expressed as

$$C = TC + D \tag{1}$$

where C is the cost function, TC is the treatment cost and D is the discount caused by grain damage. Insects also cause loss of weight, but the effect is small compare to other effects, so we ignore it here.

In order to focus on the costs that a typical grain elevator operator would face, several potential benefits of IPM strategies are not explicitly considered. First, there may be marketing advantages to using IPM strategies if consumers perceive that pesticide residuals are likely to be smaller. Second, reducing pesticides may reduce insect resistance and lower environmental impact. Third, reducing the use of pesticides also reduces the chance that their use will be restricted an eliminated through government regulation, which would reduce the range of tools available for effective insect management.

Procedures

Lukens has created a spreadsheet model for calculating direct costs of IPM treatments. However, those cost calculations implicitly assume that 100% of the insects are killed or otherwise controlled. They do not consider potential costs of grain damage and discounts due to less-than-complete control of insects. The cost of failing to completely control insects, and the resulting potential for discounts due to damaged grain or live insects detected in sampling, must be considered.

The first step is to estimate the effects of alternative treatments on insect populations. In order to predict the insect population that would result under various environmental conditions and under alternative insect control strategies, an insect growth model developed by Hagstrum, Flinn, Reed and Phillips is used. This deterministic model predicts daily populations of grain-damaging insects in the larvae, pupae, and adult stages, as a function of the previous day's population, temperature, moisture, insect immigration rate, and mortality rate due to fumigation and natural death. Some of these variables, particularly temperature and moisture, are actually random. Draws from these distributions result in a set of possible outcomes, from which the best strategies are chosen.

The second step is to use the predicted insect numbers to predict economic damage. The elevator manager wishes to minimize expected total cost due to insects by choosing the lowest-cost insect management strategy,

(2) $$\text{Min}_j\ [E(C_j) = TC_j + E(D_j) + E(L_j)]$$

where $E(C_j)$ is the expected cost of insect control strategy j, TC_j is the treatment cost associated with the jth insect control strategy; $E(D_j)$ is the expected discount due to damaged grain and $E(L_j)$ is the expected discount due to live insects at time of marketing.

(3) $$E(D_j) = f(\text{Max } (I_0,\ldots,I_T), V_j)$$

(4) $$I_t = g(M_t, T_t, I_{t-1}, R)$$

(5) $$E(L_j) = p(I_T)$$

if

(6) $$I_T \geq 2,\ L_j = Discounts_L$$
$$I_T < 2,\ L_j = 0$$

(7) $$M = q(OT, F_h)$$

(8) $$T = r(OT, F_h)$$

Equations (3) and (5) state that $E(D_j)$ is a function of the maximum insect population I_T over the storage period and V_j refers to the choice variables associated with the jth insect control strategy. $E(L_j)$ is a function of insect population at the end of storage period, while in equation (4), I_t is the adult insect population in day t where M is the grain's moisture content, T is the grain temperature, I_{t-1} is the insect population t of each life stage during the days leading to time t, and R is the immigration rate of insects into the storage facility. The insect immigration rate R, depends on cleanliness of the facility, including the area surrounding the facility. Here, it is set to either “low” or “normal” immigration rate. Equation (6) states that if I_T, the insect population at the end of the storage period, is greater then or equal to 2 per sample, L_j is a specified discount (currently \$0.05/bushel in many markets); if I_T is less than 2 per sample, then L_j is equal to zero. This assumes no sampling error; sampling error would mean that insects discovered would not equal actual insect numbers. Equations (7) and (8) express that if aeration is available, the grain moisture M and temperature T depend on the outside temperature OT and fan hours F_h if aeration is used.

Data needs and sources

The cost of each insect treatment was calculated from Lukens' economic engineering model which estimates the costs of each treatment. Table 1 illustrates the cost of treatment.

Table 1. Economic engineering model of costs of strategies

Strategy	Cost per bushel	Formula
Automatic Aeration	Depends on fan hours used	electricity cost = (fan hours x (fan horsepower/efficiency) x (factor converting horsepower to kilowatt) x electrical cost x number of fans x number of bins)/total units stored
One Fumigation	\$0.028	labor charge + training charge + fumigant charge + fumigation equipment cost + liability insurance + turning labor charge + grain turning electricity charge + turning shrink loss
Two Fumigations	\$0.051	(labor charge + fumigant charge) x 2 + training charge + fumigation equipment cost + liability insurance + (turning labor charge + grain turning electricity charge + turning shrink loss) x 2
One Sampling	\$0.015	[(((insect sampling labor x insect samples) + setup time) x samplers x hourly labor cost)/total units stored] + amortized sampling equipment cost

Two Sampling	\$0.023	[(((insect sampling labor x insect samples) + setup time) x samplers x hourly labor cost)/total units stored] x 2 + amortized sampling equipment cost

Source: Lukens

A quality discount schedule for hard red winter wheat was obtained from a terminal elevator. The relationships between the variables, *M, T, R* and *t* and insect population are specified in an insect growth model developed by Hagstrum, Flinn Reeds and Phillips and modified for the current research. As stated earlier, the model was simulated for one storage season that ran from July to December using hourly weather for Topeka, Kansas. Validation data were obtained from bins that were sampled three times or more where grain was neither fumigated nor moved, starting in September in an elevator in central Kansas. A vacuum-probe sampler was used to sample insect populations in concrete bins fill with wheat. About nine bins were sampled every two months. Means and standard errors of the simulation results were computed using SAS (Flinn, Hagstrum, Reed and Phillips 2004).

<u>Simulation Parameters</u>

The simulation assumes that grain is stored for ten months (approximately 304 days). The starting storage date is set for June 20. The selling date is set for April 19 the following year. A 25,000-bushel bin 26.2 feet wide and 50 feet deep is assumed.[1] The grain temperature on the starting date is set at 84ºF and the moisture is set at 12%. Insect

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[1] 25,000 bu = 26,736.11 ft^3; $r^2\ \pi\, 50 =$ 26,736.11 ft^3; $r^2 =$ 26,736.11 ft^3 / π 50; r = $\sqrt{\ }$ 170.21 ft^3; r = 13.05ft; 13.05ft x 2 $\approx$ 26.2ft = bin wide

numbers were predicted using the software SGAPro 2.0, based on the model by Flinn, Hagstrum, Reed and Phillips (Flinn et al 2003, Flinn et al 2004).

Eighty Excel spreadsheets were used to calculate the total cost of stored grain for several insect treatment strategies and for different locations. Insect numbers, temperature, moisture, fan hours; and IDK were obtained from SGAPro 2.0.

Treatment Cost Overview

Cost of treatment is based on work by Lukens that used an economic engineering approach to estimate components of costs of each treatment. These components include equipment, chemicals, sanitation, turning, aeration, and labor. Figure 1 shows the annual per bushel cost of several IPM and conventional strategies in a storage system with total capacity of 250,000 bushels (ten 25,000-bushel bins).

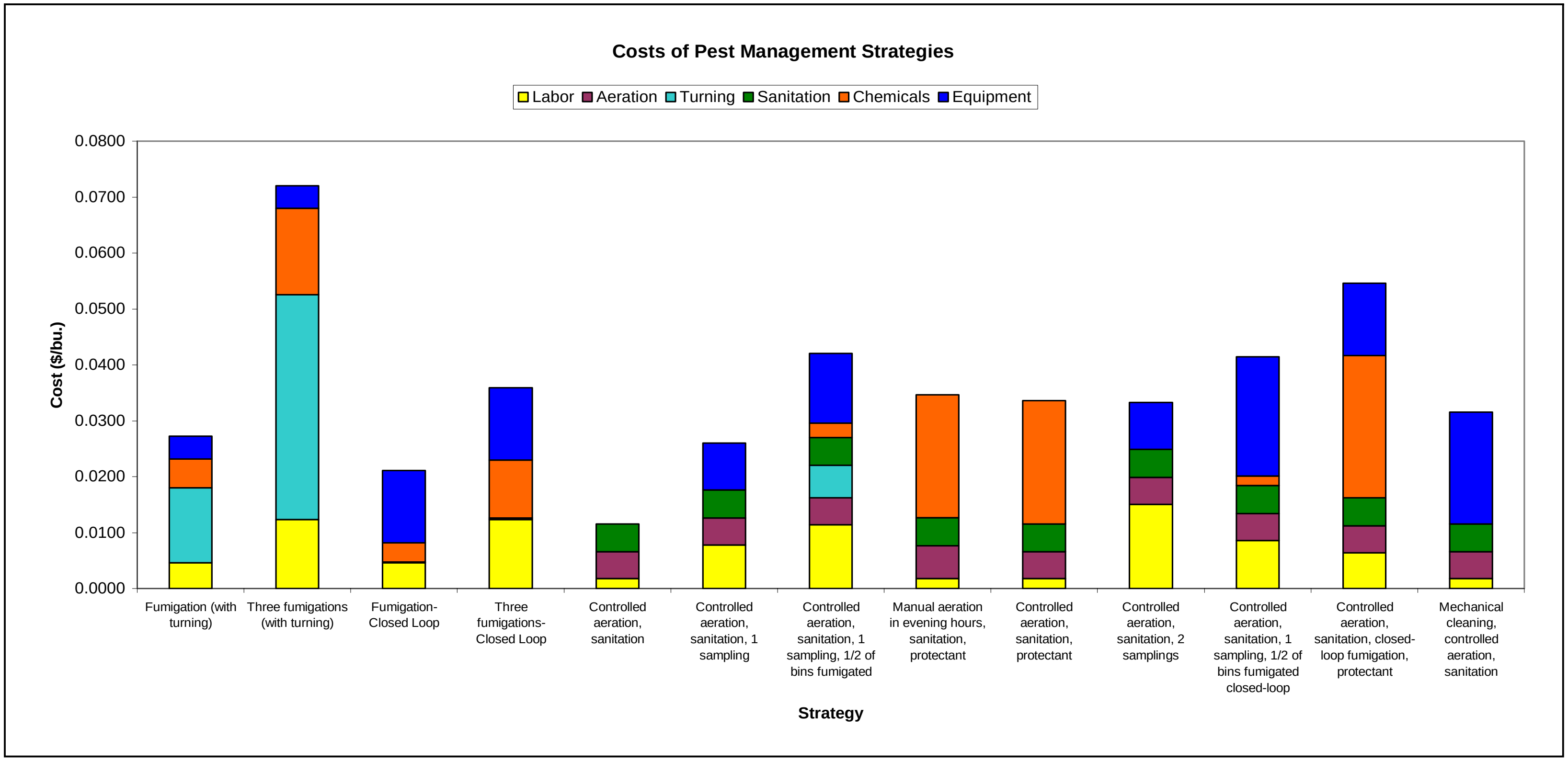

Figure 1. Cost of Pest Management Strategies.
Source: Lukens

The first component or the lower portion of each bar (strategy) measures labor cost. Since a significant portion of IPM costs is related to sampling, almost all of the sampling-based IPM strategies have the highest labor costs. However, if sampling is done upon receipt of grain and grain is stored for less than one year some of this cost can potentially be avoided.

The second component is aeration costs, composed primarily of electricity costs. Aerating immediately upon receipt of grain is less effective than aerating after outside temperatures drop, so electricity cost is higher for the same amount of cooling. Savings can be achieved if aeration fans are shut off when outside temperatures are higher than the grain temperature, and turned on only when outside temperatures are lower than grain temperature. This can be done manually, but perhaps more economically and effectively using temperature controllers.

The third component is turning cost, composed of electricity, labor, and shrink. Grain is emptied from one silo and transported on a moving belt to another silo within the facility. Fumigation can be done while turning by inserting phosphine pellets or tablets into the moving grain flow. Turning is often done in concrete silos in order to fumigate when closed loop fumigation is not used. Turning may also be done as part of other management practices such as blending for particular quality characteristics, or to break up sections of “fines” or “hot spots” to prevent insect infestation or spoilage.

The fourth component is sanitation, composed primarily of labor costs. This practice includes cleaning out empty bins, elevator legs and boots, and areas surrounding bins.

The fifth component is cost of chemicals. For both an IPM sampling strategy in which not all of the bins are fumigated, and closed loop fumigation which requires less fumigant for the same level of effectiveness, fumigant costs are lower than with routine fumigation. Closed loop fumigation would typically require 1/3 less fumigant to achieve the same level of effectiveness, and would not require turning the grain.

The sixth component is equipment. The amortized cost of equipment required for a particular strategy is included in the cost of that strategy. Sampling is assumed to require Power-Vac equipment, fumigation is assumed to required standard safety and fumigation equipment, and closed-loop fumigation is assumed to required installation of a closed-loop system. Note that if an elevator has already acquired a particular set of equipment, its cost is no longer relevant in deciding which strategy or treatment to use in a given year, since it is a sunk cost.

Insect Growth Model

To measure the cost of failing to control insects, the insect growth model developed by Flinn, Hagstrum, Reed and Phillips is used to predict the number of live larvae, pupae, and adult lesser grain borers (*Rhyzopertha dominica*) on any given day within a grain structure. In this model, beginning insect population is assumed to be zero. The growth in insect population depends on grain temperature and moisture, as well as on an assumed normal immigration rate of insects into the structure. The normal immigration assumes different immigration rates into eight different layers in the bin. Table 2 shows the immigration rates of lesser grain borers into the eight layers of the bin, where layer 1 is the top layer and layer 8 is the bottom layer of the bin.

Table 2. Immigration rates of lesser grain borers into the bin layers.

Layer	Lesser Grain Borers/ 1000 bushel/ day
1	0.6
2	0.3
3	0.15
4	0.07
5	0.01
6	0.005
7	0.005
8	0.005

Source: Flinn.

For this analysis, air temperature and moisture were taken from daily observations in five different locations in Oklahoma and Kansas (Oklahoma City and Tulsa in Oklahoma, and Wichita, Goodland, and Topeka in Kansas) from each location in the year 1989. The model adjusts these to predict grain temperature and moisture. The year 1989 is the only year available in SGA Pro. To see whether it is representative, five years (1983-1987) of daily temperature and relative humidity have been compared with year 1989 using weather data from Oklahoma City. Results show that the temperature and relative humidity of 1989 are similar to the pattern of 1983-1987. Figures 2 and 3 show these data.

The output of the model is the number of adults of the lesser grain borer (*Rhyzopertha dominica*). Since rusty grain beetles are also common in stored wheat, the prediction is multiplied by two to predict the total number of grain-damaging insects (lesser grain borers plus grain beetles). This prediction is used to determine if the grain is “infested” at the time of sale of these two insects, lesser grain borers are the most damaging, however, because they eat part of the infested kernel, causing ‘insect damaged

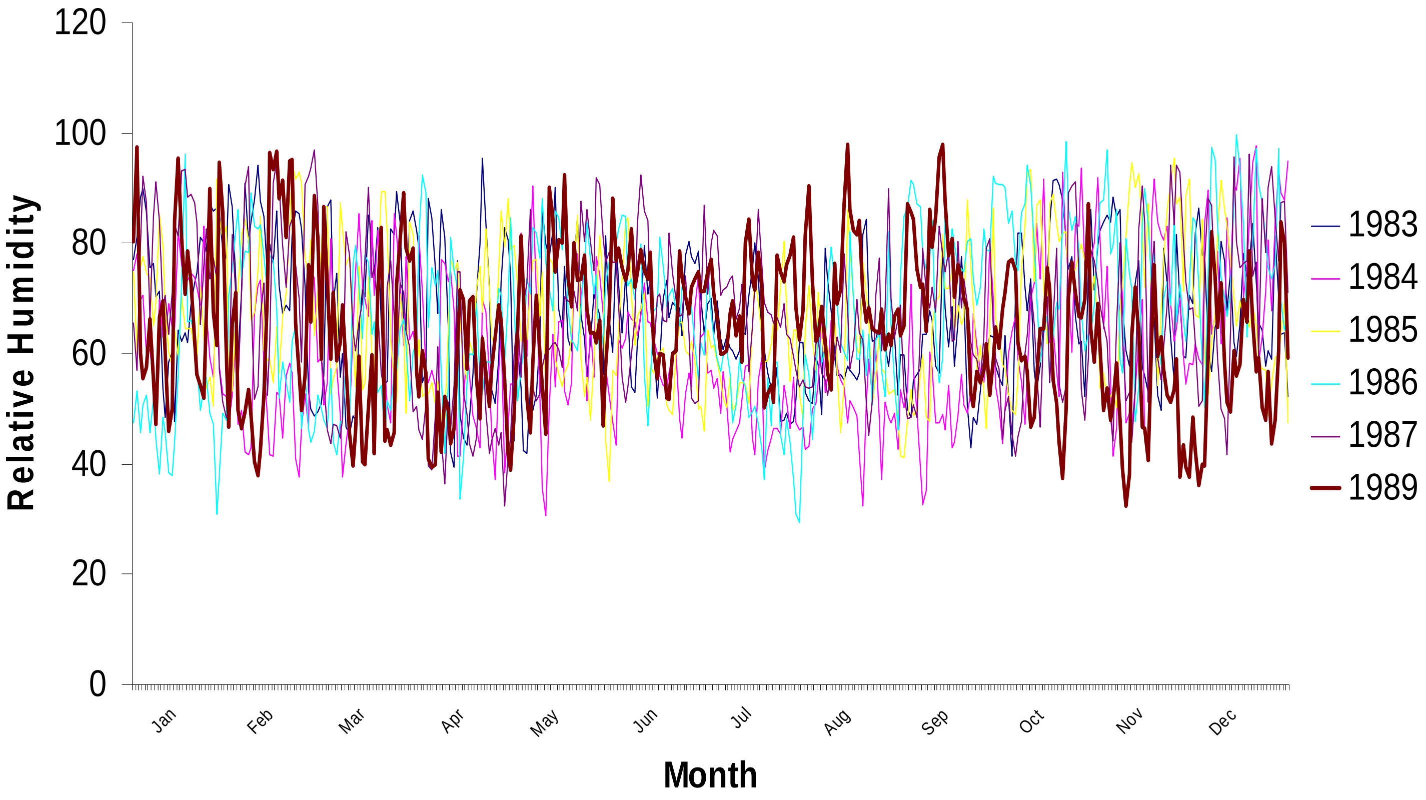

Figure 2. Comparison of Daily Average Relative Humidity of Oklahoma City for Years 1983 to 1987 and 1989.

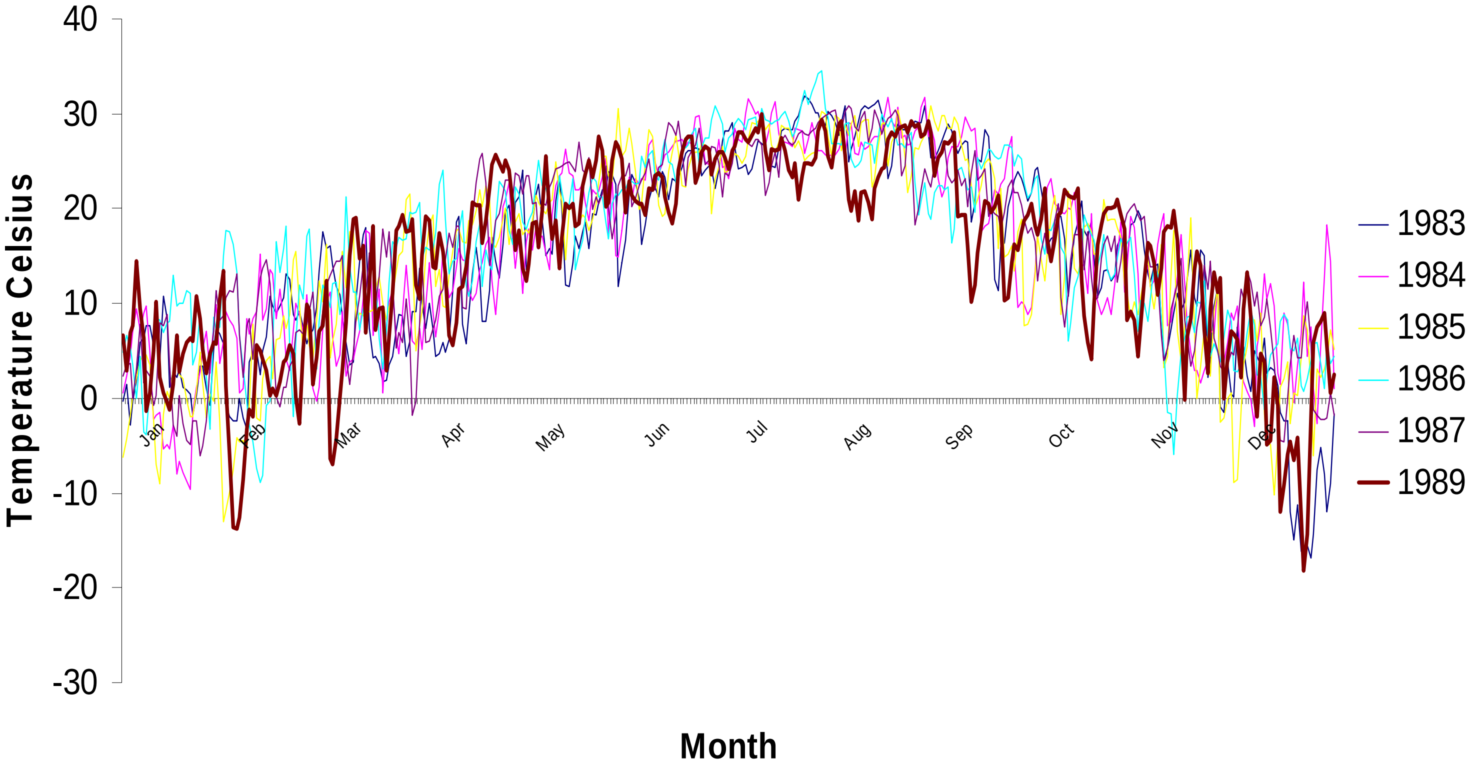

Figure 3. Comparison of Daily Average Temperature of Oklahoma City for Years 1983 to 1987 and 1989.

kernels’ (IDK). Insect-damaged kernels result when a lesser grain borer lays an egg in a crevice of a wheat kernel. When the egg hatches, the larva eats the inside of the kernel until the adult burrows out, which results in an IDK. IDK is calculated when an adult emerges from a wheat kernel. Adults that are present at the beginning of the simulation do not contribute to IDK. It is not until day 35 when a new generation of adults emerges from the kernels that IDK are generated. In the model, one IDK is accumulated each time a lesser grain borer goes from a pupa into an adult.

Cost of Failing to Control Insects

Cost of failing to control insects is made up of three parts: discount due to “infestation”, an observation of two or more live grain-damaging insects per sample (in practice, the discount is often imposed even when one live insect is observed in a sample of any size); discount due to IDK; and a sample-grade discount when the number of IDK reaches 32 in a 100-gram sample.

A sample of grain is designated “infested” if two or more live grain-damaging insects are present. In practice, the “infested” label is often assigned even if only one grain-damaging insect is detected. Grain with this designation is penalized with a discount, assumed here to be $0.05/bu., basically to cover the cost of fumigating to kill all live insects.

Insect damaged kernels reduce the quality of wheat, and discounts are imposed depending on the number of insect-damaged kernels present in a 100-gram sample. The discounts, which are accumulative as IDK increases, were current market rates from a representative terminal elevator in Oklahoma.

Table 3. IDK discounts and cleaning charges.

# of Insect-Damaged Kernels (IDK)/100g	Discount ($/bu)
1 < IDK < 5	0.00
6 < IDK < 20	0.01/IDK in sample
21 < IDK < 31	0.02/IDK above 20 in sample
32 < IDK < 70	0.40 cleaning charge
71 < IDK < 100	0.60 cleaning charge
101 < IDK < 140	0.90 cleaning charge
140 < IDK	0.01/IDK above 140 in sample

Source: Johnston Barge Terminal Grain Company.

The growth model assumes that when grain is fumigated with highly-effective fumigation effects, 90% of insects in the pupae stage, 99% of insects in the adult stage, and 99.9% of eggs and larvae are killed over a 5-day period. If the facilities have holes for gas to leak out, that will result in a fumigation failure. The model can also be specified to reflect a less effective fumigation that kills 70 % of adults, 50 % of pupae, 70 % of larvae and eggs. Since the number of insects depends on temperature and moisture, the models predictions automatically reflect the effects of aeration on insect population.

Treatment Cost

The costs of treatments including automatic aeration cost, fumigation cost and sampling cost are adapted from Lukens.

Automatic Aeration. The cost of automatic aeration is the cost of electricity for the fan hours used. The calculation of this per bushel cost is *(fan hours x (fan horsepower/efficiency) x (factor converting horsepower to kw) x electricity cost x number of fans x number of bins)/total units stored*. The fan hours are obtained from the SGAPro simulation. The fan horsepower is 33.5, which gives a rate of 1.34 horsepower per 1,000 bushels, assuming medium aeration with grain depth of 50ft. This provides an aeration rate of 0.1 cfm (cubic feet per minute), which is the appropriate rate for a 50ft depth bin (Noyes, Weinzierl, Cuperus, and Maier). The efficiency of the fan is assumed to be 75%. The factor for converting horsepower-hour to kilowatt-hour is 0.75 kwh/hp hours. The electricity cost is assumed to be $0.07/kwh, and each 25,000 bushel bin is assumed to have one fan.

Fumigation. Fumigation cost is the sum of cost of labor, chemicals (fumigants), turning, amortized equipment costs, training and liability insurance. The per-bushel fumigation costs are $0.028 and $0.051 for one and two fumigations, respectively. Since equipment cost, training and liability insurance are one time costs, they are not included in the cost of two fumigations.

Sampling. One sampling costs $0.016 per bushel and two sampling costs $0.023 per bushel which includes labor to go to a bin, probe ten required samples, sieve the grain, samples and count and identify the insects,[2] and amortized sampling equipment cost[3].

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[2] (((insect sampling labor x insect samples) + setup time) x samplers x hourly labor cost) / total units stored

[3] ((initial POWERVAC cost/PVIFA) + maintenance costs per year + insurance costs/ per year)/total units stored; where PVIFA is the present value interest factor for an annuity of n years at i percent interest rate

$$= \quad [1 - (\frac{1}{1-i})^{n}] / i$$

Treatment Description

Automatic Aeration. For the scenario using aeration it was assumed that automatic aeration controllers were available. For automatic aeration, the fan runs automatically when the air temperature is lower than the grain temperature. Aeration will not kill insects, it control the insect number by slowing their growth and development (Oklahoma State University). Three starting dates for aeration -- June 20, September 20, and October 16 -- were considered.

Routine Fumigation. Three routine fumigation scenarios were considered: fumigating once on any of three dates -- October 1, January 18, and February 10.

Selective Fumigation. Selective fumigation used sampling (a major component of IPM) to determine if insect control needed. Three scenarios for selective fumigation were: sample on October 9; sample on October 9 and April 1; and sample on October 9 and January 6; fumigate if lgb/kg is greater than 0.5.

Simulation Scenarios

Table 4. Simulation scenarios.

Scenario	Strategy	Description/ Dates of Aeration or Fumigation
1.	Doing Nothing	A baseline model, no treatment was applied.
2.	Automatic Aeration	Fan started on June 20
3.	Automatic Aeration	Fan started on September 1
4.	Automatic Aeration	Fan started on October 16
5.	Routine Fumigation (highly-effective)	Fumigate on October 1
6.	Routine Fumigation (highly-effective)	Fumigate on January 18
7.	Routine Fumigation (highly-effective)	Fumigate on February 10

Table 4. Simulation scenarios.

Scenario	Strategy	Description/ Dates of Aeration or Fumigation
8.	Routine Fumigation (less-effective)	Fumigate on October 1
9.	Routine Fumigation (less-effective)	Fumigate on January 18
10.	Routine Fumigation (less-effective)	Fumigate on February 10
11.	Selective Fumigation (highly-effective)	Sample on October 9, fumigate if lgb/kg > 0.5
12.	Selective Fumigation (highly-effective)	Sample on October 9 & April 1, fumigate if lgb/kg > 0.5
13.	Selective Fumigation (highly-effective)	Sample on October 9 & January 6, fumigate if lgb/kg > 0.5
14.	Selective Fumigation (highly-effective)	Sample on October 9, fumigate if lgb/kg > 0.5
15.	Selective Fumigation (highly-effective)	Sample on October 9 & April 1, fumigate if lgb/kg > 0.5
16.	Selective Fumigation (highly-effective)	Sample on October 9 & January 6, fumigate if lgb/kg > 0.5

Sixteen scenarios were simulated. First, a baseline scenario assumed that insects grew unchecked during the storage period. Scenarios #2-#4 used an aeration strategy in which the fan was automatically turned on when outside temperature dropped below grain temperature and automatically turned off when outside temperature was grain temperature or above. Scenario #2 allowed fans to turn on starting June 20, immediately after binning, Scenario #3 allowed them to turn on beginning September 1, and Scenario #4 allowed them to turn on beginning October 16.

Scenarios (#5 - #10) used routine fumigation, or fumigation not based on sampling. Scenario #5 simulated fumigation on October 16, Scenario #6 on January 18, and Scenario #7 on February 10, assuming highly-effective fumigation. Scenario #8 simulated fumigation on October 16, Scenario #9 on January 18, and Scenario #10 on February 10, assuming less-effective fumigation.

Scenarios #11 - #16 used monitoring/sampling to determine whether and when to fumigate. This is a major component of many IPM approaches, in which a firm should fumigate only if sampling indicates that it will be necessary. The rule used was to fumigate if sampling detected 0.5 or more lesser grain borer per kilogram sample. Each sampling costs about one cent per bushel, adding to the treatment cost. Scenarios #11 and #14 assume sampling once on October 9. Scenarios #12 and #15 assume sampling once on October 9 and once on April 1. Scenarios #13 and #16 assume sampling once on October 9 and once on January 6. Scenarios #11 - #13 assume highly-effective fumigation and scenarios #14 - #16 assume less-effective fumigation.

For each scenario, lesser grain borer numbers were predicted each day based on grain temperature, moisture, number of insects at each of three life stages the previous day, and any fumigation treatment. Aeration controls insect numbers by reducing the temperature of the grain where the low temperature slow down the development of insects. The effects of both aeration and fumigation are reflected in the insect numbers predicted by the growth model. Based on these numbers, the model predicts IDK and number of live adult insects in the grain. These predictions were used in the economic model to estimate per bushel costs of each scenario.

“An additional set of scenarios is conducted under which wheat is stored until January 31 rather than April 20. Brorsen and Anderson find that most Oklahoma wheat producers well their wheat by the end of January. These additional scenarios assume that everything is the same as in the previous scenarios, except that grain is stored only until January 31."

CHAPTER IV

RESULTS

Doing Nothing

Figure 4 shows the insect numbers predicted by the insect growth model when no treatment strategies were used. Number of lesser grain borers (lgb) had reached more than 100 live lgb/kg by February 20 in locations 1 and 4, and by the end of March in locations 2, 3, and 5.

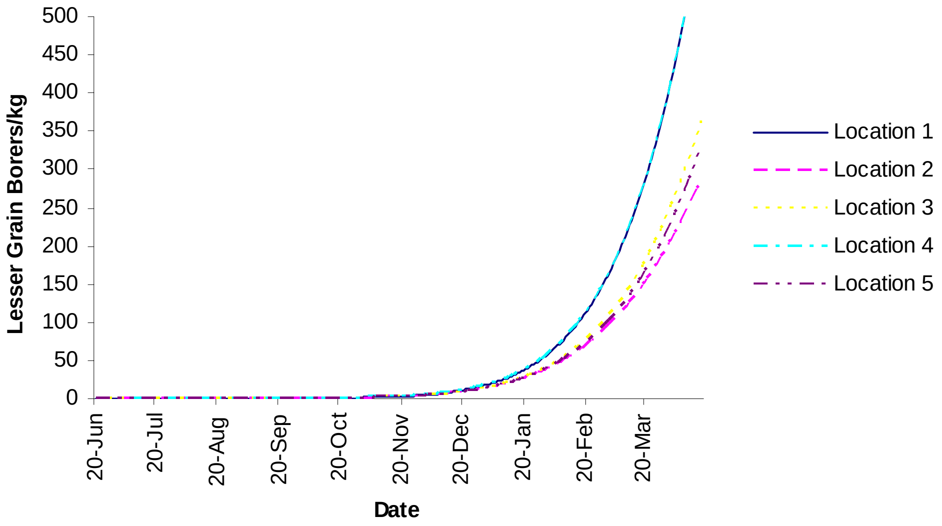

Figure 4. Insect Numbers by Location; Doing Nothing

Figure 5 shows the costs of doing nothing in all five locations. There is no treatment cost, so all costs are due to failure to control insects. Insect numbers grow to a level high enough that there is an “infested” designation in all locations, a discount due to IDK, and a discount due to a sample grade designation. Since insects did not grow as quickly in location 2, its IDK discount is less than in the other locations, and location 2 did not incur a sample-grade designation. The costs of doing nothing ranged from 9¢/bu to 31¢/bu.

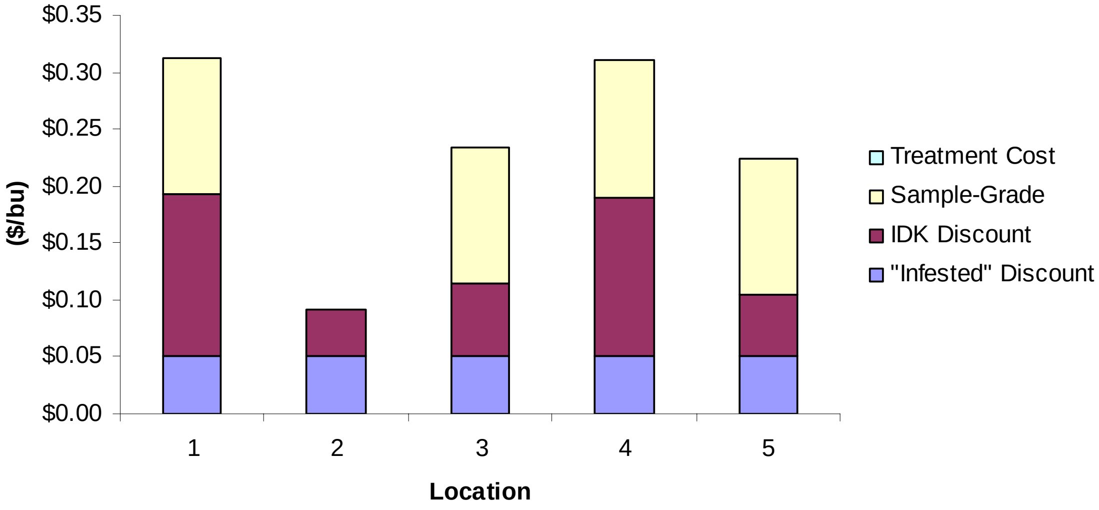

Figure 5. Total Costs of Doing Nothing.

Automatic Aeration

Figures 6-8 show the insect numbers when using aeration starting June 20, September 1, and October 16. Starting aeration earlier resulted in lower insect numbers, because the grain was cooled earlier, and insects had less opportunity to grow and reproduce. However, even when aeration was not started until October 16, number of lesser grain borers never reached 1.0 lgb/kg at any location.

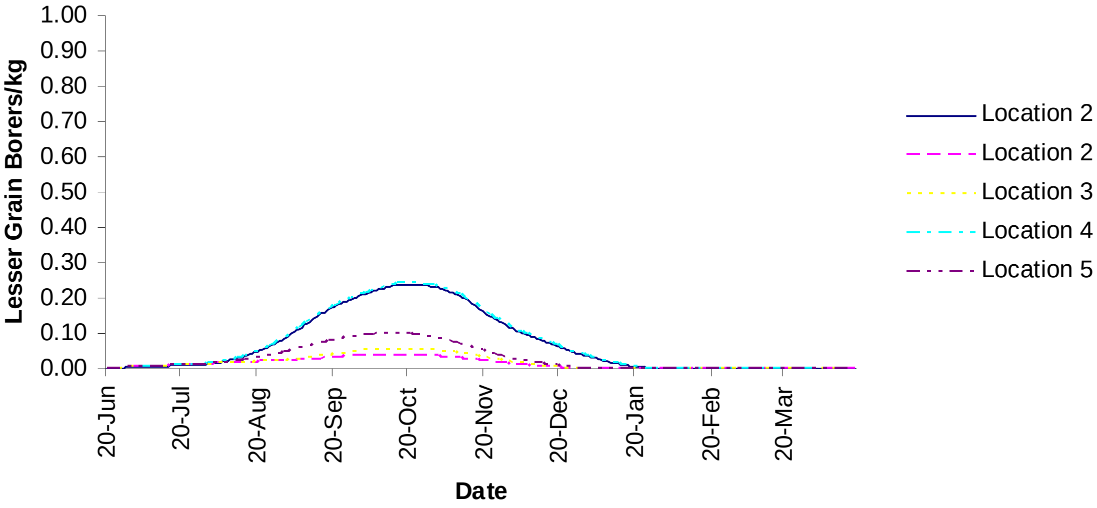

Figure 6. Insect Numbers: Automatic Aeration Starting June 20.

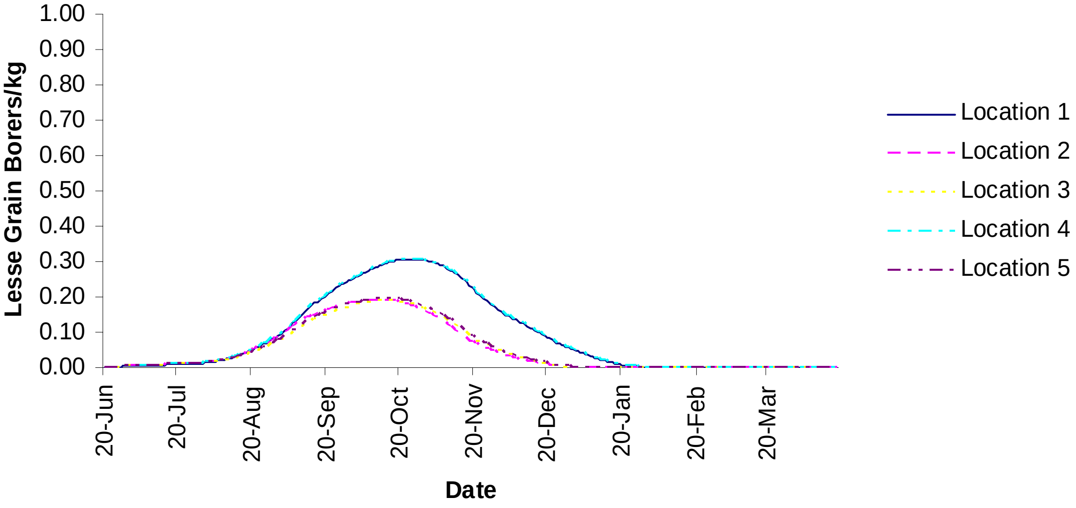

Figure 7. Insect Numbers: Automatic Aeration Starting September 1.

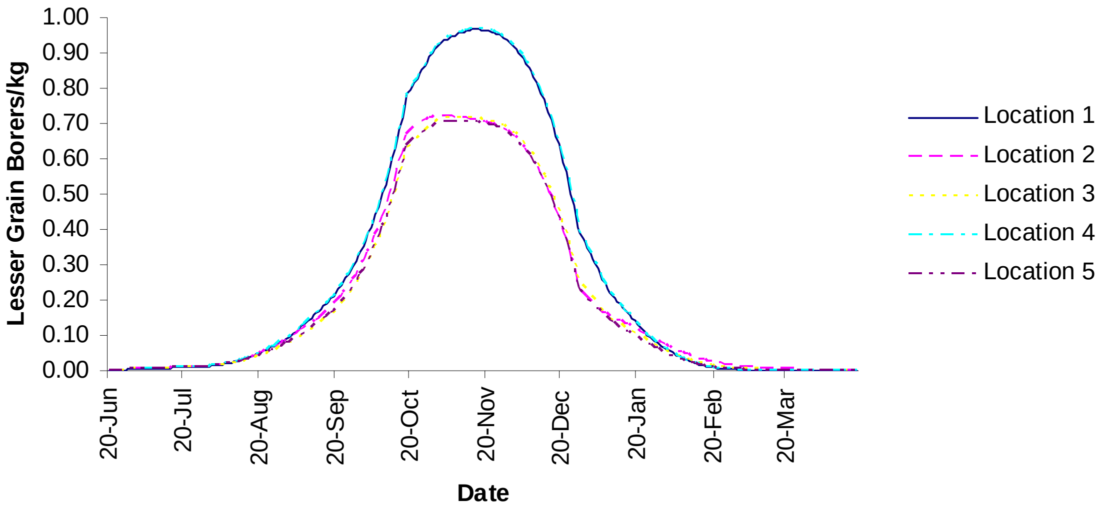

Figure 8. Insect Numbers: Automatic Aeration Starting October 16.

As a result, as Figure 9 shows, there was no cost due to insects themselves. The only cost was treatment cost. This cost differed among locations because different weather conditions triggered the fans to turn on for different amounts of time. The earlier the starting time, the higher the cost. Thus, in the case of aeration, the best insect control was not the most economical strategy. The cost of the aeration strategy ranged between 2.5¢/bu. and 5.7¢/bu, depending on location and starting date.

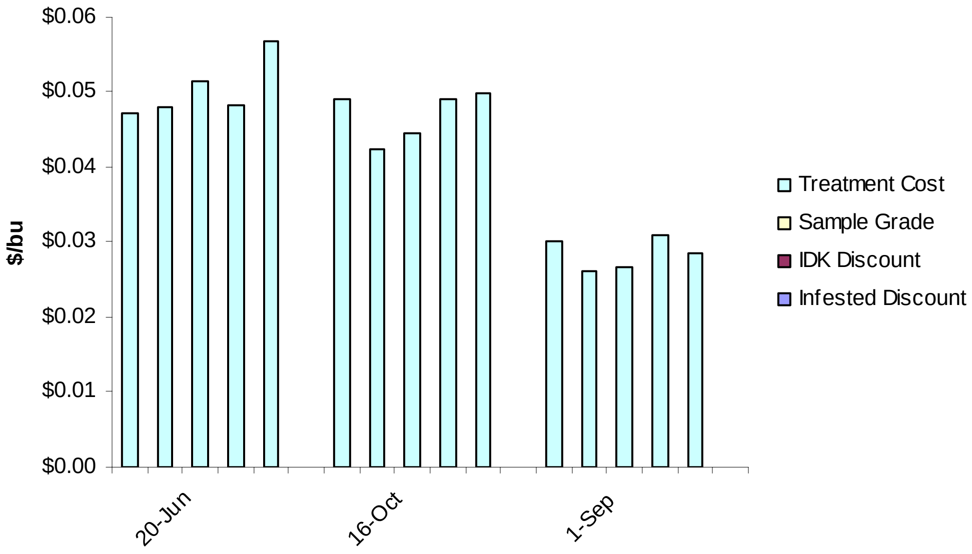

Figure 9. Total Costs of Automatic Aeration by Starting Dates.

Routine Fumigation With Highly-Effective Fumigation

Figures 10-12 show insect numbers from fumigating once during the storage period with Highly-Effective fumigation. Figure 10 shows that fumigating October 1 arrested insect growth as it reached 0.3 lgb/kg, and even though insect growth began to recover, it did not reach 0.4 lgb/kg at any location before the sale date of April 19.

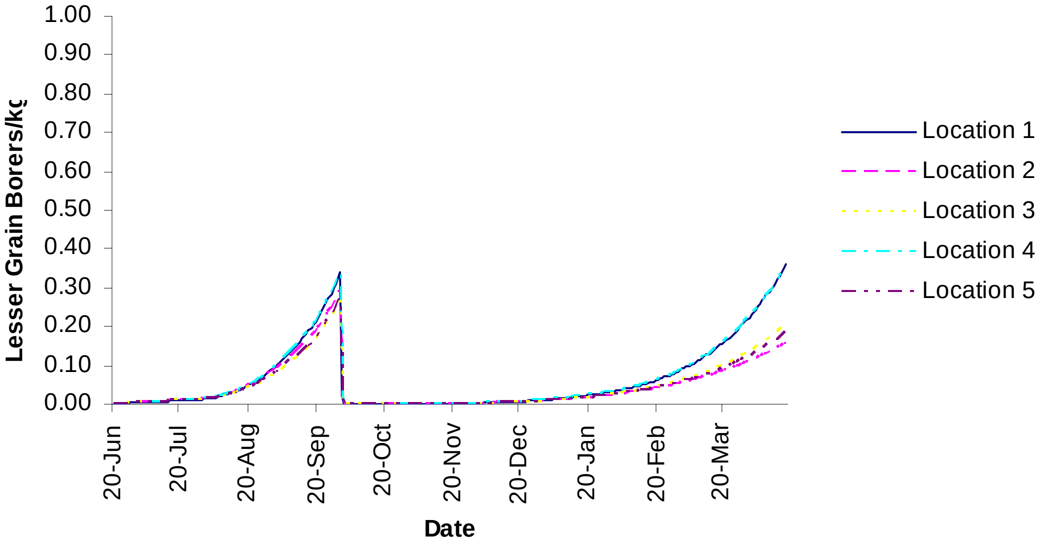

Figure 10. Insect Numbers: One Fumigation on October 1.

In order to maintain the same scale on Figure 11a as on the previous graphs, the maximum insect population has not been displayed in the graph. Figure 11b has been scaled to show the highest lesser grain borer numbers. Waiting until January 18 to fumigate allowed the number of lesser grain borers to reach 23-33 lgb/kg, depending on location. Because fumigation occurred at a later date, insect population did not recover to a significant level before sale (Figure 9).

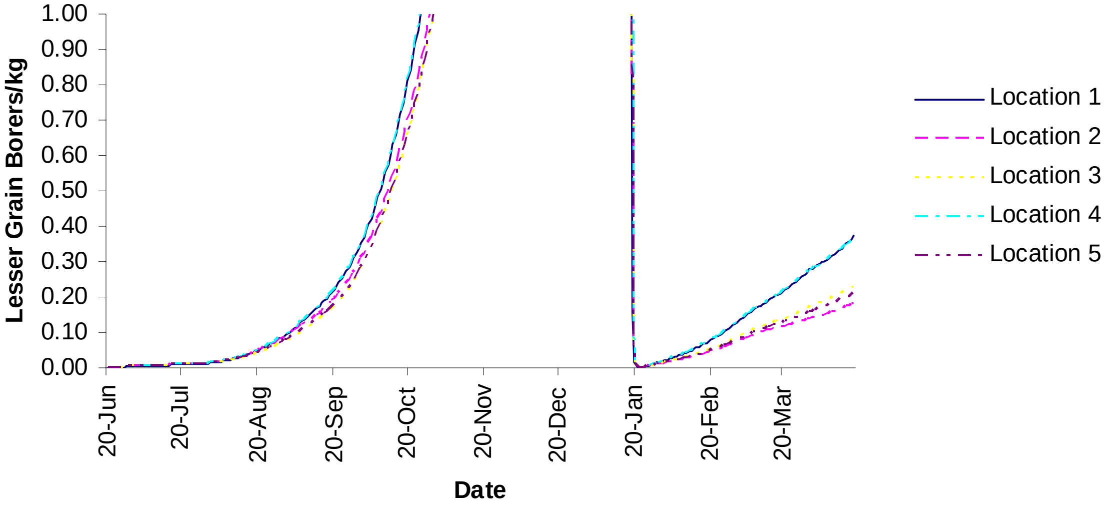

Figure 11a. Insect Numbers: One Fumigation on January 18

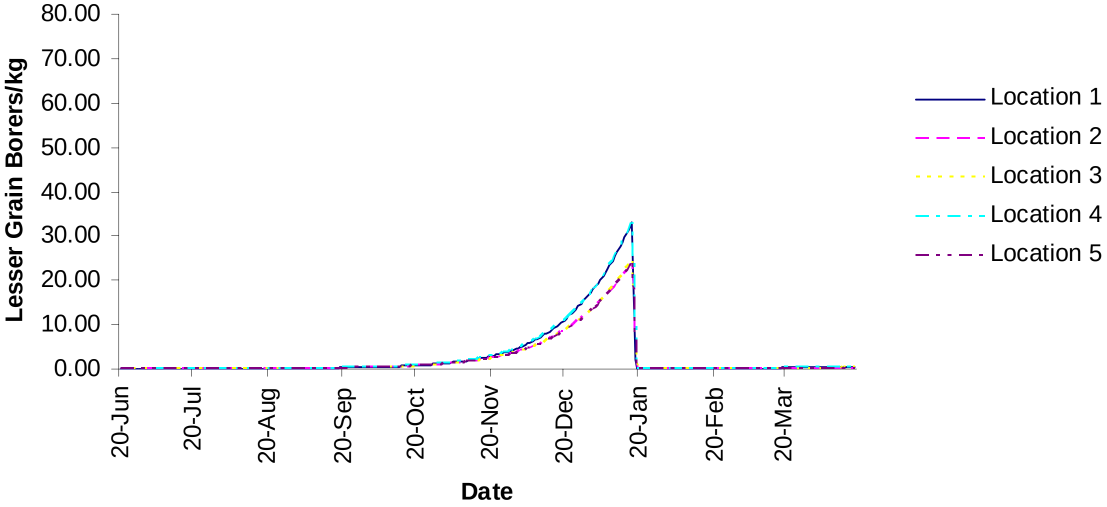

Figure 11b. Insect Numbers: One Fumigation on January 18

Figure 12a and 12b show lesser grain borer numbers in different scales, waiting until February 10 allowed lesser grain borers to reach a high level of 50-77 lgb/kg before the fumigation reduced them to approximately zero.

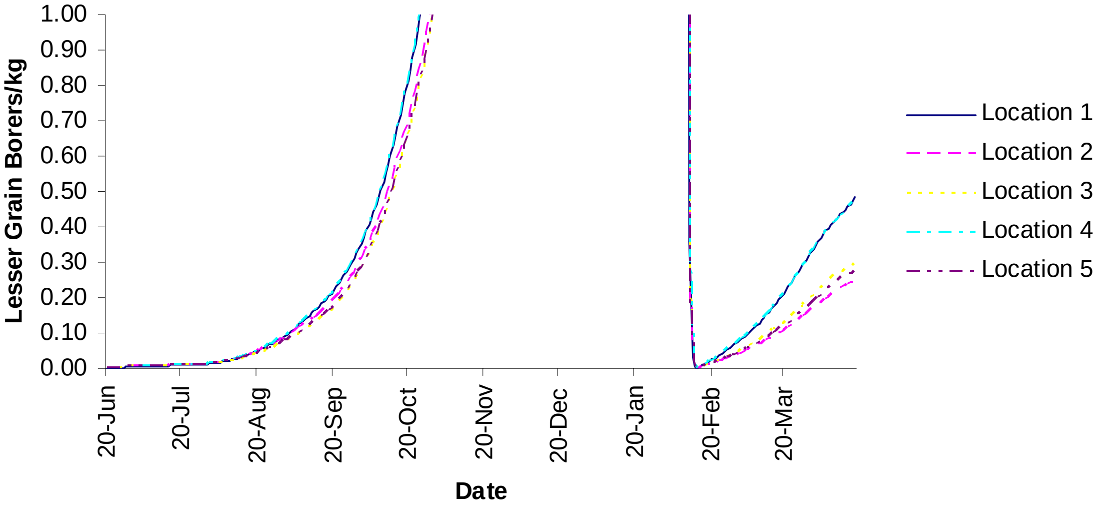

Figure 12a. Insect Numbers: One Fumigation on February 10.

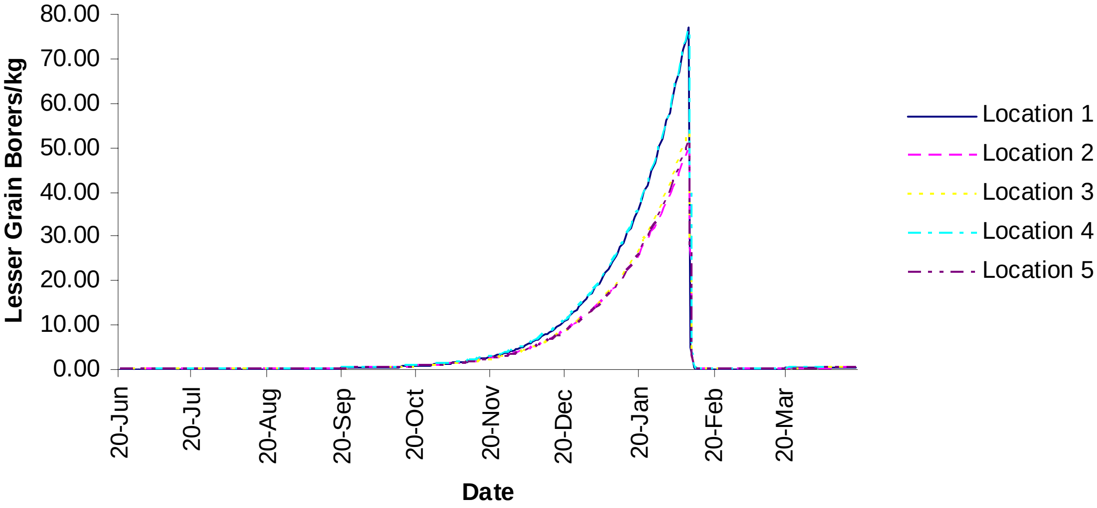

Figure 12b. Insect Numbers: One Fumigation on February 10

As Figure 13 shows, none of these three fumigation dates led to any IDK discounts, so the treatment cost of almost 2.8¢/bu was the only cost in all five locations and for all three fumigation dates.

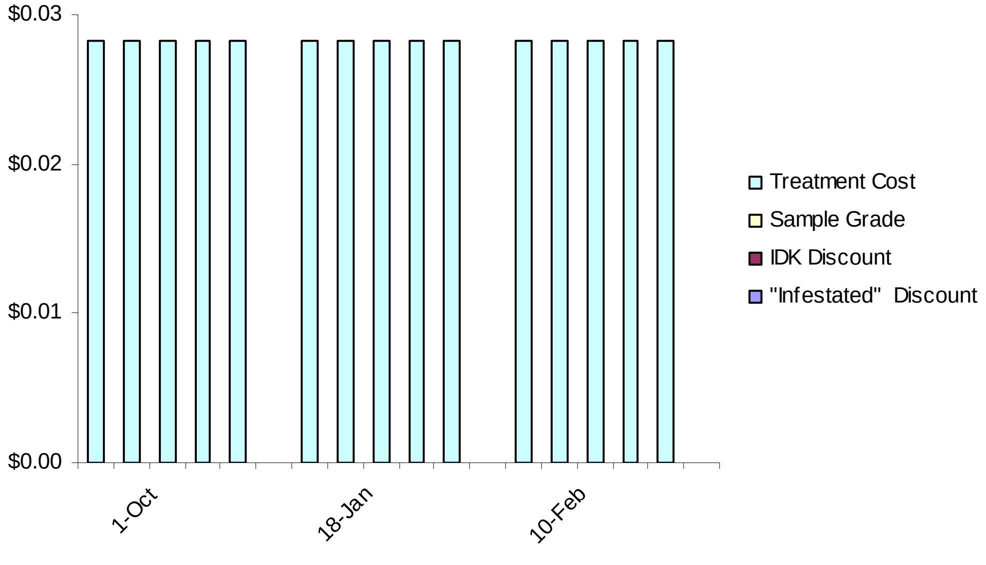

Figure 13. Total Costs of Fumigation by Dates.

Routine Fumigation With Less-Effective Fumigation

Figures 14-16 show insect numbers from fumigating once during the storage period with Less-Effective fumigation. Figure 14 shows that fumigating October 1 arrested insect growth as it reached 0.3 lgb/kg, but since the Less-Effective fumigation did not control insects as well, insect growth began to recover after 60 days. Insect numbers reach 27 lgb/kg to 57 lgb/kg before the sale date of April 19.

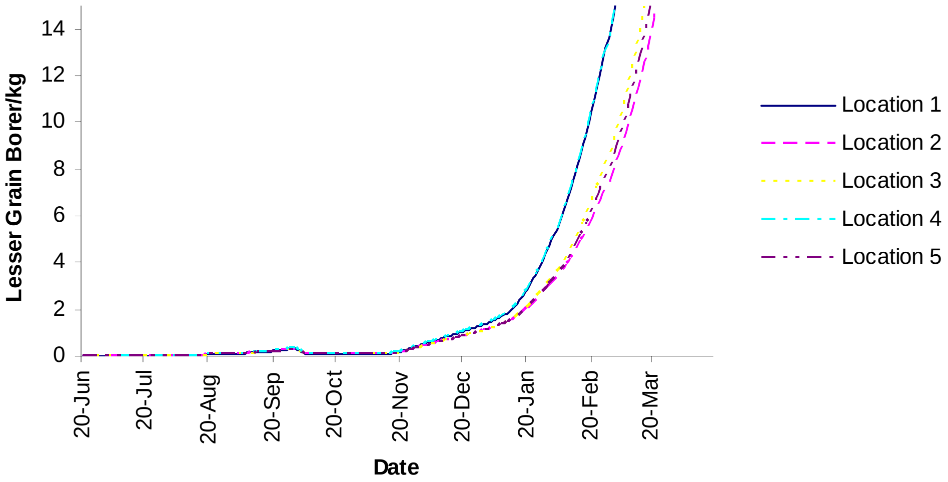

Figure 14. Insect Numbers: One Less-Effective Fumigation on October 1.

Figure 15a and 15b show that waiting until January 18 to fumigate allowed number of lesser grain borers to reach 23-33 lgb/kg, depending on location. Because the fumigation was later, and the less-effective fumigation did not control the insect as well, population of lesser grain borers was reduced to 6-10 lgb/kg. Insect population began to recover within 50 days after fumigation. Fumigations on either October 1 or January 18 allowed lesser grain borers to reach 24-56 lgb/kg before the sale date of April 20.

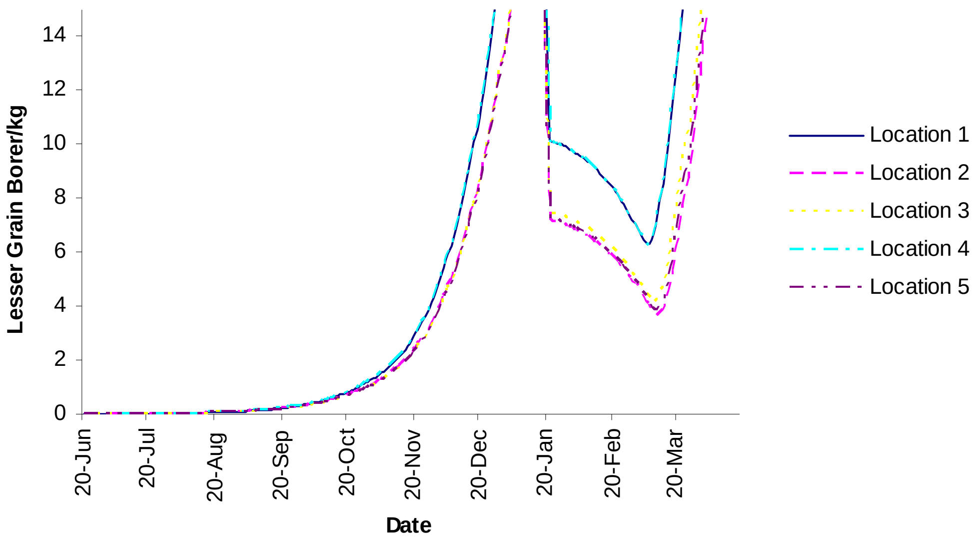

Figure 15a. Insect Numbers: One Less-Effective Fumigation on January 18.

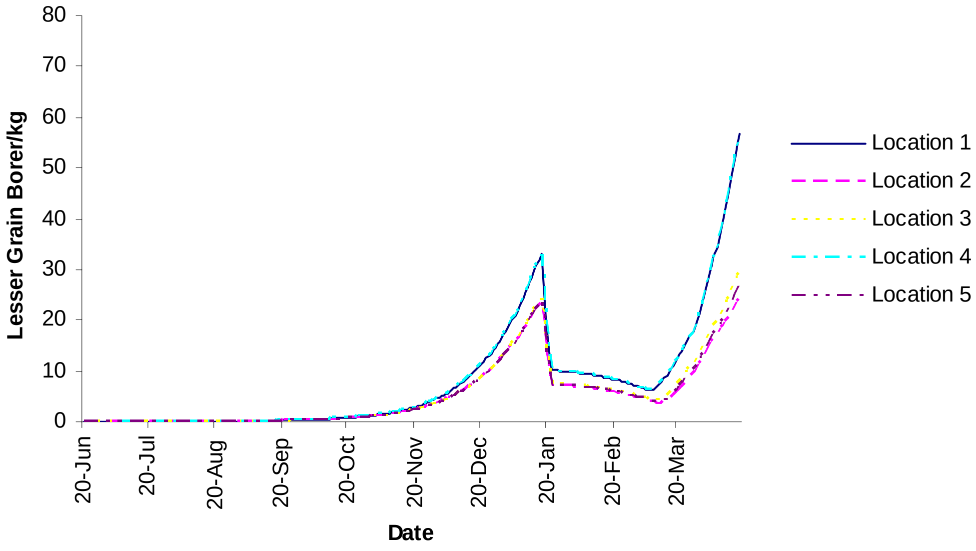

Figure 15b. Insect Numbers: One Less-Effective Fumigation on January 18.

Figure 16a and 16b show that waiting until February 10 allowed lesser grain borers to reach a high level of 50-77 lgb/kg before the fumigation reduced them to 15-25 lgb/kg. Comparing the former two situations (fumigating on October 1 or on January 18), fumigating closer to the selling date resulted in a smaller insect population before the selling date. The lesser grain borer population on April 20 ranged between 4-27 lgb/kg, depending on the location.

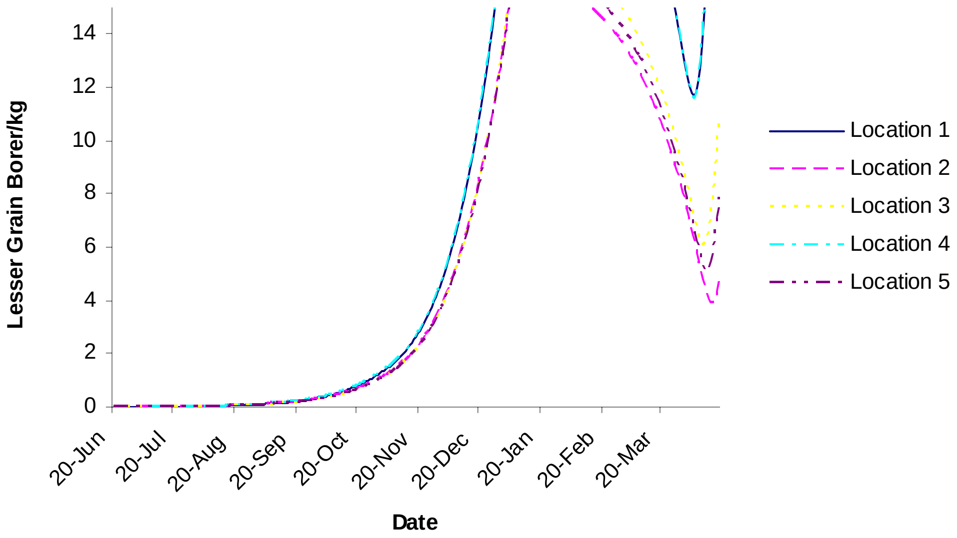

Figure 16a. Insect Numbers: One Fumigation on February 10.

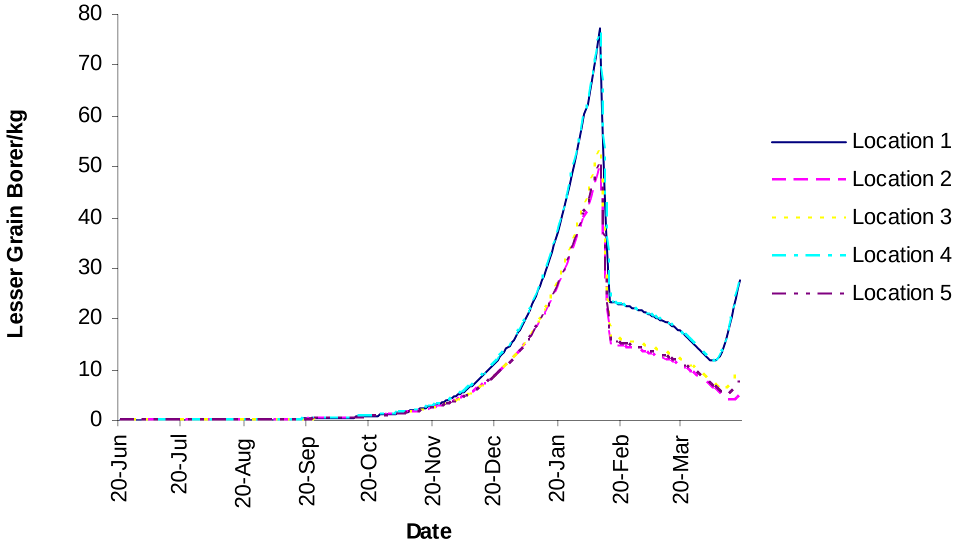

Figure 16b. Insect Numbers: One Fumigation on February 10.

Figure 17 shows the cost of one fumigation by date on October 1, January 18 and February 10 with less-effective fumigation. Due to the less effective insect control, the high ending insect numbers added 5¢/bu to the cost because of an “infested” designation. The total costs were 7.8¢/bu, regardless of location.

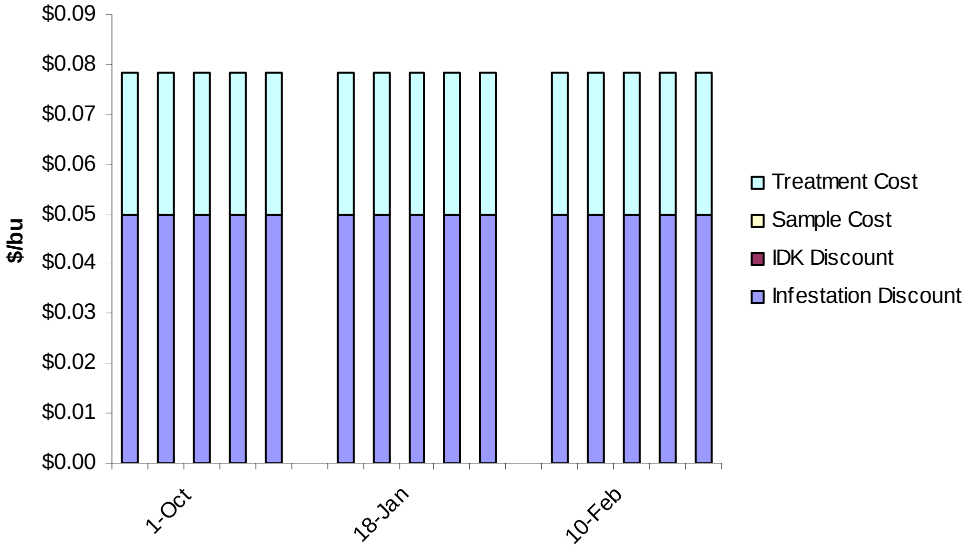

Figure 17. Total Costs of Less-Effective Fumigation by Dates.

IPM: Highly-Effective Fumigation Based on Sampling

Figure 18 shows number of lesser grain borers that resulted when sampling was conducted on October 9 and fumigation was conducted in those locations where number of lesser grain borers was greater than 0.5 lgb/kg. Insect numbers in locations 1 and 4 reached this trigger by October 9, so those locations were fumigated on October 10. Locations 2, 3, and 5 were not fumigated because they did not reach the trigger by October 9. Thus, by the time of sale, lesser grain borers in those locations reached very high numbers (similar to those shown in Figure 4).

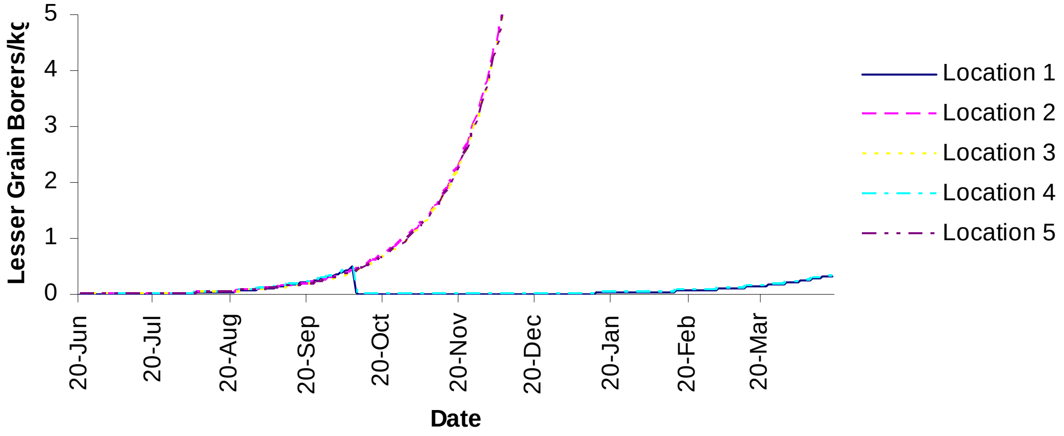

Figure 18. Insect Numbers Using Selective Fumigation- Sample on October 9 and Fumigate if More Than 0.5 Lesser Grain Borers/kg.

In Figure 19a and 19b, when sampling was conducted a second time on April 1, fumigation was conducted in locations 2, 3, and 5 on April 1 because of the high insect numbers. Because the fumigation was quite effective, the number of lesser grain borers was less than 0.4 lgb/kg at all locations at the time of sale, and the numbers were not high enough for a long enough time to cause economically significant IDK.

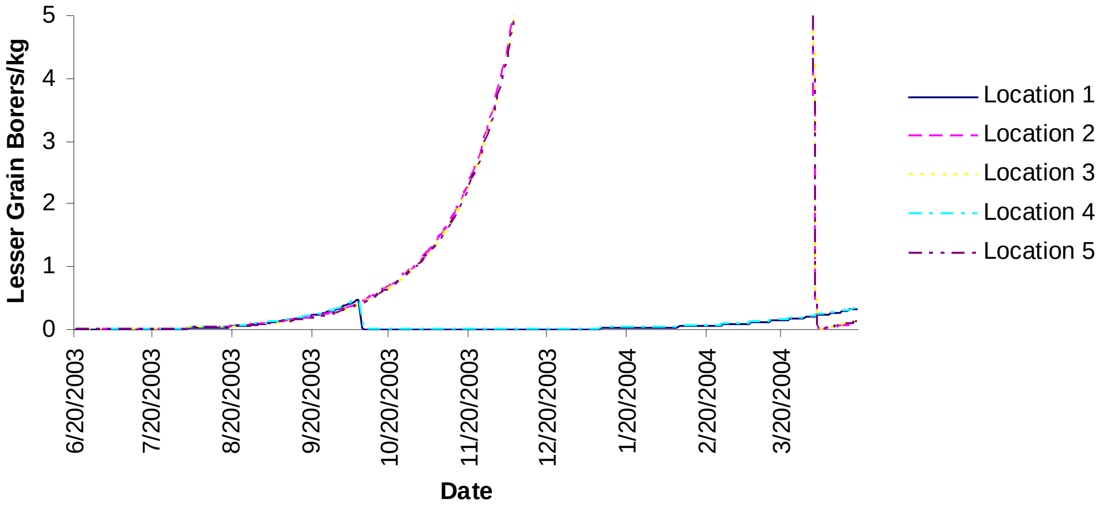

Figure 19a. Insect Numbers Using Selective Fumigation- Sample on October 9 and April 1, Fumigate if More Than 0.5 Lesser Grain Borers/kg.

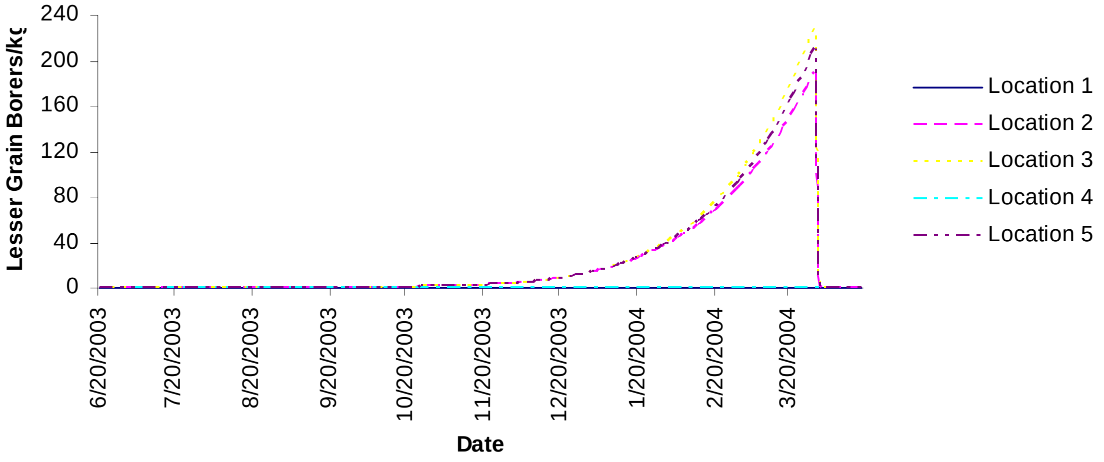

Figure 19b. Insect Numbers Using Selective Fumigation- Sample on October 9 and April 1, Fumigate if More Than 0.5 Lesser Grain Borers/kg.

Figure 20a and 20b show the insect numbers that resulted when the second sampling was conducted earlier, on January 6. This earlier sampling led to fumigation of locations 2, 3, and 5 much earlier, so that insect numbers did not increase as much.

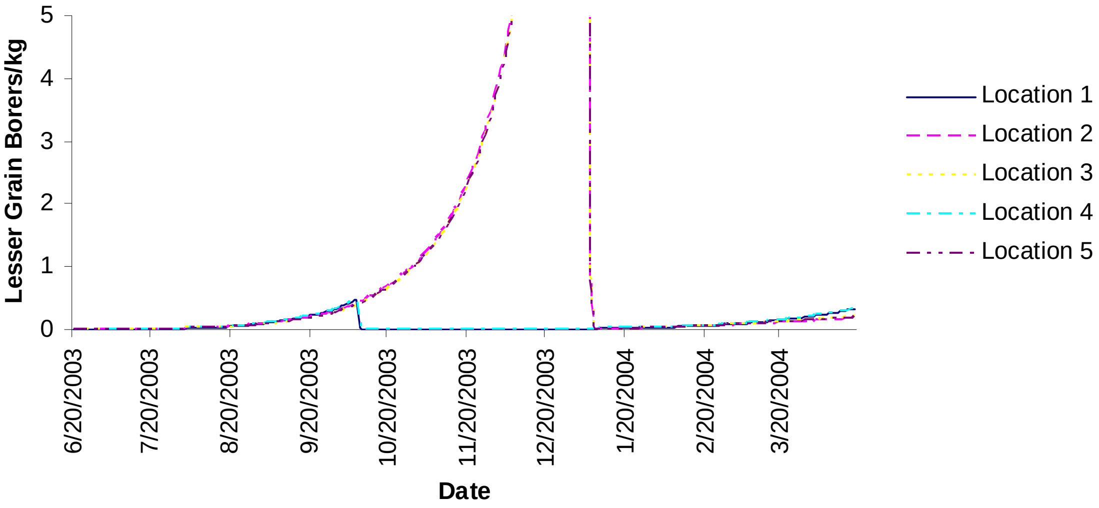

Figure 20a. Insect Numbers Using Selective Fumigation- Sample on October 9 and January 6, Fumigate if More Than 0.5 Lesser Grain Borers/kg.

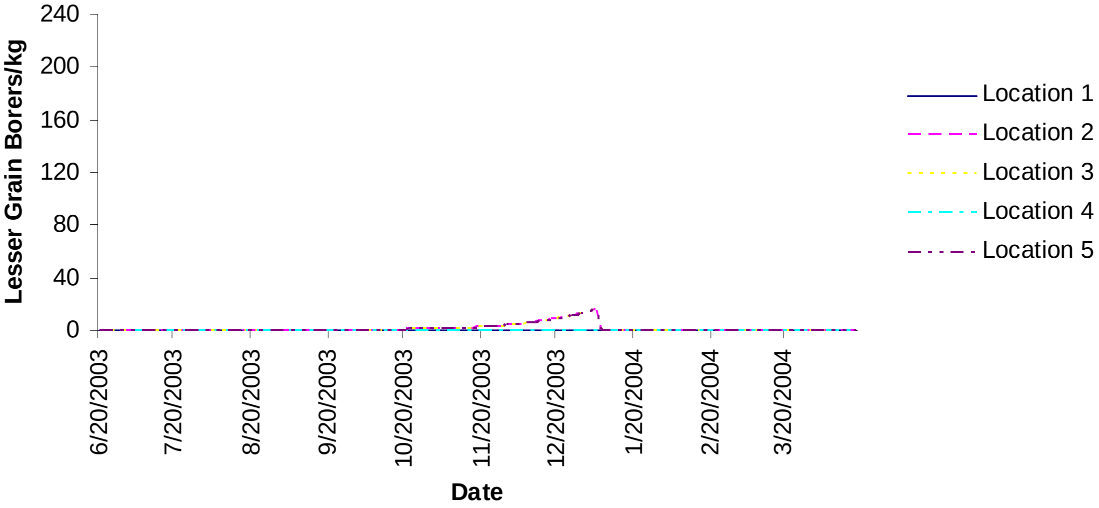

Figure 20b. Insect Numbers Using Selective Fumigation- Sample on October 9 and January 6, Fumigate if More Than 0.5 Lesser Grain Borers/kg.

Figure 21 shows that sampling only once led to high costs of grain damage in locations 2, 3, and 5 because insects were not controlled. There was no fumigation cost, but there was a cost of sampling plus a high cost of IDK and, in locations 3 and 5, a sample-grade designation. Sampling October 9 and again on April 1 reduced the IDK costs substantially, but increased the treatment costs, because all locations were sampled twice, and all were fumigated. Sampling October 9 and on January 6 eliminated all costs due to insect damage, but the treatment cost still included cost of sampling in all locations plus cost of fumigation in all locations.

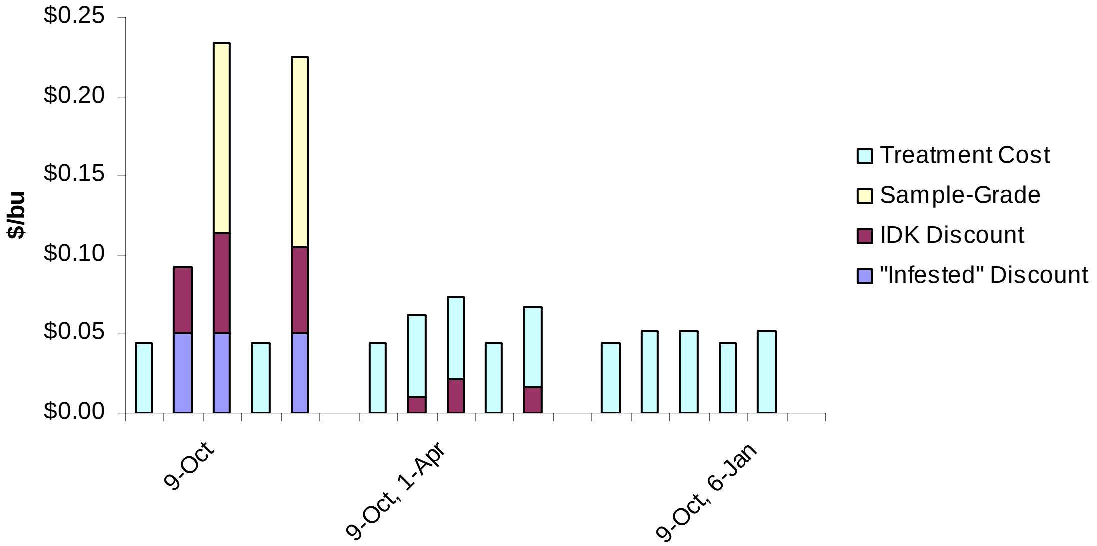

Figure 21. Cost Comparison of Selective Fumigation Strategies Using Highly-Effective Fumigation.

IPM: Less-Effective Fumigation Based on Sampling

Figures 22-24 show numbers of lesser grain borers that resulted when selective Less-Effective fumigation was used together with sampling. The sampling dates were set to be the same as before; on October 9; on October 9 and April 1; and on October 9 and January 6. Fumigation was conducted if there were more than 0.5 adult lesser grain borers per kg on the sample date (approximately 1.0 lesser grain borers plus rusty grain beetles per kg). In Figure 22, sampling was conducted on October 9 and fumigation was conducted in those locations where number of lesser grain borers was greater than 0.5/kg.

Lesser grain borer numbers in locations 1 and 4 reached this trigger, so those locations were fumigated on October 9. Due to less-effective fumigation, insects were not controlled as effectively as with highly-effective fumigation, so that the number of lesser grain borers reached approximately 62 lgb/kg by the sale date, April 20. Locations 2, 3, and 5 were not fumigated because they did not reach the trigger by October 9. Thus, by April 20, lesser grain borers in those locations reached very high numbers (similar to those shown in Figure 4).

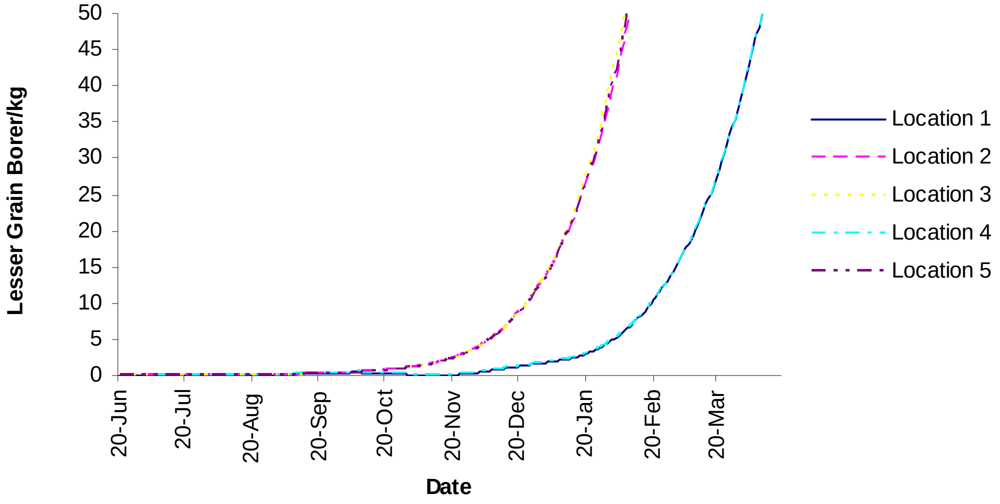

Figure 22. Insect Numbers Using Selective Fumigation: Sample on October 9 and Fumigate If More Than 0.5 Lesser Grain Borers/kg using Less-Effective Fumigation.

In Figure 23a and 23b, fumigation was conducted in locations 1 and 4, based on sampling on October 9. When sampling was conducted a second time on April 1, fumigation was conducted all locations. Thus, two fumigations were conducted in locations 1 and 4, on October 9 and April 1. Due to the fact that the fumigation was not as effective, insect numbers grew to a high level before the second fumigation, so that insects were not killed completely after fumigation and recovered to reach high levels by the time of sale. By April 20, insect population had reached approximately 23 lgb/kg in

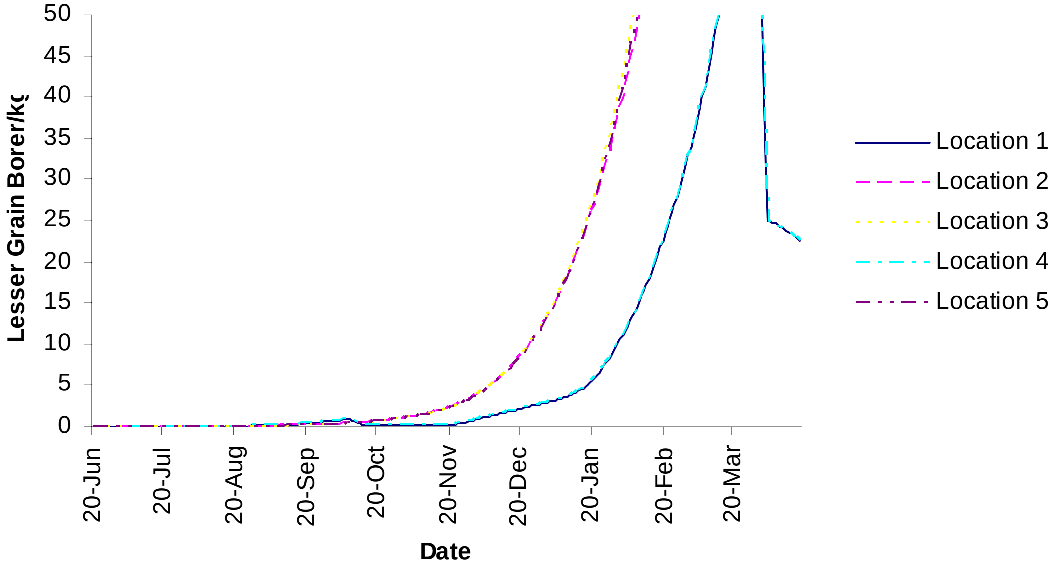

Figure 23a. Insect Numbers Using Selective Fumigation: Sample on October 9 and April 1 and Fumigate If More Than 0.5 Lesser Grain Borers/kg Using Less-Effective Fumigation.

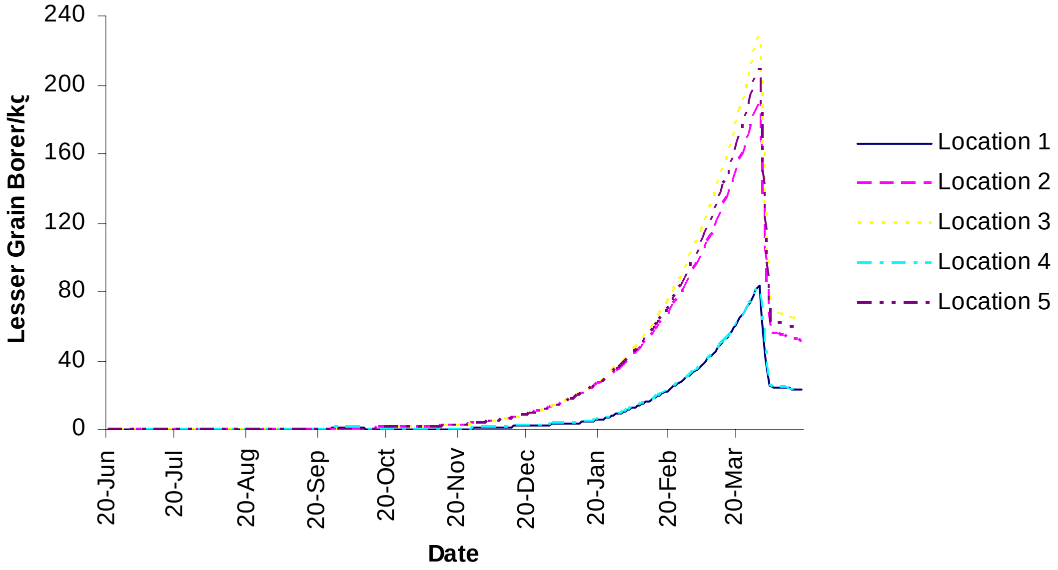

Figure 23b. Insect Numbers Using Selective Fumigation: Sample on October 9 and April 1 and Fumigate If More Than 0.5 Lesser Grain Borers/kg Using Less-Effective Fumigation.

locations 1 and 4 (which had been fumigated twice on October 9 and April 1). For locations 2, 3 and 5 (which had been fumigated only on April 1), the number of lesser grain borers on the selling date had reached 50-60 lgb/kg.

Figure 24a and 24b show the insect numbers that resulted when the second sampling was conducted earlier, on January 6. This earlier sampling led to fumigation of locations 2, 3, and 5 much earlier. In addition, because of a less effective first fumigation, locations 1 and 4 needed to have a second fumigation on January 6 as well. Since the fumigation was less effective, the insect population recovered about 40 days after fumigation and led to high insect numbers before the selling date, reaching to as high as 30 lgb/kg.

These results indicate that decision rule "fumigate if lgb > 0.5/kg" is arbitrary and not optimal, as indicated by its high costs. Further research will attempt to optimize this decision rule.

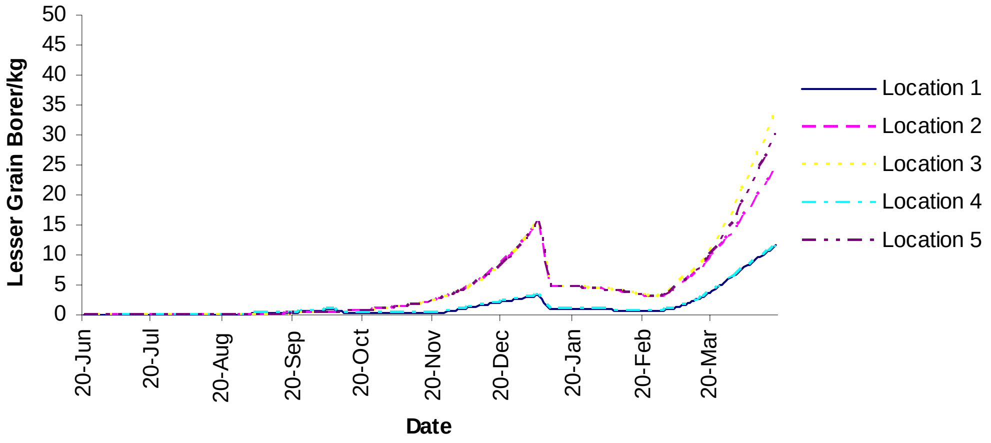

Figure 24a. Insect Numbers Using Selective Fumigation: Sample on October 9 and January 6 and Fumigate If More Than 0.5 Lesser Grain Borers/kg Using Less-Effective Fumigation.

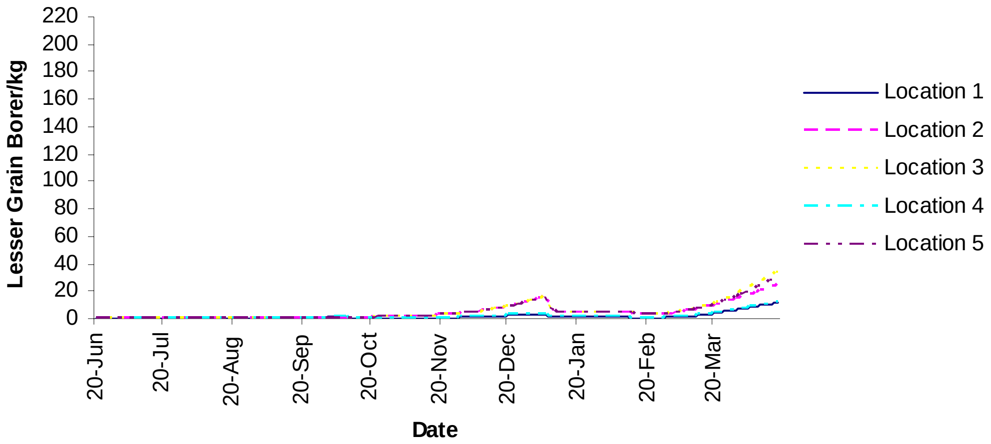

Figure 24b. Insect Numbers Using Selective Fumigation: Sample on October 9 and January 6 and Fumigate If More Than 0.5 Lesser Grain Borers/kg Using Less-Effective Fumigation.

Figure 25 compares costs of selective fumigation: sampling on October 9; sampling on October 9 and April 1; and sampling on October 9 and January 6. It shows that sampling only once led to high costs of grain damage in locations 3 and 5 because insects were not controlled, and to a lesser extent in location 2. The grain damage costs included IDK costs and infested costs. In these locations there was no fumigation cost, but there was a cost of sampling, plus a high cost of IDK and, in locations 3 and 5, a sample-grade designation. Sampling October 9 and again on April 1 reduced the IDK costs substantially, but increased treatment costs because all locations were sampled twice. Treatment costs in locations 1 and 4 were higher because they were fumigated twice. Sampling October 9 and January 6 eliminated IDK costs, but treatment cost included cost of sampling twice in all locations, one fumigation in locations 2, 3, and 5, and two fumigations in locations 1 and 4. The less effective fumigation led to high insect numbers by the sale date, which triggered an infested discount in each location.

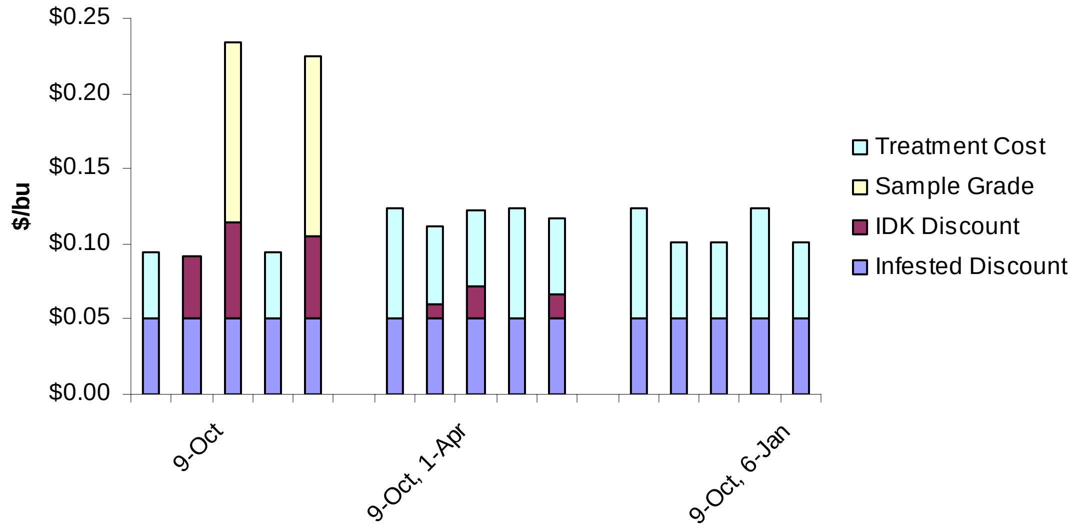

Figure 25. Cost Comparison of Selective Fumigation Strategies Using Less-Effective Fumigation.

Figure 26 compares on a common scale the cost of each type of strategy, using the most economical approach to each type of strategy. The strategies compared are: automatic aeration starting October 16; routine highly-effective fumigation on January 18; selective highly-effective fumigation, which included sampling on October 9 and January 6 and fumigating if needed; and, for comparison purposes, fumigating January 18 and April 1, without sampling, to represent a manager who fumigates once during the storage period, and then again before sale “just to be sure”.

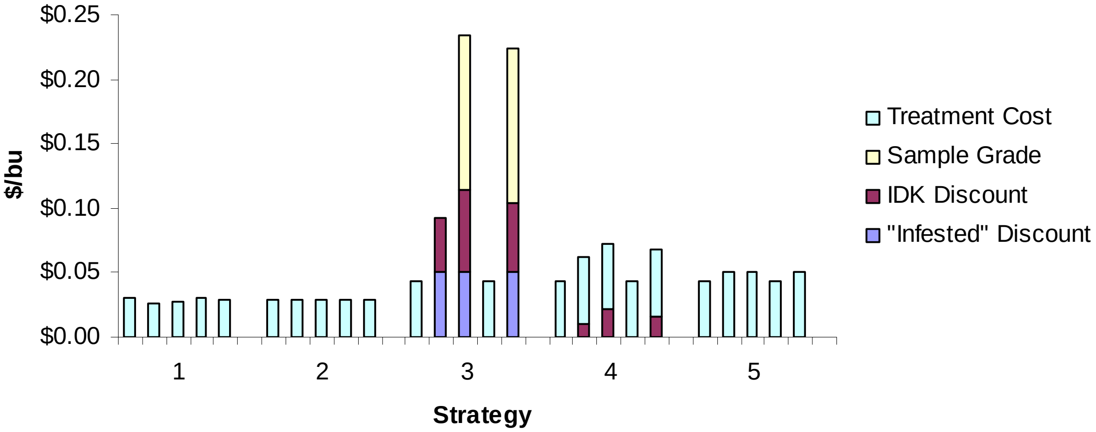

Figure 26. Cost Comparison of Best Strategies: 1- Aeration on October 16; 2- Routine Fumigation; and 3, 4 and 5- Selective Fumigation Using Highly-Effective Fumigation Where 3-Sample on October 9, 4- Sample on October 9 and April 1, 5- Sample on October 9 and January 6.

The two best strategies in this simulation were automatic aeration and one routine fumigation. In some locations, automatic aeration was slightly better than routine fumigation, and in some locations it was slightly worse. However, aeration is not available at many facilities with concrete silos.

The IPM strategy of sampling October 9 and January 6 and fumigating only if necessary controlled insects well, but was higher cost than simply fumigating once without sampling. All locations were sampled twice, which added about 2.3¢/bu to the cost, but since fumigation was required once in each location, there were no savings in fumigation.

Figure 27 compares the costs of each strategy when Less-Effective fumigation was used. The results were similar to Figure 24 except there was 5¢/bu an additional "infested" cost for each strategy involving fumigation due to the Less-Effective fumigation.

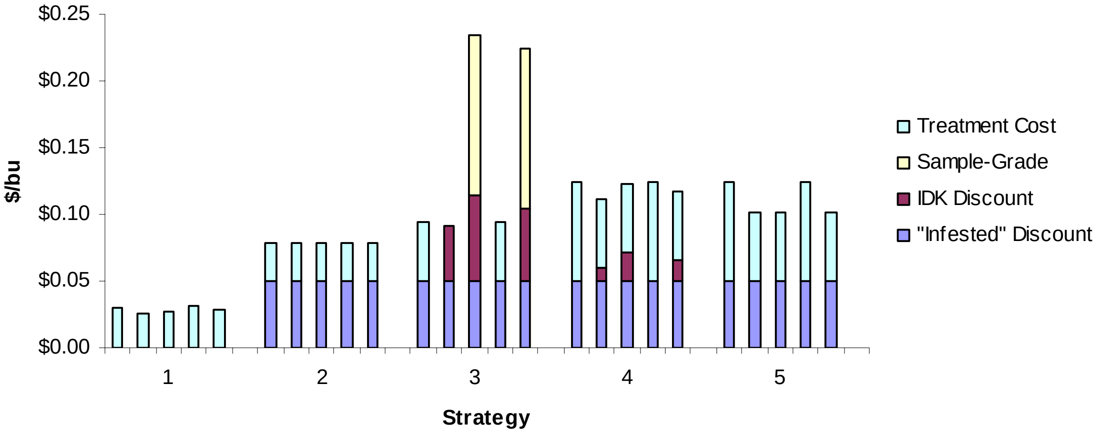

Figure 27. Cost Comparison of Best Strategies: 1- Aeration on October 16; 2- Routine Fumigation; and 3, 4 and 5- Selective Fumigation Using Less-Effective Fumigation Where 3-Sample on October 9, 4- Sample on October 9 and April 1, 5- Sample on October 9 and January 6.

Results of the scenarios simulated under the assumption that the wheat is sold January 31 rather than April 20 indicate that storing a shorter time results in no insect damage, although in some cases there is an "infested" discount. However, these results seem inconsistent with industry observations that IDK often is a significant problem. Therefore, further research is needed to validate the insect growth model under these assumptions.

CHAPTER V

CONCLUSION

Both automatic aeration and a single, routine fumigation can be effective in controlling insects, and can be the lowest-cost strategies. However, many storage facilities, particularly concrete silos, do not have aeration capabilities; they must consider other alternatives. Also, the relatively low cost of a single, routine fumigation depends on its effectiveness in controlling insects. If the fumigation is only as effective as the less effective fumigation simulated here, its total cost is much higher. An IPM strategy, sampling twice during the year and fumigating only when needed, also controls the insects. However, it has a higher cost because of sampling twice and because fumigation is needed once in each of the five locations. Sampling changes the timing, but not the frequency, of fumigation.

In some elevators, fumigation may be less effective due to poor facilities that allow gas to leak out and due to improper application of the chemical. For the strategies involving fumigation simulated here, the difference between highly-effective and less-effective fumigation in total cost was the “infested” discount.

Thus, to the extent that this simulation reflects reality, it is understandable why more elevator managers have not adopted IPM practices, particularly sampling. Sampling is costly and, depending on prevailing weather in a particular location, may not substantially change the preferred insect control strategy. In these cases, sampling adds unnecessary cost.

Some caveats should be noted, though. First, these calculations do not recognize any environmental benefits from reducing the use of pesticides, since firm managers do not currently realize those benefits. Second, these simulations have used weather information from only one year. Weather conditions may be sufficiently variable from year to year that sampling may indeed reduce the number of fumigations required. Further work should incorporate weather variability in the simulation.

Third, a constant immigration rate of insects into storage facilities has been assumed. It is likely that some facilities have higher immigration rates than others, and even that some storage silos within a facility have higher immigration rates than other silos within the same facility. Taking variable immigration rates into consideration would likely increase the attractiveness of sampling relative to routine fumigation, since variable immigration rates would increase the uncertainty about the need for fumigation. Future work should incorporate variable immigration rates.

Fourth, these calculations do not take into account probabilities that insects will or will not be detected in sampling procedures. Essentially, the simulation assumes that sampling is perfect. For example, if sampling occurs on October 9, the simulation assumes that the number of insects predicted by the growth model is the number that sampling detects. Also, the simulation assumes that when the grains are sold, the number of insects predicted by the simulation is the number that is detected by the purchaser.

In spite of these limitations, however, it appears rational that many grain elevator managers have not chosen to adopt IPM practices in managing insects in stored wheat in

Oklahoma and Kansas. However, reductions in sampling cost, increased cost of pesticide use, or increased uncertainty in the need for pesticides could increase the attractiveness of sampling as an IPM practice.

Using SGA Pro as a decision support system to predict insect growth may enable elevator managers to reduce sampling frequency and its costs. The model can be used to predict when insects will reach an economic injury threshold and thus reduce the frequency of fumigation as well as the likelihood that an insect problem will go undetected and cause economic damage (Flinn, Hagstrum, Reed and Phillips 2004).

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APPENDICES

Appendix 1. Cost of Doing Nothing

Strategy	**Location**	**Infestation Discount ($/bu)**	**IDK Discount ($/bu)**	**Sample Discount ($/bu)**	**Treatment Cost ($/bu)**	**Insect Cost ($/bu)**	**Total Cost ($/bu)**
Doing Nothing							
	1	$0.05000	$0.14235	$0.12000	$0.00000	$0.31235	$0.31235
	2	$0.05000	$0.04208	$0.00000	$0.00000	$0.09208	$0.09208
	3	$0.05000	$0.06421	$0.12000	$0.00000	$0.23421	$0.23421
	4	$0.05000	$0.14035	$0.12000	$0.00000	$0.31035	$0.31035
	5	$0.05000	$0.05450	$0.12000	$0.00000	$0.22450	$0.22450

Appendix 2. Cost of Automatic Aeration.

Strategy	Location	Hours Run	Fan Starting Date	Infestation Discount ($/bu)	IDK Discount ($/bu)	Sample Discount ($/bu)	Treatment Cost ($/bu)	Insect Cost ($/bu)	Total Cost ($/bu)
Automatic Aeration									
	1	283	20-Jun	$0.00000	$0.00000	$0.00000	$0.04732	$0.00000	$0.04732
	2	287	20-Jun	$0.00000	$0.00000	$0.00000	$0.04799	$0.00000	$0.04799
	3	308	20-Jun	$0.00000	$0.00000	$0.00000	$0.05150	$0.00000	$0.05150
	4	289	20-Jun	$0.00000	$0.00000	$0.00000	$0.04832	$0.00000	$0.04832
	5	339	20-Jun	$0.00000	$0.00000	$0.00000	$0.05668	$0.00000	$0.05668
	1	181	16-Oct	$0.00000	$0.00000	$0.00000	$0.03026	$0.00000	$0.03026
	2	156	16-Oct	$0.00000	$0.00000	$0.00000	$0.02608	$0.00000	$0.02608
	3	160	16-Oct	$0.00000	$0.00000	$0.00000	$0.02675	$0.00000	$0.02675
	4	185	16-Oct	$0.00000	$0.00000	$0.00000	$0.03093	$0.00000	$0.03093
	5	171	16-Oct	$0.00000	$0.00000	$0.00000	$0.02859	$0.00000	$0.02859
	1	293	1-Sep	$0.00000	$0.00000	$0.00000	$0.04899	$0.00000	$0.04899
	2	254	1-Sep	$0.00000	$0.00000	$0.00000	$0.04247	$0.00000	$0.04247
	3	266	1-Sep	$0.00000	$0.00000	$0.00000	$0.04448	$0.00000	$0.04448
	4	294	1-Sep	$0.00000	$0.00000	$0.00000	$0.04916	$0.00000	$0.04916
	5	299	1-Sep	$0.00000	$0.00000	$0.00000	$0.04999	$0.00000	$0.04999

Appendix 3. Cost of Highly-Effective Routine Fumigation.

Strategy	Location	Fumigation Date	Infestation Discount ($/bu)	IDK Discount ($/bu)	Sample Discount ($/bu)	Treatment Cost ($/bu)	Insect Cost ($/bu)	Total Cost ($/bu)
Routine Fumigation								
	1	1-Oct	$0.00000	$0.00000	$0.00000	$0.02823	$0.00000	$0.02823
	2	1-Oct	$0.00000	$0.00000	$0.00000	$0.02823	$0.00000	$0.02823
	3	1-Oct	$0.00000	$0.00000	$0.00000	$0.02823	$0.00000	$0.02823
	4	1-Oct	$0.00000	$0.00000	$0.00000	$0.02823	$0.00000	$0.02823
	5	1-Oct	$0.00000	$0.00000	$0.00000	$0.02823	$0.00000	$0.02823
	1	18-Jan	$0.00000	$0.00000	$0.00000	$0.02823	$0.00000	$0.02823
	2	18-Jan	$0.00000	$0.00000	$0.00000	$0.02823	$0.00000	$0.02823
	3	18-Jan	$0.00000	$0.00000	$0.00000	$0.02823	$0.00000	$0.02823
	4	18-Jan	$0.00000	$0.00000	$0.00000	$0.02823	$0.00000	$0.02823
	5	18-Jan	$0.00000	$0.00000	$0.00000	$0.02823	$0.00000	$0.02823
	1	10-Feb	$0.00000	$0.00000	$0.00000	$0.02823	$0.00000	$0.02823
	2	10-Feb	$0.00000	$0.00000	$0.00000	$0.02823	$0.00000	$0.02823
	3	10-Feb	$0.00000	$0.00000	$0.00000	$0.02823	$0.00000	$0.02823
	4	10-Feb	$0.00000	$0.00000	$0.00000	$0.02823	$0.00000	$0.02823
	5	10-Feb	$0.00000	$0.00000	$0.00000	$0.02823	$0.00000	$0.02823

Appendix 4. Cost of Less-Effective Routine Fumigation.

Strategy	Location	Fumigation Date	Infestation Discount ($/bu)	IDK Discount ($/bu)	Sample Discount ($/bu)	Treatment Cost ($/bu)	Insect Cost ($/bu)	Total Cost ($/bu)
Routine Fumigation								
		Fum Date						
	1	1-Oct	$0.05000	$0.00000	$0.00000	$0.02823	$0.05000	$0.07823
	2	1-Oct	$0.05000	$0.00000	$0.00000	$0.02823	$0.05000	$0.07823
	3	1-Oct	$0.05000	$0.00000	$0.00000	$0.02823	$0.05000	$0.07823
	4	1-Oct	$0.05000	$0.00000	$0.00000	$0.02823	$0.05000	$0.07823
	5	1-Oct	$0.05000	$0.00000	$0.00000	$0.02823	$0.05000	$0.07823
	1	18-Jan	$0.05000	$0.00000	$0.00000	$0.02823	$0.05000	$0.07823
	2	18-Jan	$0.05000	$0.00000	$0.00000	$0.02823	$0.05000	$0.07823
	3	18-Jan	$0.05000	$0.00000	$0.00000	$0.02823	$0.05000	$0.07823
	4	18-Jan	$0.05000	$0.00000	$0.00000	$0.02823	$0.05000	$0.07823
	5	18-Jan	$0.05000	$0.00000	$0.00000	$0.02823	$0.05000	$0.07823
	1	10-Feb	$0.05000	$0.00000	$0.00000	$0.02823	$0.05000	$0.07823
	2	10-Feb	$0.05000	$0.00000	$0.00000	$0.02823	$0.05000	$0.07823
	3	10-Feb	$0.05000	$0.00000	$0.00000	$0.02823	$0.05000	$0.07823
	4	10-Feb	$0.05000	$0.00000	$0.00000	$0.02823	$0.05000	$0.07823
	5	10-Feb	$0.05000	$0.00000	$0.00000	$0.02823	$0.05000	$0.07823

Appendix 5. Cost of Highly-Effective Selective Fumigation

Strategy	Location	Fumigation Date	Infestation Discount ($/bu)	IDK Discount ($/bu)	Sample Discount ($/bu)	Treatment Cost ($/bu)	Insect Cost ($/bu)	Total Cost ($/bu)
Selective Fumigation								
(Sampling on 10/9,	1	9-Oct	$0.00000	$0.00000	$0.00000	$0.04393	$0.00000	$0.05964
fumigate if	2		$0.05000	$0.04208	$0.00000	$0.00000	$0.09208	$0.09208
lesser grain borer #	3		$0.05000	$0.06421	$0.12000	$0.00000	$0.23421	$0.23421
>= 0.5/kg)	4	9-Oct	$0.00000	$0.00000	$0.00000	$0.04393	$0.00000	$0.05964
*$0.016 sampling cost	5		$0.05000	$0.05450	$0.12000	$0.00000	$0.22450	$0.22450
(Sampling on 10/9 & 4/1	1	9-Oct	$0.00000	$0.00000	$0.00000	$0.04393	$0.00000	$0.05964
fumigate if lesser grain	2	1-Apr	$0.00000	$0.01040	$0.00000	$0.05123	$0.01040	$0.08463
borer # >= 0.5/kg)	3	1-Apr	$0.00000	$0.02168	$0.00000	$0.05123	$0.02168	$0.09591
*$0.023 sampling cost	4	9-Oct	$0.00000	$0.00000	$0.00000	$0.04393	$0.00000	$0.05964
	5	1-Apr	$0.00000	$0.01631	$0.00000	$0.05123	$0.01631	$0.09054
	1	9-Oct	$0.00000	$0.00000	$0.00000	$0.04393	$0.00000	$0.05964
(Sampling on 10/9 & 1/6	2	6-Jan	$0.00000	$0.00000	$0.00000	$0.05123	$0.00000	$0.07423
fumigate if lesser grain	3	6-Jan	$0.00000	$0.00000	$0.00000	$0.05123	$0.00000	$0.07423
borer # >= 0.5/kg)	4	9-Oct	$0.00000	$0.00000	$0.00000	$0.04393	$0.00000	$0.05964
*0.023 sampling cost	5	6-Jan	$0.00000	$0.00000	$0.00000	$0.05123	$0.00000	$0.07423

Appendix 6. Cost of Less-Effective Selective Fumigation

Strategy	Location	Fumigation Date	Infestation Discount ($/bu)	IDK Discount ($/bu)	Sample Discount ($/bu)	Treatment Cost ($/bu)	Insect Cost ($/bu)	Total Cost ($/bu)
Selective Fumigation								
	1	9-Oct	$0.05000	$0.00000	$0.00000	$0.04393	$0.05000	$0.10964
(Sampling on 10/9,	2		$0.05000	$0.04208	$0.00000	$0.00000	$0.09208	$0.09208
fumigate if	3		$0.05000	$0.06421	$0.12000	$0.00000	$0.23421	$0.23421
lesser grain borer #	4	9-Oct	$0.05000	$0.00000	$0.00000	$0.04393	$0.05000	$0.10964
>= 0.5/kg)	5		$0.05000	$0.05450	$0.12000	$0.00000	$0.22450	$0.22450
*$0.016 sampling cost								
	1	9-Oct	$0.05000	$0.00000	$0.00000	$0.07386	$0.05000	$0.14686
(Sampling on 10/9 & 4/1	2	1-Apr	$0.05000	$0.01040	$0.00000	$0.05123	$0.06040	$0.13463
fumigate if lesser grain	3	1-Apr	$0.05000	$0.02168	$0.00000	$0.05123	$0.07168	$0.14591
borer # >= 0.5/kg)	4	9-Oct	$0.05000	$0.00000	$0.00000	$0.07386	$0.05000	$0.14686
*$0.023 sampling cost	5	1-Apr	$0.05000	$0.01631	$0.00000	$0.05123	$0.06631	$0.14054
	1	9-Oct	$0.05000	$0.00000	$0.00000	$0.07386	$0.05000	$0.14686
(Sampling on 10/9 & 1/6	2	6-Jan	$0.05000	$0.00000	$0.00000	$0.05123	$0.05000	$0.12423
fumigate if lesser grain	3	6-Jan	$0.05000	$0.00000	$0.00000	$0.05123	$0.05000	$0.12423
borer # >= 0.5/kg)	4	9-Oct	$0.05000	$0.00000	$0.00000	$0.07386	$0.05000	$0.14686
*0.023 sampling cost	5	6-Jan	$0.05000	$0.00000	$0.00000	$0.05123	$0.05000	$0.12423

VITA

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Master of Science

Thesis: COST OF CONTROLLING (OR FAILING TO CONTROL) INSECTS IN STORED GRAIN: A COMPARISON OF CHEMICAL-BASED AND INTEGRATED MANAGEMENT STRATEGIES

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