COST AND EFFECTIVENESS OF INTEGRATED PEST MANAGEMENT STRATEGIES COMPARED TO CHEMICAL-BASED METHODS IN STORED WHEAT

By

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CHAPTER 1

INTRODUCTION

The United States is a world leader in wheat production and stores more than 15 billion bushels of grain each year (Cuperus and Krischick 1995). Grain's best quality is at harvest and it decreases when it is stored. However, storing grain increases risks of storage problems, such as insect, mold, and heat damage, which cause economic losses (Cuperus and Krischik 1995). Increases in insect populations strongly depends on key environmental factors such as temperature, relative humidity and, in some species, day length (Phillips and Burkholder 1996).

Wheat is often infested by several species of insects soon after harvest in June or July, and at warm summer temperatures, insects multiply rapidly (Hagstrum 1987, 1989). Many grain insects fly and move to newly stored grain from fields and from infested grain bins (Krischik and Burkholder 1995). The most damaging pests for stored wheat in Oklahoma are the lesser grain borers and the rice weevils, because larvae and adults feed on the endosperm of the grain kernel, hollowing it out and causing insect damaged kernels (IDK).

Insecticides are generally the most effective pest management tool to control insects. Many times they are the only feasible method of reducing insect pest populations or holding them at acceptable levels (Harein and Davis 1992). Fumigants, insecticides that kill in the gaseous forms should only be used when large quantities of live insects are found in a commodity, which will result in damage or quality reduction (Leesch et al. 1995). However, partly as a result of inadequate treatments, insects have developed resistance to phosphine gas, the fumigant of choice for stored grain. Such resistance has been discovered in Oklahoma (Zettler and Cuperus 1990), and is widespread in other countries like Bangladesh, Pakistan and Australia (Zettler and Beeman 1995).

Non-fumigant insectides have similar resistance problems. Populations of lesser grain borers in Oklahoma were found to be uniformly resistant to Malathion (Zettler and Beeman 1995), a residual insecticide with relatively high toxicity to insects and low toxicity to humans (Harien and Davis 1992). However, it is unknown if such resistance is severe or marginal. If pesticide dosage is too high, insect pests may be exposed to significant residues for a longer time causing increased resistance. However, if the dosage is too low, marginally resistant insects may survive and reproduce, giving resistance an opportunity to intensify (Zettler and Beeman 1995).

In January 2005, the Environmental Protection Agency (EPA) will ban methyl bromide -- a very toxic and quick-acting fumigant -- from sale and use, because it is considered an ozone-depleting substance (Phillips 2001). The EPA also proposed fifteen new risk mitigation measures (RMMs) for all products containing magnesium and aluminum phosphide. The Food Quality Protection Act of 1996, HR 1627, which restricts pesticide use, will make grain protectants more difficult to use on food grains in the United States (Environmental Protection Agency).

Elevator managers across the country use several methods to control pest infestation and keep the insect numbers under the levels required by regulations and market standards. Among the methods of controlling pests are turning and blending the grain, aeration, temperature control, sanitation, fumigation, etc. Nevertheless, managers still depend primarily on chemical control, such as fumigation, without accurate knowledge of insect infestation.

An issue of concern is whether insects can be profitably controlled using less chemicals. An approach to this issue is the adoption of a pest management program that will help elevator managers reduce the use of chemical pesticides, yet still reduce losses from insects through targeted applications of chemicals only when needed. Integrated Pest Management (IPM) is an approach to pest control that uses cost-benefit analysis in decision-making. In such programs, control is cost-effective when the cost of control is less than the reduction in market value due to pests (Hagstrum and Flinn 1992). Also, for elevator operators to choose IPM strategies, their costs should be less than or equal to conventional strategies. IPM is ecologically based and integrates chemical and non-chemical pest management methods to control insects while minimizing problems associated with chemical control such as resistance, residues, and worker and consumer health risks.

Analyses of the environmental and market effects of IPM on crops and its economic impact have been conducted for other commodities such as peaches (Fernandez-Cornejo and Ferraioli 1995), cotton (White and Wetzstein 1995), and oranges (Fernandez-Cornejo and Jans 1996). However, very little research has been done for stored commodities, especially wheat.

It is unknown if IPM is cost-effective compared to other techniques for pest management in stored grain such as routine fumigation. This thesis analyzes the costs effectiveness of IPM and conventional, chemical-based strategies.

Objectives

The general objective of this study is to evaluate costs of alternative insect control strategies for stored wheat in Oklahoma and Kansas. Specifically, costs of IPM strategies will be compared with those of traditional insect control strategies. A second objective is to estimate for each strategy the expected number of live insects per kilogram remaining after a control treatment is applied, as a measure of effectiveness.

CHAPTER 2

LITERATURE REVIEW

Chapter Overview

This chapter covers the evolution of grain storage and pest control techniques, the origins of IPM and its components, the insecticide revolution and later criticism, and a brief description of stored product insects.

Evolution of Grain Storage and Pest Control Techniques

Brief history of Grain Storage

Some historians believe that the first permanent agricultural communities developed in river-bathed arid and semiarid areas, rather than in the highlands or humid tropics, as is commonly thought (Reed 1992). Those river valleys provided fertile soil and a stable source of water, and insects and diseases were less frequent. During the hunting and gathering stage of the human civilization, all grain found was collected and eaten. As nomads settled and started planting, some of the grain was preserved for seed with about one-fourth kept to secure the next crop (Ordish 1976).

Granaries and storage pits in Sumeria dating from around 2000-1000 B.C., Egyptian grain storage in straw-lined small pits, mud houses from around 5000 B.C. found between Wales, Norway and Sudan, and pre-Mayan and Mayan storage in pits, woven baskets, or in wooded or mud structures indicate that grain was grown and stored in bulk at least 7,000 years ago. The Roman Empire (300 A.D. to 500 A.D.), with its idea of world unification through a common form of government, culture, and language, perhaps expanded grain handling and storage techniques, with the exception of the Far East and Africa, where little change was observed until the Europeans arrived to colonize during the 17th and 18th centuries. Accounts also describe manors with strong timber barns for wheat, oats, barley, and other grain storage during the Middle Ages (Reed 1992).

In the 1830s, North America engaged in the technological revolution of grain handling and storage techniques led by Cyrus McCormick. The creation of reapers and threshing machines, first powered by animals and then with mobile steam power, led to the marketing of larger volumes of grain at a much faster pace (Reed 1992). Finally, in 1842, a Buffalo retail merchant by the name of Joseph Dart constructed the first grain elevator in the United States, following almost identical mechanical methods used in ancient times (Reed 1996, Grain Elevators: A History). Yet, the impact of this structure affected the grain market dramatically, becoming what it is today.

Pest and the Pest Control Evolution

Along with agriculture came pests. Pests are any problems that affect crops and domestic animals, which lead to their yield reduction, and cause the humans who consume these products to be largely affected (Ordish 1976). Pests include not only insects, but also weeds, pathogens and nonarthropod animals (Kogan 1998). There is archaeological evidence that pest attacks have occurred and caused crop and animal losses and localized famines, but all that is left are minute remnants of insects and fungi, which are hard to identify (Ordish 1976, McIntyre 1987). The Bible contains numerous references to crop pests and the damage they cause. The Bible talks particularly about locusts, the eighth plague of Egypt:

> "… So Moses stretched out his staff over Egypt, and the Lord made an east wind blow across the land all that day and all that night. By morning the wind had brought the locusts; they invaded all Egypt and settled down in every area of the country in great numbers. Never before had there been such a plague of locusts, nor will there ever be again. They covered all the ground until it was black. They devoured all that was left after the hail – everything growing in the fields and the fruit on the trees. Nothing green remained on tree or plant in all the land of Egypt."
>
> Exodus 10:13-15 (Holy Bible, New International Version)[1]

With pest attacks arose a need for pest control. McCarl (1981) stated that in earlier days, "pests were managed by cultural and manual practices, or by natural mechanisms (p.5)". Early pest control methods consisted of picking off insects, such as large beetles, caterpillars, slugs and snails from plants. These insects were consumed, and were considered tasty treats (Ordish 1976).

Ordish (1976) stated that to the ancients, insect pests and diseases fell under the same category: "they were all troubles sent to worry the farmer (p. 16)". For thousands of years, humans were not able to do much in the fight against pests, but to resort to rituals and magic (Smith 1978, Ordish 1976). Charms, the moon, the stars and even other animals were thought to be great tools for pest control. For example, during the time of Pliny the Elder (AD 23-79), it was thought that before storing grain, a toad had to be

[1] Other references to this pest and to the palmerworm are found in Joel 1:4, Joel 2:24-25, Deuteronomy 28:38-40, Proverbs 30:27, Amos 4:9, and Revelation 9:1-5.

hung by one of its longer legs to the barn door in order to scare weevils away (Ordish 1976). Even during the Middle Ages, when agriculture advanced at a slow pace, people relied on the knowledge of classical writers, like Virgil (c. 70-19 BC), Varro (116-28 BC) and Pliny the Elder, as well as the Church, for remedies against pests.

During the Middle Ages, when the Church had the last word, several actions regarding pests were taken in order to keep the idea that Divine Justice shall prevail. An example of a case dealing with insects occurred in 1488, when the High Vicar of Autun ordered the priests of surrounding parishes, "to command the weevils to stop their attacks on crops and grain and to excommunicate the creatures" (Ordish 1976, p.44).

Along with these methods to combat pest attacks, humans developed many cultural, physical, mechanical, biological, and chemical practices to protect their crops. Several of the practices have been proven to be scientifically valid and useful today (Smith 1978). These methods include turning (moving grain from one storage facility to another), grain storage at the right time, sanitation, tillage and crop rotation, and releasing insect predators, among others (Smith 1978, Ordish 1976). During the 19th and 20th century, crop protection specialists relied on cultural practices and knowledge in pest biology to control pests (Kogan 1998). However, the big break in pest control practices came with the advent of the insecticide.

Insectides: A New Technology

Throughout the world and particularly in industrialized nations, insecticides are the basis of most insect control management actions in agriculture (Perkins 1982). McIntyre (1987) offers a definition for pesticides: "A generic term referring to most of the lethal chemical techniques employed by humans to limit/prevent pest damage to food products during growth and storage, and to fiber, health and habitation (p. 534)".

Oil, sulphur, nicotine, rotenone, and pyrethrum were used as chemical control methods (Perkins 1982), some of them even before the chemical age. Homer's *Odyssey* gives an account of using sulphur for plant disease control: "Eurycleia, bring me some disinfectant sulphur, and make a fire so that I can fumigate the house[2]" (Ordish 1976). In 1868, an unknown inventor discovered that the dye Paris green was toxic to insects. Paris green was arsenic, and became the first compound used besides sulfur whose chemical composition was known. By 1910, Paris green and lead arsenate were the most widely used insecticides sold on a commercial basis (Perkins 1982).

Development of the synthetic insecticide industry continued throughout the early part of the 20th century. In 1939, Paul Herman Mueller, a staff chemist from the Geigy firm of Switzerland, found that p, p'-dichlorodiphenyltrichloroethane, or DDT, had remarkable contact-killing powers and long outdoor duration (Perkins 1982). Muir (1978) noted, "the widescale employment of DDT temporarily resulted in the complete riddance of serious public health pests such as malaria mosquitoes from entire countries" (p. 3). The materials for post-WWII pesticides were inexpensive, efficient, highly toxic against a wide variety of pests, and non-labor intensive (Muir 1978). Compared to all other existing methods, DDT was inexpensive and more effective. From 1944 to 1951, total production of DDT by the United States increased from 10 million pounds to more than 100 million pounds. Through the 1970s, pesticide production and sales grew

[2] Homer. *The Odyssey*, trans. Sir Arthur Hort, London and Cambridge, Mass., 1961. Homer's date of birth has been assumed to be as far back as 1200 B.C. but, based on the style of his two epic poems, 850-800 B.C. seems more likely.

gradually, exceeding half a billion pounds per year (McIntyre 1987). Synthetic insecticides had a major impact on the pest control techniques people commonly used, displacing such strategies as biological, environmental, and cultural controls, along with others like sanitation and other chemical practices used by farmers (Muir 1978, Perkins 1982).

Insecticide Crisis

"Pesticides can reduce the effectiveness of natural pest controls and lead to outbreaks of resistant pests (McCarl 1981, p.6)". McCarl also states that when pesticides interrupt the effectiveness of natural pest controls, it results in secondary pest outbreaks. Pesticide residues, particularly insecticide residues, have affected the environment, damaging the land and water, and have also caused health problems in humans, livestock and wildlife (McCarl 1981).

Before DDT was released for commercial use, there were doubts about its safety (Perkins 1982). Issues about pesticide residues, pest resistance, and environmental and health concerns arose through the late 1940s and 1950s. The FDA and the apple industry battled over arsenic, lead and fluoride residues before WWII (Perkins 1982). Perhaps, the biggest argument against insectides and pesticides was made by Rachel Carson in her book *Silent Spring*. Perkins (1982) summarized the main idea of the book, in which Carson states that insecticide use was indiscriminate, and even if the proper dosages were applied, the materials contained in the insecticides harmed humans and the wildlife. She also mentioned problems of resistance and destruction of natural enemies, and although she was not against the use of chemicals, she argued that more research needed to be done about alternative control techniques.

The crisis continued when between 1946 and 1948, several countries reported that the common housefly was resistant to DDT. In 1951, Korea reported that human head lice and carriers of typhus were resistant to DDT. In agriculture, the spotted spider mite (1949) and the spider mite (1952) were reported to be resistant to organophosphorus insectides, and the codling moth, along with other worms, were reported to be resistant to DDT (Perkins 1982). From the 1950s through the 1970s, debates surged around the areas of insecticide instability and environmental contamination (Perkins 1982). After numerous reports of insect resistance and pesticide residues, the Environmental Protection Agency (EPA) banned DDT in 1972. However, Pimentel (1978) argues that people are still at risk of DDT exposure and other chlorinated pesticides because residues are still present in the environment. Haskell (1995) notes that DDT is a relative unselective toxic chemical, meaning it affects both its target pest and non-target organisms. He states that its persistence causes build-ups in food chains and retention in non-target organisms, like humans. DDT symptoms of poisoning vary, but seem to be associated with the nervous system.

Finding an Alternative

Towards the end of the 1950s, the issues of resistance, resurgence of both primary and secondary pests, and environmental contamination gained strength, and complaints were finally being heard (Perkins 1982, Kogan 1998). These factors, along with bold statements like Carson's were key in the formulation of an integrated control concept, which by the late 1960s was starting to gain popularity. Perhaps, this is why to some, Integrated Pest Management (IPM) is synonymous with non-chemical controls (McCarl 1981).

However, the concept of IPM did not originate during the late 1960s. In the early 1920s, a group of scientists from the University of Arkansas introduced the concept of IPM as a formal agricultural practice. Led by Dwight Isley, these scientists pioneered the concepts of integrated insect management, plant disease control, and alternative controls, by using the principles of scouting, economic thresholds and trap crops along with insecticides to control boll weevils in Arkansas cotton (University of Arkansas). However, it was not until 1972 that the concept of integrated pest management and its acronym IPM were incorporated in the English language and the scientific community (Kogan 1998). By 1980, the concept of IPM was accepted as an economically efficient and environmentally preferable approach to pest control in agriculture, forestry, public health and urban systems (Bajwa and Kogan 1996).

What is IPM?

After much debate over the definition of integrated pest management during the late 1960s, four points were clear: "1. *integration* meant the harmonious use of multiple methods to control single pests as well as the impacts of multiple pests; 2. *pests* were any organism detrimental to humans, including invertebrate and vertebrate animals, pathogens, and weeds; 3. IPM was a multidisciplinary endeavor; and 4. *management* referred to a set of decision rules based on ecological principles and economic and social considerations" (Kogan 1998, p. 247)

In 1996, Kogan and Bajwa conducted a survey that collected 64 definitions of integrated control, pest management, or integrated pest management. Kogan (1998) 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). Phillips (2001) defines IPM as "the integration of different knowledge and practices of various types to provide efficient, safe, cost-effective management of a pest population, and to reduce the damage to the community".

IPM is not a synonym for absolute control; pests are managed at tolerable levels. IPM does not equal 'no chemicals'; there is a judicious use of pesticides if needed. IPM is a combination and integration of other pest management tactics, which include legal, biological, cultural, physical, genetic and chemical controls[3]. The use of conventional pesticides in an IPM program may differ from traditional chemical control tactics. Under IPM, chemical materials used should be "1) specific to the pest species; 2) used at the lowest effective rate; 3) short-lived in the environment; 4) least toxic to beneficial insects and humans; and 5) alternated with other chemicals to help prevent resistance" (Cornell University 1995)".

[3] Legal control is abiding by state and federal guidelines designed to prevent the spread of pests; biological control is using beneficial organisms such as predators, parasites and diseases, to suppress pest organisms; cultural control is using methods such as rotation, cultivation, sanitation, and other practices that reduce persistent pest problems; physical control is using mechanisms like barriers, traps, trap crops, adjusting planting locations or timing to evade or diminish pest pressure; genetic control is choosing resistant plant materials to avoid pest problems; and chemical control is using conventional pesticides, biopesticides, pheromones and other chemicals to prevent or suppress a pest outbreak. (Integrated Pest Management (IPM): What is it? 1995)

IPM in Stored Grains

Although the concept of IPM remains the same throughout any area, whether it is in crop fields, processed commodities or stored products, this thesis focuses on IPM of stored grains.

David W. Hagstrum and Paul W. Flinn have conducted numerous studies on IPM for stored grains, and note that IPM uses cost-benefit analysis for decision-making (Hagstrum and Flinn 1996). For IPM to be effective, the cost of control has to be less than the reduction in market value due to pests.

Ideally, elevator managers would monitor pest populations in the bins, determine how serious the problem is, select a management approach corresponding to the situation, and take action. This contrasts with the routine calendar fumigations, fumigating 'just in case', or treatments in response to pests without proper knowledge of the infestation levels. Although IPM requires meticulous work that takes additional time, it can be offset by the resulting benefits of reduced costs of chemical inputs, a cleaner environment reduced resistance and increased worker safety.

A sound IPM program requires information, action thresholds, and adequate sampling. IPM users must know the agricultural ecosystem in order to efficiently implement an IPM program. IPM uses action thresholds to help managers decide when they need to control insect populations. These thresholds are instituted to conclude if pest control measures are cost-effective. Cost-benefit analyses are based on the economic injury level (EIL). "An EIL is the insect density that causes a reduction in market value greater than the cost of insect control (Hagstrum and Flinn 1996)."

Economic thresholds (ET) are developed through research and take into account three main factors: the damage caused to the commodity by the presence of the pests at a known level of infestation, the revenue losses caused by that particular damage, and the cost of treatment (Cornell University 1995). The ET, therefore, is the density at which control measures should be determined to prevent an increasing pest population from reaching the EIL (Stern et al. 1959). Onstad (1987) defines ET as a current pest population density that represents a future population, the control of which will prevent economic loss equal to the cost of implementing the control tactic (Figure 1).

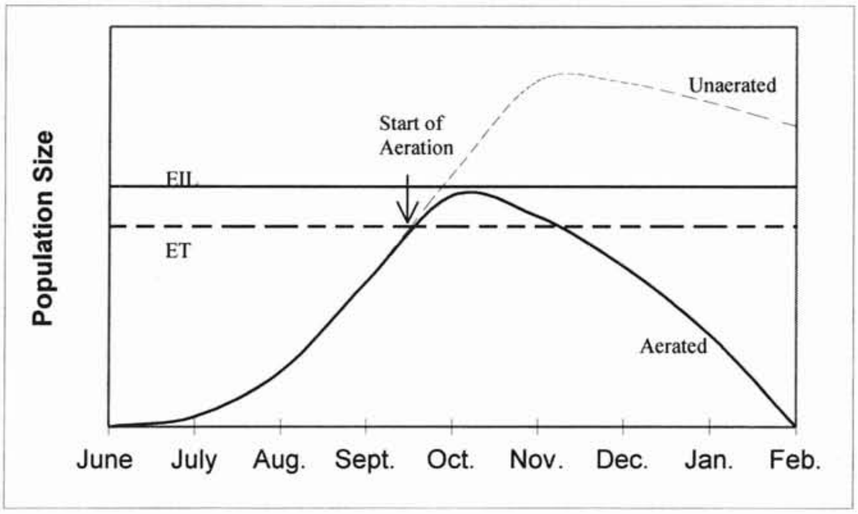

Figure 1. Economic threshold concept shows when aeration to cool grain needs to begin to prevent insect population from reaching economic injury level. (Redrawn from Hagstrum and Flinn 1995, 1996.)

Loss of quality or loss of weight can be used to develop EILs for commodities. It is easier to quantify weight loss and assign a monetary value to it, than it is to quantify quality loss. Losses due to insects in stored wheat include the "infested" designation given when insect densities are two or more live insects per kilogram of wheat, and "sample grade" given when insect damaged kernels (IDK) exceed 32 per 100 grams of wheat (Hagstrum and Flinn 1996). The monetary loss due to sample grade wheat is typically much greater than that due to infested wheat, since fumigating the grain to kill insects can eliminate infestation. A "sample grade" designation can sometimes be avoided by blending the wheat with higher quality wheat, a costly procedure, but often requires sale of the wheat as livestock feed at a much lower price.

Finally, a periodic and systematic sampling of the pests is needed to estimate the population levels, and determine if insect populations have reached the economic threshold (Hagstrum and Flinn 1995). The more samples taken, the higher chances of detecting insects in time for cost-effective treatments.

Stored Product Insects

Stored product insects belong to the orders Coleoptera (beetles) and Lepidoptera (moths and butterflies). They are peridomestic insects, meaning that they are associated with human structures such as human-stored food, and are not found in wild habitats (Phillips 2001).

Stored product insects can be divided into two groups: internal and external feeders. Internal feeders are those whose larvae develop mostly inside the grain kernel. These insects increase surface area, heat and moisture, contributing to IDK, and dry matter loss (between 50-80% per kernel). Examples of internal feeders include the lesser grain borer and the rice weevil. External feeders feed off the dust and broken grains. Although they cannot infest sound grain because they cannot penetrate undamaged seeds, they attack the germ first. External feeders are a major pest in processed foods, and include the sawtoothed grain beetle, the rusty grain beetle, and the red flour beetle (Phillips 2001, Arthur and Flinn 2000).

The insects mentioned above are widely found in grain elevators in Kansas and Oklahoma. According to Arthur and Flinn (2000), studies have detected insect pests in stored wheat during summertime in Oklahoma, and in Kansas several beetle species have been plentiful in farm–stored wheat and commercial facilities during the first two months after harvest. The presence of live insects in processed grain products is considered more serious than an equivalent infestation in grains (Pedersen 1992).

Insect Growth

According to Pedersen (1992), stored-product insects possess certain characteristics that allow them to rapidly reproduce in a relatively short amount of time. Biotic and abiotic factors play an important role in stored product insects' growth and development. Biotic factors include such components like food and other insects and animals. Abiotic factors are physical components such as temperature and moisture.

For stored product insects, food is always abundant. Each species has a certain preference, but the nutritional quality of the grains they consume is the same. Yet, where there is food, there are several species competing for it. One particular species or predators or parasites, may push another out of the ecological environment leading to habitat partitioning.

Insect development speed is directly affected by temperature and some by moisture. As temperatures reach 15° C or below, development is very slow and mortality rates are high. Development is fastest in an optimal range of higher temperatures (Table 1).

Table 1. Effects of Temperature on the Predicted Egg-to-Adult Development in Times (in Days) of Stored-Product Insects

	Temperature (°C)								
Species	17.5	20	22.5	25	27.5	30	32.5	35	37.5
Long-lived beetles									
Cryptolestes ferrugineus	--	--	53.4	37.0	28.1	23.2	20.6	19.0	18.2
Cryptolestes pusillus	--	--	53.1	45.1	38.5	32.9	28.4	25.1	24.5
Oryzaephilus surinamensis	--	--	48.5	36.4	27.9	22.4	19.8	20.8	27.0
Sitophilus oryzae	--	52.9	43.2	35.9	30.6	27.4	26.7	29.1	36.7
Tribolium castaneum	--	--	--	41.8	32.7	28.4	26.3	23.4	21.7
Tribolium confusum	--	--	56.2	44.6	35.6	28.5	23.0	20.0	34.1
Rhyzopertha dominica	--	--	--	58.8	49.9	42.4	36.1	31.0	--
Average	--	--	50.9	42.8	34.7	29.4	25.8	24.1	27.0

Note: Predicted development times of long-lived beetles based on equations from Hagstrum and Milliken (1988).

Moisture content (relative humidity) also affects larval development, although not as much as temperature does. The amount of moisture needed for survival is different for every species. Stored-grain and processed-food insects depend greatly on "their food supply for the moisture needed to carry on their life processes" (Pedersen 1992, p. 469).

Strategies to be Analyzed

Several strategies that can be included in IPM strategies are compared with conventional strategies in this thesis. Strategies considered are routine fumigation, closed loop fumigation, controlled aeration, manual aeration, and sanitation, and combinations amongst them (see Table 2).

Table 2. IPM and Chemical-Based Strategies to be Analyzed

Strategy number	IPM Based Strategy	Strategy number	Chemical-Based Strategy
5	Controlled aeration plus sanitation	1	One fumigation with turning
6	Controlled aeration, sanitation and 1 insect sampling	2	Three fumigations with turning
7	Controlled aeration, sanitation, 1 insect sampling, ½ of bins fumigated	3	One closed-loop fumigation
10	Controlled aeration, sanitation and 2 insect samplings	4	Three closed-loop fumigations
11	Controlled aeration, sanitation, 1 insect sampling, ½ of bins fumigated closed-loop	8	Routine manual aeration in evening hours plus grain protectant
13	Mechanical cleaning, aeration and sanitation	9	Controlled aeration, sanitation and grain protectant
		12	Controlled aeration, sanitation, closed-loop fumigation of all bins, plus grain protectant application

Routine fumigation consists of fumigating one or more times during storage based on criteria such as time of year, or convenience rather than sampling. Fumigation is the most hazardous type of pesticide treatment. It is expensive, provides no long-term residual protection, and may cause resistance problems if conducted repeatedly (Leesch et al. 1995). Common fumigants include methyl bromide and phosphine. Methyl bromide will penetrate most commodities and is highly toxic to most life stages of stored-product insects. Methyl bromide is nonflammable, non-explosive, non-corrosive on most metals except aluminum, and reacts with several plastic and organic materials.

Turning is a process whereby grain is emptied from one bin and transported on a moving belt to another empty bin within the facility. Phosphine pellets are inserted into the turned grain for fumigation. Turning may also be done as part of other management practices such as blending for particular quality characteristics, to break up sections of fines or hot spots to prevent grain infestation or spoilage. Most elevators with concrete storage facilities fumigate while turning, although some elevators have installed closed loop fumigation equipment.

Phosphine is one of the most toxic fumigants to stored-product insects. Its low molecular weight and low boiling point makes phosphine very effective, rapidly diffusing and penetrating into grains. Phosphine comes in tablet, pellet and powder sachet forms (Harein and Davis 1992). Fumigation is often recommended when no other method can solve an infestation problem.

"Closed loop fumigation uses low-pressure, low volume centrifugal blowers to draw fumigant/air mixtures through pipes from the headspace and push the gas into the base of the structures, forcing it upwards through the grain to the headspace in a closed loop cycle (Noyes et al. 1995, p. 153)." Closed loop fumigation reduces worker chemical exposure, improves worker safety, and uses less fumigant than non-closed-loop fumigation.

Aeration is the primary tool used to manipulate grain temperatures. It consists in forcefully moving the air through the grain, usually by means of fans, in order to lower or balance temperatures. Temperature is the key in regulating insect and mold growth. There is less activity by these agents when temperatures are below 15° C (60° F). Aeration also helps control grain moisture, which is a critical factor in grain storage. The higher the moisture content of the grain, the higher the potential for insect and mold activity. Aeration is also important because it prevents moisture from migrating to other locations in the grain (Noyes et al. 1995).

The aeration systems used in controlled aeration manage grain temperatures by cooling the grain to constant temperature levels in the fall, winter and early spring. During aeration, grain moisture content is reduced by about 1/3 to ½ percent during one fall aeration cooling cycle, and by ¼ to 1/3 percent during one winter cooling cycle. Using automatic aeration controllers during this operation provides precise fan temperature management. Automatic aeration controllers regulate the temperature range for fan operation. It automatically turns fans on or off to prevent over-drying and heating. It is recommended that during any type of aeration practice, any vents or openings in silos be properly sealed (Noyes et al. 1995).

Sanitation is considered a preventive measure. It is the practice of thoroughly cleaning the silo inside and outside, especially before storing fresh grain each season. Debris, weeds, trash and spilled grain are sources of grain infestation (Noyes et al. 1995). During sanitation, empty bin treatments with chemicals can be applied to the grain bins. Kenkel et al. (1993) state the empty bin treatments help eliminate initial insect populations levels before incoming grain is loaded in the bin. Among the chemicals used for this treatment is chlorpyrifos-methyl, or Reldan. This chemical is also used as a grain protectant. Grain protectants will be explained in more detail on Chapter 3.

CHAPTER THREE

MODEL AND PROCEDURES

Chapter Overview

The first part of this chapter describes the model and procedures used to calculate costs of several insect control strategies. In addition, a sensitivity analysis is conducted for the most influential variables in the model in order to accomplish the first objective. The second part describes the determination of measures of effectiveness for each of the strategies in order to accomplish the second objective.

Cost Analysis

The cost analysis is based on Rulon's study on pest management in popcorn (Rulon 1996). A spreadsheet is used to calculate the costs of managing stored grain for alternative insect control strategies. The spreadsheet is divided into six worksheets summarized in Table 3. In the first worksheet (Table 4), the user specifies information about the facility. Worksheets two through five (Tables 5-8) calculate insect sampling costs, aeration costs, fumigation costs and turning costs. The sixth worksheet (Table 9) computes the annual operating cost of each scenario in dollars per bushel. The contents of these tables have been modified to fit needs of this particular study.

The first column of each worksheet contains field names, the second column contains the numbers and costs associated with the field names, and the third column contains an explanation of the number entered or the formula used. Terms used in the tables are described in detail later on in this chapter.

Table 3. Summary of Economic Model Sheets

Sheet Number	Sheet Title
1	Facility Description
2	Insect Sampling Worksheet
3	Bin Aeration Worksheet
4	Bin Fumigation Worksheet
5	Grain Turning Worksheet
6	Annual Operating Costs Analysis Worksheet

Table 4. Worksheet 1: Facility Description

Parameter	Description and/or formula
Location	Elevator location.
Bin Type	Specify concrete w/aeration, concrete w/o aeration, steel or flat.
Number of bins (#)	Number of bins in the elevator facilities.
Bin Size (unit of grain)	Total bin capacity expressed in grain units: lbs., bu., kg. Once the unit has been selected, it has to be consistent throughout the spreadsheet.
Units stored (unit of grain)	Units of grain stored in an individual bin.
Total units stored (unit)	Total amount of grain stored in the elevator.
Grain Price ($/unit)	Used only for calculation of a shrink charge for various storage situations. In this case, the price per unit represents the commodity price paid by the elevators.
Initial Power Vac cost ($)	Initial purchase cost of the equipment needed for insect sampling in the bin.
Expected Power Vac life (yrs)	Expected life of the equipment.
Initial closed loop fumigation facility cost ($)	Initial investment of the closed loop fumigation system (if available) in the elevator.
Expected CL fumigation facility life (yrs)	Expected life of the facility.

Initial fumigation equipment cost ($)	Initial purchase cost of all safety and application equipment needed to apply fumigants within regulatory guidelines.
Initial fumigation monitoring device cost ($)	Cost of Draeger Pac III, device used to check for concentration levels
Annual fumigation monitoring device recalibration cost ($)	
Expected fumigation equipment life (yrs)	Expected life of the equipment.
Equipment maintenance (#)	Estimated percent of initial equipment cost spent on annual equipment up-keep and consumables, expressed as a decimal.
Equipment insurance (#)	Percent of initial equipment cost spent on insurance annually, expressed as a decimal.
Salvage Value ($)	Expected value of equipment at end of expected life.
Cost of capital (#)	Interest rate on the loan used to buy the equipment. It is a percentage expressed as a decimal.
PVIFA (#)	Present value interest factor for an annuity of n years at i percent interest.
Fan Horsepower (HP)	Total fan HP used for aeration in a single bin
Centrifugal Blower Horsepower (HP)	Horsepower per blower used during closed loop fumigation in a single bin
Hourly labor cost ($/hr.)	Represents not only the hourly wage paid to the employee, but also all taxes paid by the employer and benefits such as insurance and bonuses. For the base case a reasonable wage was assessed for full time employees with minimal management abilities.
Mechanical cleaning cost ($/unit)	Mechanically cleaning the grain

Sanitation cost ($/unit)	
Total grain protectant cost per case ($)	Total price of grain protectant. Assume Reldan.
Grain protectant charge ($/unit)	Price of grain protectant per unit of grain stored.
Electricity cost ($/kwhrs)	Average cost per KW hr. of electrical usage.
Fan Efficiency	
Fumigant type	Pellets or tablets
Per flask (#)	Number of tablets or pellets per flask.
Flask/case (#)	Number of flasks in each case.
Tablets or pellets available (#)	Number of tablets or pellets per flask per case.
Price per case ($)	Price per case of tablet or pellet flasks.
Price per tablet or pellet ($)	Price per individual tablet or pellet.
Dosage per 1000 bu.	Dosage of fumigant needed per thousand bushels, or the unit to be used.
Price of fumigant ($/unit)	The price of the fumigant expressed in dollars per unit of grain stored.

Table 5. Worksheet 2: Insect Sampling

Parameter	**Description and/or formula**
Insect samples (#)	Number of samples typically required to effectively monitor the insects in stored product.
Insect sampling labor per bin (hr.)	Amount of time required to go to a bin, probe for the required samples, sieve the grain, remove the insects and count and identify the insects.
Setup time (hr.)	Includes the time it takes to set up and take down the vacuum probe and inclined sieves. However, it is done only once for each elevator.
Samplers (# of people)	Includes number of people involved in the sampling process.

Insect Sampling labor charge ($/unit)	(((insect sampling labor x insect samples) + setup time) x samplers x hourly labor cost)* # bins / total units stored
Sampling equipment cost ($/unit)	((initial Power Vac cost / PVIFA) + maintenance costs per year + insurance costs per year) / total units stored

Table 6. Worksheet 3: Bin Aeration and Conditioning

Parameter	**Description and/or formula**
Moisture samples (#)	Number of samples typically required during the storage season to effectively monitor the condition of the stored product.
Sampling labor (hr./bin)	Amount of time it takes to go to a bin, probe for the required samples, test moisture and record results.
Samplers (#)	Number of employees taking the moisture samples.
Conditioning labor (hr.)	The amount of time spent during the storage season to monitor moisture sampling results, ambient conditions and supervise operation of aeration fans.
Aeration season	Assume summer, fall or spring storage. Fan hours depend on storage season.
Fans (#)	Number of fans per bin.
Fan hours (hrs.)	Number of hours fans run in a bin during the storage season for conditioning. Depends on temperature and moisture.
Shrink factor	Amount of shrink observed during the storage season in a bin under aeration and conditioning.
Sampling labor charge ($/unit)	(moisture samples x sampling labor x hourly labor cost x samplers) x # bins / total units stored
Conditioning labor charge ($/unit)	(conditioning labor x hourly labor cost) x # bins / total units stored
Electricity charge-for evening cooling only ($/unit)	(fan hours x (fan HP / efficiency) x electrical cost x # fans x # bins) / total units stored
Shrink loss charge ($/unit)	Shrink loss % x grain price

Controlled aeration electricity charge ($/unit)	(fan hours x 0.5 x (fan HP / efficiency) x electrical cost x # fans x # bins) / total units stored

Table 7. Worksheet 4: Bin Fumigation

Parameter	**Description and/or formula**
Type of fumigation	1=CL, 0=OTHER
Number of in-season fumigations (#)	Expected number of fumigations per bin during the storage season.
Pre-unloading fumigation (#)	Indicates whether or not a bin will be fumigated just prior to unloading to prevent insects from entering the processing facility. 0=NO, 1=YES
Proportion of bins to be fumigated (#)	Sampling will indicate if there are bins infested in the elevator, and if so, the number of bins infested is expressed as a proportion in relation to the total number of bins in the elevator.
Fumigant cost ($/unit)	Chemical cost per unit of grain for fumigation materials.
Employees per fumigation crew (#)	Number of employees per fumigation crew.
Training per employee (hrs.)	Number of hours required per employee on a fumigation crew per year for certification, continuing education, and safety training.
Man hours per fumigation (hrs)	Number of hours required per employee per fumigation to seal bin, administer fumigant, and check concentrations.
Liability insurance ($/unit)	Cost per unit of liability insurance associated with fumigation including worker and environmental safety.
Fumigation Labor charge ($/unit)	(man hrs. per fumig. x employees per crew x hourly labor cost x # fumig.) x # bins /total units stored

Fumigation training charge ($/unit)	(training per employee x (hourly labor cost + registration fee) x employees per crew) / total units stored
Fumigant charge ($/unit)	chemical cost per fumigation x number of fumigations
Fumigation equipment cost ($/unit)	((initial fumigation equipment cost / PVIFA) + maintenance costs per year + insurance costs per year) + ((initial monitoring equipment cost / PVIFA) + recalibration costs per year + insurance cost per year) / total units stored
Electricity and fumigant charges change if closed loop fumigation is used. An additional facility cost is added to the equipment used for fumigation	
Blower hours (hrs)	Blower operating hours to distribute fumigant gas evenly throughout the bin during CL.
CL blower charge ($/unit)	blower hrs. x blower HP x efficiency x electrical cost x # fumig. x # bins) / total units stored
CL facilities cost ($/unit)	((initial CL facilities cost / PVIFA) + maintenance costs per year + insurance costs per year) x # bins / total units stored
CL fumigant charge ($/unit)	Fumigation costs x # fumigations x 0.67 (Closed loop fumigation uses 2/3 of the fumigant quantities that regular fumigation uses.)

Table 8. Worksheet 5: Grain Turning

Parameter	**Description and/or formula**
Grain turning	1=turning while fumigating, 0=no turning
Man hours for turning grain (hrs)	Number of hours required to turn the grain in each bin.
Turning Labor charge ($/unit)	(man hrs.turning x hourly labor cost x num. of fumig. x # bins) / total units stored
Grain turning electricity charge ($/unit)	
Turning shrink factor (%)	Percentage of shrink observed during the summer storage season in a bin when grain is turned while fumigating.
Grain turning shrink ($/unit)	Shrink loss % * grain price

Table 9. Worksheet 6: Annual Operating Cost Analysis

Strategy	Description and/or formula
One fumigation with turning ($/unit)	labor cost + training cost + fumigant cost + fumigation equipment cost + monitoring equipment cost + liability insurance + turning labor cost + grain turning electricity cost + turning shrink loss
Three fumigation with turning ($/unit)	(labor cost + fumigant cost) x 3 + training costs + fumigation equipment cost + monitoring equipment cost + liability insurance + (turning labor cost + grain turning electricity cost + turning shrink loss) x 3
One fumigation-closed loop ($/unit)	labor cost + training cost + CL blower cost + fumigant cost + fumigation equipment cost + closed loop system facilities cost + liability insurance
Three fumigations-closed loop ($/unit)	(labor cost x 3) + training cost + (CL blower cost + fumigant cost) x 3 + fumigation equipment cost + closed loop system facilities cost + liability insurance
Controlled aeration and sanitation ($/bu.)	moisture sampling labor cost + conditioning labor cost + controlled aeration electricity cost + shrink loss + sanitation cost
Controlled aeration, sanitation, 1 sampling ($/bu.)	insect sampling labor cost + conditioning labor cost + insect sampling equipment cost + shrink loss + controlled aeration electricity cost + sanitation cost
Controlled aeration, sanitation, 1 sampling, 1/2 of bins fumigated ($/bu.)	insect sampling labor cost + conditioning labor cost + insect sampling equipment cost + shrink loss + controlled aeration electricity costs + (fumigant cost x 1/2 of bins fumigated) + (fumigation labor cost x 1/2 of bins fumigated) + fumigation training cost + fumigation equipment cost + (turning labor cost + turning shrink loss + turning electricity cost) x 1/2 of bins fumigated + liability insurance + sanitation cost
Manual aeration in evening hours, sanitation, protectant ($/bu)	moisture sampling labor cost + conditioning labor cost + electricity cost + shrink loss + sanitation cost + grain protectant cost
Controlled aeration, sanitation, protectant ($/bu.)	moisture sampling labor cost + conditioning labor cost + controlled aeration electricity cost + shrink loss + sanitation cost + grain protectant cost

Controlled aeration, sanitation, 2 samplings ($/unit)	(insect sampling labor cost x 2) + conditioning labor cost + insect sampling equipment cost + shrink loss + controlled aeration electricity costs + sanitation cost
Controlled aeration, sanitation, closed loop fumigation, protectant ($/bu.)	moisture sampling labor cost + conditioning labor cost + controlled aeration electricity costs + shrink loss + sanitation cost + fumigation labor cost + fumigation training cost + CL blower cost + fumigant cost + fumigation equipment cost + closed loop system facilities cost + liability insurance + sanitation costs + grain protectant cost
Controlled aeration, sanitation, 1 sampling, 1/2 of bins fumigated, closed loop($/bu.)	insect sampling labor cost + conditioning labor cost + controlled aeration electricity cost + shrink loss + sanitation cost + insect sampling equipment cost + (fumigant cost x 1/2 of bins fumigated) + (fumigation labor cost x 1/2 of bins fumigated) + fumigation training cost + fumigation equipment cost + monitoring equipment cost + liability insurance
Mechanical cleaning, controlled aeration, sanitation ($/bu.)	mechanical cleaning cost + moisture sample labor cost + conditioning labor cost + shrink loss cost + controlled aeration electricity cost + sanitation cost

The base model computes costs for an elevator with 10 concrete silos, each with a capacity of 26,000 bushels of grain. Each silo is assumed to currently contain 25,000 bushels, totaling 250,000 bushels. The base model assumes a wheat price of $3.75/bu. and it is used for the calculation of shrinkage, whether it results from aeration or turning. Shrinkage is a variable cost and refers to the loss in volume or weight of the grain placed in a bin (Anderson et al 1995). Costs are calculated on a per-bushel basis. Specific costs considered are labor, aeration, turning, sanitation, chemicals and equipment.

Labor costs per task are calculated as *hourly labor cost* (including employee wages, taxes and benefits paid by employer) *x employee hours per task*. For the base case, a labor cost of $16/hr. (including benefits) was assumed for full-time employees with minimal management responsibilities.

Aeration costs, which are primarily electricity costs, are calculated as *cooling hours per fan x number of fans used x horsepower per fan x efficiency of the fans x electricity cost in $/KWh*, all divided by the number of bushels cooled.

Fumigant costs are calculated as *cost per tablet (pellet) x number of tablets (pellets) used*. There are 500 tablets (1,660 pellets) per flask, and 14 flasks per case (21 flasks of pellets per case), for a total of 7,000 tablets (34,860 pellets) per case. The base price is $300 per case of tablets ($235 per case of pellets), or $0.043 per tablet ($0.007 per pellet). A base dosage of 120 tablets (600 pellets) per 1000 bushels of grain is assumed. However, if closed loop fumigation is used, the base dosage is set at 80 tablets (400 pellets) per 1000 bushels.

Equipment costs are calculated by dividing the initial cost by a present value interest factor, PVIFA[4], to amortize the equipment cost over its useful life, assumed to be 10 years. In addition, an annual insurance cost of 5% of the initial equipment cost, and an annual maintenance cost of 5% of the initial equipment costs are assumed.

Several potential benefits of using IPM, including improved environmental effects and reduced insect resistance, are more difficult to quantify and are not directly

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[4] The Present Value Interest Factor Annuity, or PVIFA, for an annuity of *n* years at *i* percent interest, is calculated as: $PVIFA = \frac{\left[1 - \left(\frac{1}{1-i}\right)^{n}\right]}{i}$

considered here. Differences among the strategies in effectiveness are considered in the effectiveness analysis section of this thesis.

Procedures

Cost Analysis

The first worksheet (Facility Description) allows the user to enter information on the elevator locations, their capacity in thousands of bushels, and the kind of bin the facility has, whether these are concrete, steel or flat bins. Bailey (1992) offers a description of the different types of bins used for grain storage. Concrete bins are built using a slip-form construction method. The slip-form is a concentric, double-ring jacket into which concrete is poured. As the concrete settles in the lower parts, the jacket is pulled upwards and more concrete is poured in. This process continues in increments until the desired height is obtained. Concrete silos have been built at heights ranging from 80 to 140 ft., yet there is not a set formula for height. Sometimes, more than two rows of round silos are built next to each other to form a block. The space in between the bins is also used for grain storage, and is called interstitial or star bins.

Steel bins are always round. Both concrete and steel bins are usually constructed in a row, so that one straight-line conveyor belt can serve a group of them. Flat bins are built wider and lower than the other types of storage. Floors are directly on the ground and the roof tends to follow the slope of the pile of grain (Bailey 1992, p. 165).

Initial equipment costs are entered, along with the expected life of the equipment, maintenance and insurance costs, and salvage values. The equipment used includes the PowerVac, which is the instrument used to sample insects; fumigation equipment, which includes safety, bin sealing and application devices; fumigant monitoring devices; and closed loop facilities. All equipment is assumed to have a salvage value of zero.

This sheet also contains the fan horsepower for the fans used during aeration; the centrifugal fan horsepower for facilities with closed loop systems; the fan efficiency; electricity costs expressed in dollars per kilowatt-hours; and hourly labor costs. Fumigant type and costs, and mechanical cleaning and sanitation costs are also included in this sheet. A grain protectant cost calculated in dollars per bushel allows the user to specify the cost of any chemical grain protectant or other one-time treatment of the grain in terms of unit. Grain protectants are materials applied to grain, which remain for long periods of time at concentration levels toxic to insects (Harein and Davis 1992). Grain protectants offer residual control during storage, but do not control existing insect infestations during storage. Infested grain must be fumigated before the grain protectant can be applied (Arthur and Pitts 1995). For strategies using a protectant, Reldan (chlorpyrifos-methyl) is assumed, at a cost of 2.2¢/bu. (Kenkel et al. 1993)

The second worksheet (Insect Sampling) contains the number of samples used to monitor insects in the stored product; sampling labor hours per bin, which are the amount of time required to go to a bin, probe for the required samples, sieve the grain, and count and identify the insects; the time it takes to set up and take down the vacuum probe and inclined sieves; and the number of people it takes to do the job. The equipment setup is done once for each elevator per sampling. The base model assumes 3 samplers taking 10 insect samples per bin, each sampler working 0.08 hours per bin, and using a total of 3 hours to set up the sampling equipment. Insect sampling labor charges and sampling equipment costs are expressed in dollars per bushel. Table 5, shown previously, contains the formulas for the calculation of these parameters.

The third worksheet (Bin Aeration and Conditioning) contains the number of samples typically required during the summer storage season to effectively monitor the condition of the stored product; sampling labor hours per bin (the amount of time it takes to go to a bin, probe for the required samples, test moisture and record results) and conditioning labor hours (the amount of time spent during the summer storage season to monitor moisture sampling results, ambient conditions and supervise operation of aeration fans); the number of samplers; the number of fans in the bin; and the fan hours, which are the number of hours a fan runs on a bin during the summer storage season for conditioning, dependent on temperature and moisture. The base model uses 40 fan hours, which is the amount of time needed for medium aeration (0.3 cfm) during the fall (Noyes et al. 1995, pg.78). The base model uses 10 moisture samples taken by 2 samplers, using 0.1 hours of sampling labor each and 0.75 hours of conditioning labor.

This worksheet contains a shrink factor, which is the amount of weight loss observed during the storage season in a bin under aeration and conditioning, and which is used to calculate of shrinkage loss. The shrinkage loss charge is the *shrink factor x grain price*.

Calculations for sampling labor, conditioning labor, evenings-only aeration electricity, and controlled aeration electricity charges are next. Controlled aeration is assumed to use 50% less cooling hours than evenings-only cooling. These costs are calculated by using the formulas in Table 6 (shown previously).

The fourth worksheet (Fumigation) includes costs for regular fumigation and closed loop system fumigation, if the system is available in the bins. The base model assumes that only one fumigation is done for the storage season. However, this number can be adjusted. To keep track of the activity, a binary variable is used to indicate whether or not a bin will be fumigated just prior to unloading to kill any insects present before grain is marketed: 0=No, 1=Yes. In this worksheet the elevator manager is able to enter the proportion of the bins to be fumigated, in case sampling determines that a certain number of bins are at risk of infestation. This is crucial for IPM strategies because it avoids unnecessary fumigation. The strategy used here in which sampling indicates fumigation is needed assumes that sampling indicates half of the fins should be fumigated.

The base model uses three employees per crew, each requiring an 8-hour day of training per year. The number of training hours represents the hours required per employee on a fumigation crew per year for certification, continuing education, and safety training. Two man-hours per employee per fumigation are required to seal a bin, administer fumigant, check concentrations, and aerate the bin. A liability insurance cost expressed in dollars per bushel is included in this worksheet, which is associated with fumigation and includes worker and environmental safety. The base model uses a liability insurance cost of $0.0001/bu. Calculations for fumigation labor, fumigation training, fumigant charges for routine fumigation, and fumigation equipment follow.

Costs of closed loop fumigation are included in a separate section of the worksheet. The number of blower hours required to distribute fumigant gas evenly throughout the bin can be specified in this worksheet if the facility uses closed loop systems. For the base case, 48 blower hours is assumed. Closed loop fumigation is assumed to require two-thirds of the fumigant needed for routine fumigation. Costs for closed loop facilities are also included. The formulas for these calculations are found in Table 7 (shown previously).

The fifth worksheet (Turning) uses a binary variable, which equals 1 if the grain is turned while fumigating, 0 if not. The base model uses 3 hours of labor for turning the grain, and assumes that electric costs for turning the grain are $0.004/bu.(Noyes et al. 1995, p. 154). A shrink factor of 0.3% is associated with turning the grain. Turning costs are calculated in Table 8 (shown previously).

Several specific insect management strategies are considered:

1. One fumigation (fumigation at a fixed period of time after receipt of grain), assuming that grain must be turned for effective fumigation;
2. Three fumigations with turning;
3. Routine fumigation as in (1), but with a closed loop system;
4. Three closed-loop fumigations;
5. Controlled aeration of grain (aeration only when outside temperatures are cooler than grain), plus sanitation (assumes that the number of fan hours can be reduced by half to achieve same level of cooling – shrinkage is assumed to be the same as that for manual aeration since although half of the fan hours are required, most shrinkage occurs during the first few hours of aeration);

6. Controlled aeration plus sanitation, plus 1 sampling in which 10 samples are drawn from various depths of each bin in which grain is stored using a Power Vac;
7. Strategy (5), assuming that the insect sampling indicates that ½ of the bins need to be fumigated;
8. Routine manual aeration in evening hours plus grain protectant (Reldan, at a cost of $0.022/bu.);
9. Strategy (5), plus grain protectant;
10. Controlled aeration plus sanitation, plus two insect samplings several months apart;
11. Controlled aeration plus sanitation, plus one insect sampling, and assuming that insect sampling indicates that ½ of the bins need to be closed-loop fumigated;
12. Controlled aeration plus sanitation, closed-loop fumigation of all bins, plus application of protectant;
13. Mechanical cleaning for better aeration and insect control (in place of protectants), plus aeration, plus sanitation.

For those strategies involving fumigation, cost of sealing bins is included in labor costs of fumigation. The formulas for the computation of the strategies are listed in Table 9 (shown previously).

Sensitivity Analysis

A sensitivity analysis on the base model input parameters was performed in order to understand the extent to which each component influences the end result. Four parameters that were assumed to affect costs and benefits the most are labor, electricity, fumigant and protectant costs. These parameters were varied one at a time, multiplying by incremental factors of 25%, 50%, 75%, 100% and 200%.

Effectiveness Analysis

The effectiveness of each strategy is evaluated by predicting the number of live insects that would remain at the end of the storage period. A distributed delay insect growth model provided by Paul Flinn is used for this prediction. An earlier version of this model is found in Flinn and Hagstrum (1990). The distributed delay model simulates insect population dynamics under a range of pest management practices such as no control, aeration, fumigation, and use of protectant, etc. With aeration, the user can specify none, manual, semiautomatic (3 cycles based on air temperature), and automatic (fans run if air temperature is less than temperature of stored grain).

The model can simulate a metal or concrete bin with a wide range of widths and heights. It uses historical weather data for several locations in Oklahoma and Kansas to model the likely effects of temperature and humidity in insect growth.

One of the outputs of the model is live number of insects per kilogram. These results were used to approximate the number of insect damaged kernels (IDK), which in turn helped determine loss of grain market value due to pests. An Oklahoma grain terminal provided discounts and charges for IDK and wheat cleaning (Table 10).

Table 10. IDK Discounts and Cleaning Charges (kernels per 100 grams)

Kernels	Discounts and Cleaning Charges (CC)
1-5	$0.00
6-20	$0.01/kernel
21-31	$0.02/kernel
32-70	$0.40 CC
71-100	$0.60 CC
101-140	$0.90 CC
Over 140	$0.01/kernel

A second terminal elevator discounts 12 cents per bushel if the wheat receives a "sample" grade. For example, if 7 IDK are detected in a 100-gram sample, the wheat price is discounted by $0.07/bu. Both terminals discount $0.05 per bushel of wheat if the grain is infested.

For this study, eight scenarios are simulated: no control, manual aeration only, automatic (controlled) aeration only, fumigation only, protectant only, manual aeration with protectant, automatic (controlled) aeration with protectant, and automatic (controlled) aeration with fumigation. The grain is assumed to be in storage for nine months, starting at harvest (June 20) and ending in March 20, when the grain is sold. The grain is assumed to be stored in a concrete silo that measures 24.9 ft. wide by 100.1 ft. tall.

A temperature of 91° F and a moisture content of 12% are assumed. These conditions are common around June 20. The moisture content is changed to 15% in some instances, to compare scenarios. For the manual aeration option, the aeration date is set at September 20, when air temperatures start to cool off. Forty fan hours are used at 0.3 cfm/bu. However if automatic aeration is selected, the model assumes 120 fan hours. This number cannot be modified in this case.

Four species of stored product insects can be simulated one at a time. This study models the lesser grain borer, a predominant insect in the state of Oklahoma and Kansas, and they are most damaging to stored wheat.

CHAPTER FOUR

RESULTS

Chapter Overview

This chapter presents the results of the cost, sensitivity, and effectiveness analyses. Some observations about the analyses are noted at the end of the chapter.

Cost Analysis

Figure 2 and Table 11 show the annual cost of several IPM and conventional strategies in a storage system with total capacity of 250,000 bushels. Costs considered for each of the thirteen strategies include labor, aeration, turning, sanitation, chemicals, and equipment. Comparisons of these strategies assume that cost of appropriate equipment is part of the consideration. If equipment has already been purchased, however, the equipment portion of these costs should be ignored in comparisons since no additional equipment costs would be incurred. This is depicted in Figure 3, where it is assumed that elevator managers already have the equipment, and are only interested in the sunk costs. Sunk costs are costs that have already been paid and cannot be recovered. Each bar represents one of the 13 strategies analyzed.

The first component of each bar is labor cost. Sampling is a significant portion of IPM costs; therefore, the IPM strategies have the highest labor costs. However, in cases

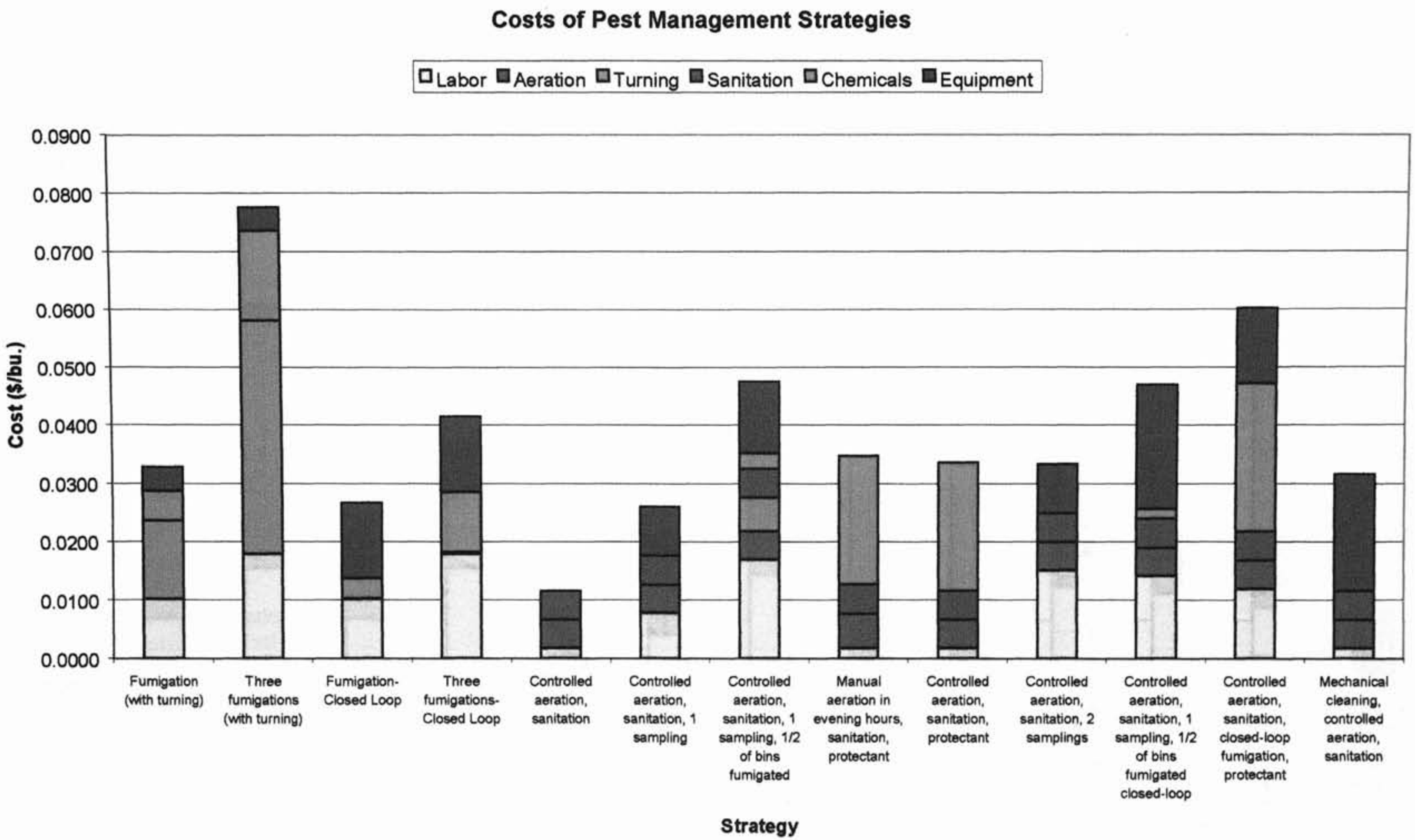

Figure 2. Costs of Pest Management Strategies

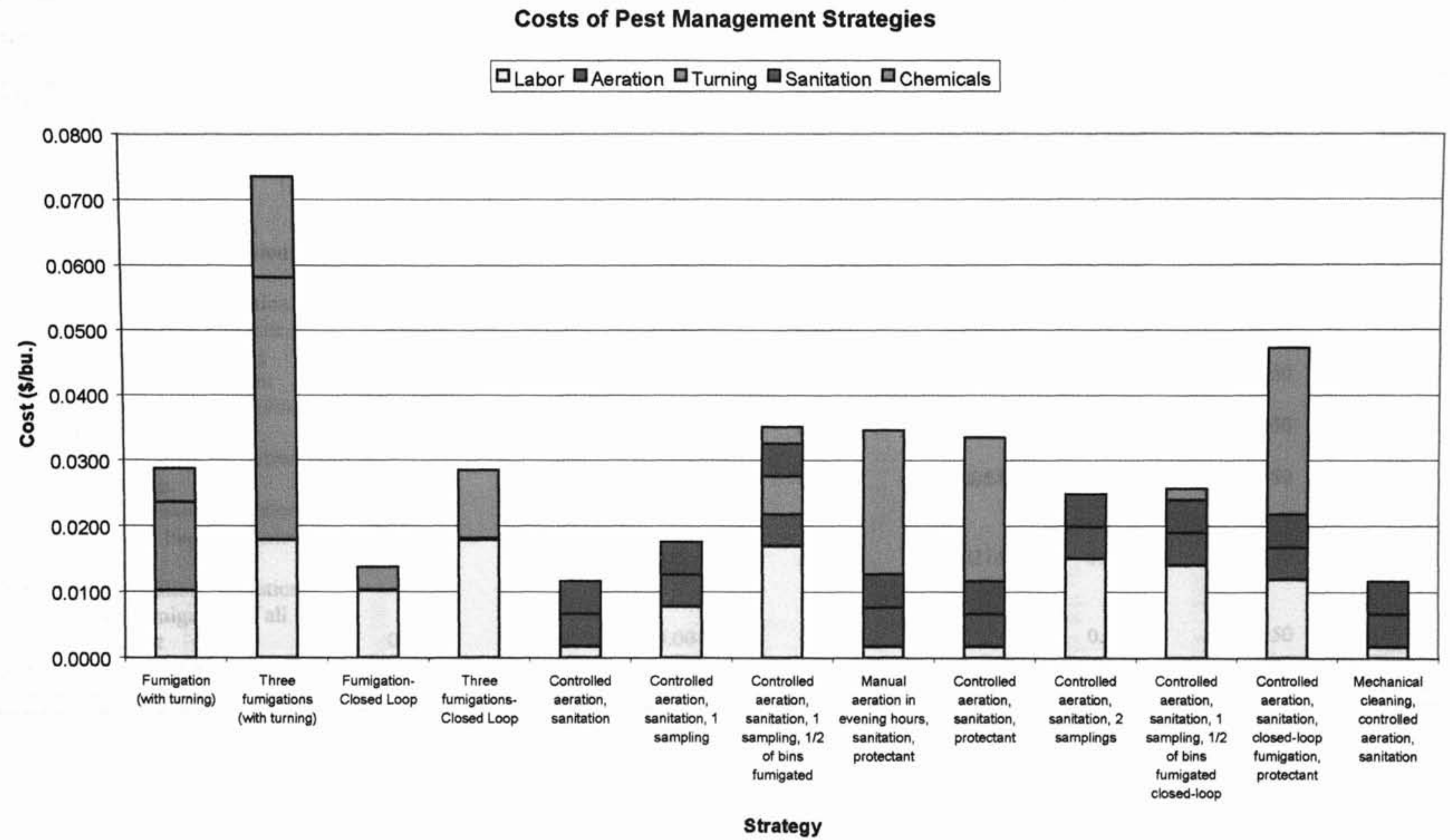

Figure 3. Costs of Pest Management Strategies, No Equipment Costs Included

Table 11. Annual Operating Costs for the Thirteen Strategies

				COSTS ($/bu.)				
STRATEGY	**Labor**	**Chemicals**	**Aeration**	**Turning**	**Equipment**	**Liability Insurance**	**Sanitation**	**Total Cost**
1. One fumigation with turning	0.0040	0.0051	0.0000	0.0134	0.0032	0.0001	0.0000	0.0267
2. Three fumigations with turning	0.0117	0.0154	0.0000	0.0403	0.0040	0.0001	0.0000	0.0715
3. One fumigation-closed loop	0.0040	0.0034	0.0001	0.0000	0.0129	0.0001	0.0000	0.0206
4. Three fumigations-closed loop	0.0117	0.0103	0.0003	0.0000	0.0129	0.0001	0.0000	0.0354
5. Controlled aeration plus sanitation	0.0018	0.0000	0.0048	0.0000	0.0000	0.0000	0.0050	0.0116
6. Controlled aeration, sanitation, 1 insect sampling	0.0078	0.0000	0.0048	0.0000	0.0084	0.0000	0.0050	0.0260
7. Controlled aeration, sanitation, 1 sampling, ½ of bins fumigated	0.0109	0.0026	0.0048	0.0058	0.0124	0.0001	0.0050	0.0415
8. Manual aeration in evening hours, sanitation, protectant	0.0018	0.0220	0.0059	0.0000	0.0000	0.0000	0.0050	0.0346
9. Controlled aeration, sanitation, protectant	0.0018	0.0220	0.0048	0.0000	0.0000	0.0000	0.0050	0.0336
10. Controlled aeration, sanitation, 2 insect samplings	0.0151	0.0000	0.0048	0.0000	0.0084	0.0000	0.0050	0.0333
11. Controlled aeration, sanitation, 1 sampling, ½ of bins fumigated-closed loop	0.0080	0.0017	0.0048	0.0000	0.0214	0.0001	0.0050	0.0410
12. Controlled aeration, sanitation, closed loop fumigation of all bins, protectant	0.0058	0.0254	0.0048	0.0000	0.0129	0.0001	0.0050	0.0541
13. Mechanical cleaning, controlled aeration, sanitation	0.0018	0.0000	0.0048	0.0000	0.0200	0.0000	0.0050	0.0316

where grain is emptied out of one bin and transported to another one or grain is transported from one elevator to another, and sampling is done upon receipt of the grain and stored for less than one year, much of this cost can be avoided.

Aeration costs are the second component of the bars. Variable costs for manual aeration are higher than for controlled aeration. Aerating upon receipt of grain is less effective than aerating after outside temperatures drop, so the electricity cost is higher for the same amount of cooling. Additional savings can be achieved if aeration fans are shut off when outside temperatures are higher that the grain temperature, and turned on only when outside temperatures are lower than grain temperatures. Although this can be done manually, it may be more economical and effective if done by using automatic temperature controllers.

Turning costs are the third component, and include electricity, labor and shrink. 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.

Chemicals include fumigant and grain protectant costs, and are the fifth component in the bars. For IPM strategies where only a portion of the bins are fumigated or for closed loop fumigations, fumigant costs are lower than with routine fumigation. Closed loop fumigations usually require 1/3 less fumigant to achieve the same level of effectiveness, and would not require turning of the grain.

The sixth component of costs is equipment. It is assumed for IPM strategies that sampling equipment is required (in this case, a Power Vac sampler is used), and for fumigation strategies, that fumigation and monitoring equipment is needed. For closed loop fumigation, amortized installation costs of the system are included in the cost.

The first bar is fumigation with turning. Its costs total 2.67¢/bu. The biggest component of this strategy is turning the grain for effective fumigant dispersion. In the case of closed loop fumigation (third bar), turning costs are avoided, and fumigant costs are reduced by about a third. However, its equipment cost is higher than routine fumigation. The cost of this strategy is 2.06¢/bu.

The second and fourth bars represent three fumigations per year; the first one with turning, the second with closed loop. Costs for the second strategy exceed 7¢/bu., with turning being its greatest component. This is the most expensive strategy in this analysis. Using three closed loop fumigations instead would reduce costs to 3.54¢/bu.

The fifth bar represents controlled aeration with sanitation. This strategy uses no chemicals and its cost is 1.16¢/bu. The sixth bar adds to the fifth strategy sampling for insects and other quality factors after the grain has been in storage for a time. This is an expensive practice because it requires specialized equipment (e.g. Power Vac), and requires two workers to take several samples at various depths in each grain bin. This strategy totals 2.60¢/bu. If sampling indicates that the insect population has reached or surpassed an economic threshold, other treatment strategies such as chemical control would be used.

The strategy represented by the seventh bar is one in which sampling has determined that half of the elevator bins were infested, requiring fumigation. This strategy includes equipment and labor costs for both sampling and fumigation, and cost of turning, making it one of the most expensive strategies at 4.15¢/bu.

The eighth bar represents a strategy in which aeration fans are turned on in mid-fall as temperatures become cool and are run most of the evenings. Sanitation is practiced, and a grain protectant is applied. The protectant accounts for 60% of the 3.46¢/bu that this strategy costs. The ninth strategy replaces manual aeration with controlled aeration, running the fans only when outside temperatures are cooler than the grain being cooled. This practice is assumed to need only half the fan hours for the same amount of cooling, reducing the cost slightly to 3.36¢/bu.

The tenth bar represents the cost of controlled aeration, sanitation, and two samplings for insects of grain already in storage (for example, if the grain has been in storage for longer than expected or if environmental conditions have been favorable to insect growth, the firm may wish to sample for insects again 2-3 months after the first sample). This strategy costs 3.33¢/bu. The eleventh bar represents controlled aeration, sanitation, one insect sampling, and closed loop fumigation for ½ of the bins. The cost of this strategy is 4.10¢/bu.

The twelfth bar represents a chemically intensive strategy that also uses some IPM practices. Controlled aeration and sanitation are combined with closed-loop fumigation of all the bins and a protectant applied to all grain. This strategy is the second most expensive, costing 5.41¢/bu. Finally, the thirteenth bar represents a strategy in which the firm mechanically cleans the grain before storing it, in an attempt to avoid the use of chemicals, and conducts controlled aeration and sanitation practices. This strategy costs 3.16¢/bu.

Sensitivity Analysis

Figures 4-7 show comparisons between the base model and models with 100% increases in the labor, fumigant, electricity and protectant costs. Bars labeled with an "a" after the strategy number represent the costs of the strategies after the increment. Appendix A contains the complete results of all the percent changes for all the parameters.

The sensitivity analysis determined that the parameters had greatest impact on the cost of the strategies that most heavily employed them. Labor-intensive strategies were sensitive to labor prices. These strategies were the fourth -- three closed-loop fumigations--, the sixth -- controlled aeration plus sanitation and 1 sampling--, and the tenth -- controlled aeration plus sanitation and two insect samplings several months apart. Strategies including fumigation were sensitive to the price of fumigant. Strategies were less sensitive to electricity price changes because electricity costs are low, and make up a small proportion of each strategy's cost. Strategies including use of protectant were very sensitive to price of protectant because it makes up a large proportion of the cost of these strategies.

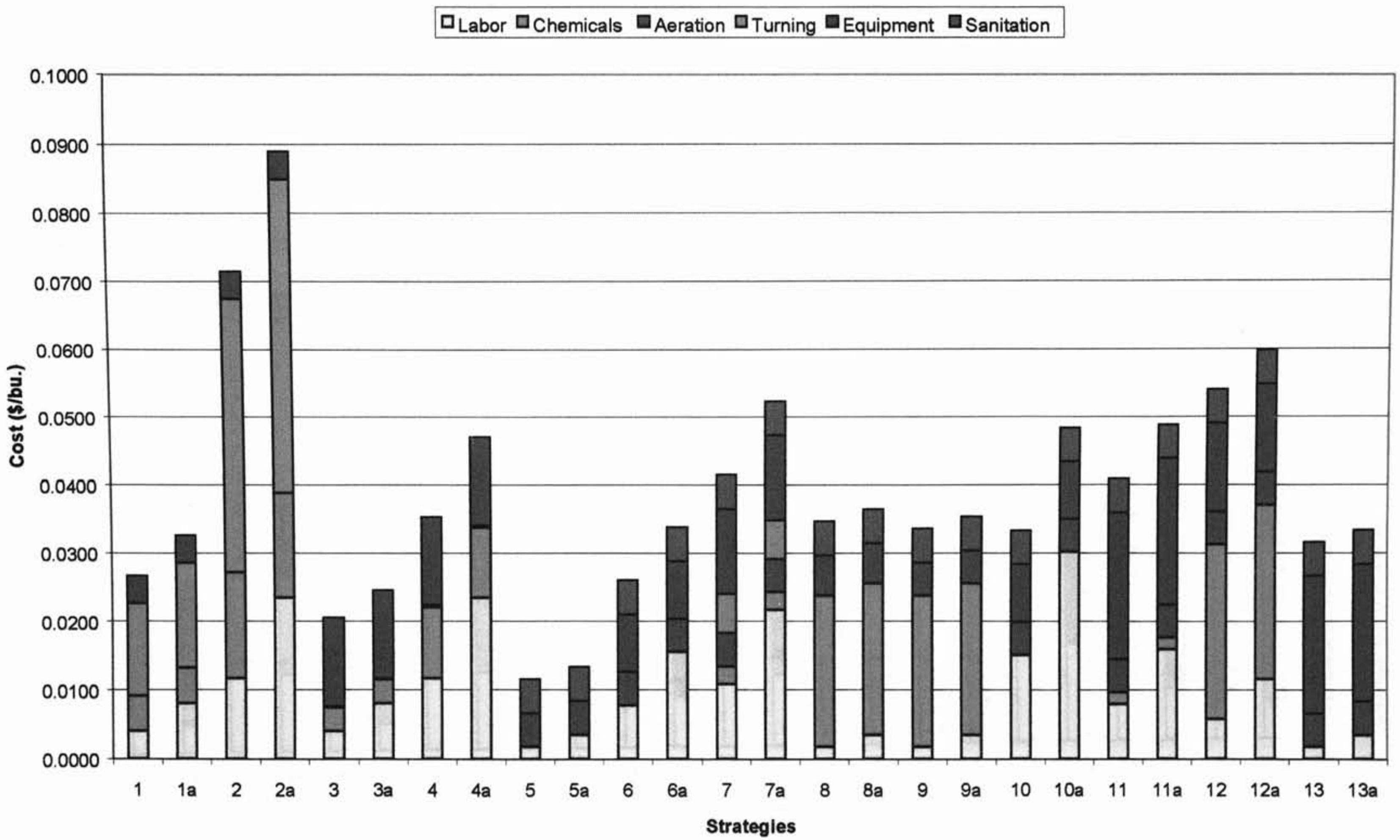

Figure 4. Comparison between Base Model and Model with 100% Increase in Labor Costs

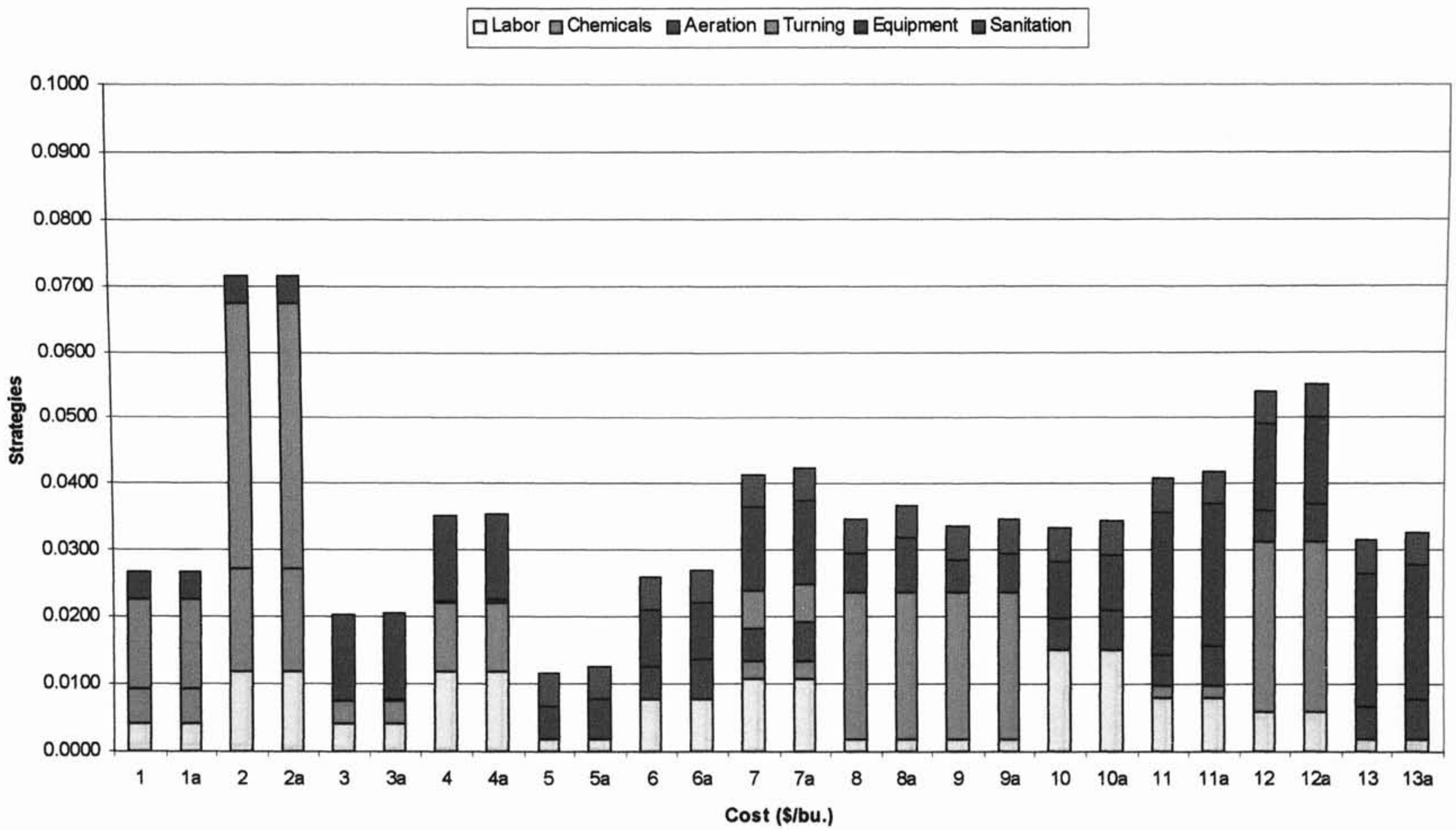

Figure 5. Comparison between Base Model and Model with 100% Increase in Electricity Cost

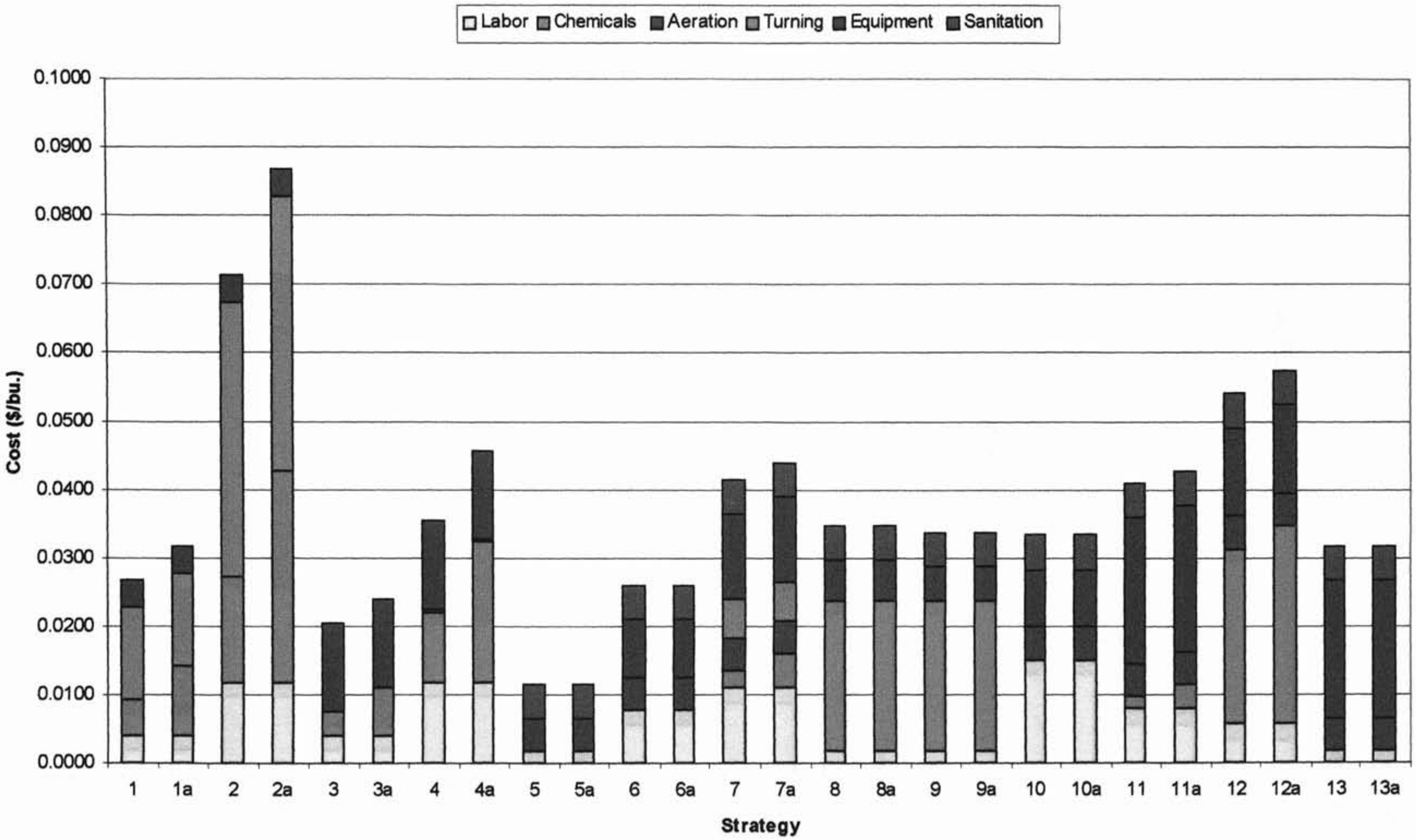

Figure 6. Comparison between Base Model and Model with 100% Increase in Fumigant Costs

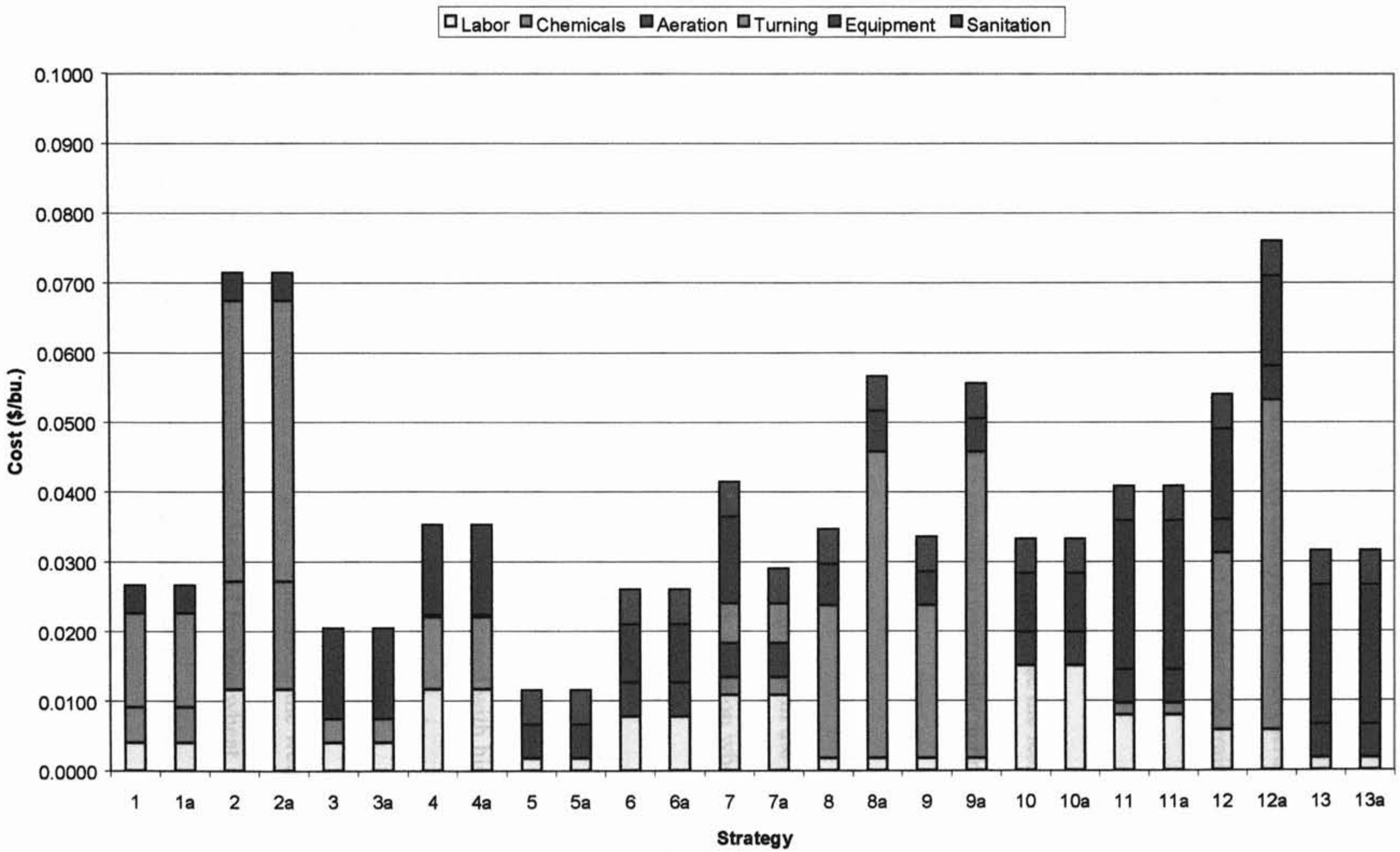

Figure 7. Comparison between Base Model and Model with 100% Increase in Protectant Costs

Effectiveness Analysis

The growth model's predictions are for one type of insect (here, the lesser grain borer is used), so the results cannot be used to predict whether the grain will be graded "infested". The "infested" grade results when two or more live insects per kilogram are detected, without regard to type of insect. Thus, predicting numbers of one type of insect will underestimate the total number of insects. However, since the lesser grain borer is the primary internal feeder, it can be used to provide a reasonable approximation to number of insect damage kernels (IDK). Thirty-two or more IDK per 100 grams of wheat result in the designation of "sample " grade. The results graphed in Figures 8-16 indicate the average number of lesser grain borers per kilogram in the bin.

Figure 8 describes the first scenario, a benchmark situation where the elevator manager decides not to apply any control methods. Under the given conditions, there will be 509 lesser grain borers per kilogram of wheat in March 20, when the grain is sold. This means there would be at least 51 IDK per 100 grams, which will result in a designation of sample grade. If the grain happens to be stored with higher moisture content of 15% (Figure 9), the model yielded 44,733 lesser grain borers per kilogram, implying at least 4,473 IDK per 100 grams of wheat. Their grain would be noted as sample grade, resulting in a discount of $0.12/bu. In addition, the weight of wheat would be reduced so that the elevator manager would be paid for less wheat.

For the second scenario (Figure 10) manual aeration was simulated. Aeration started in September 20, when temperatures start to cool off. The simulation results in

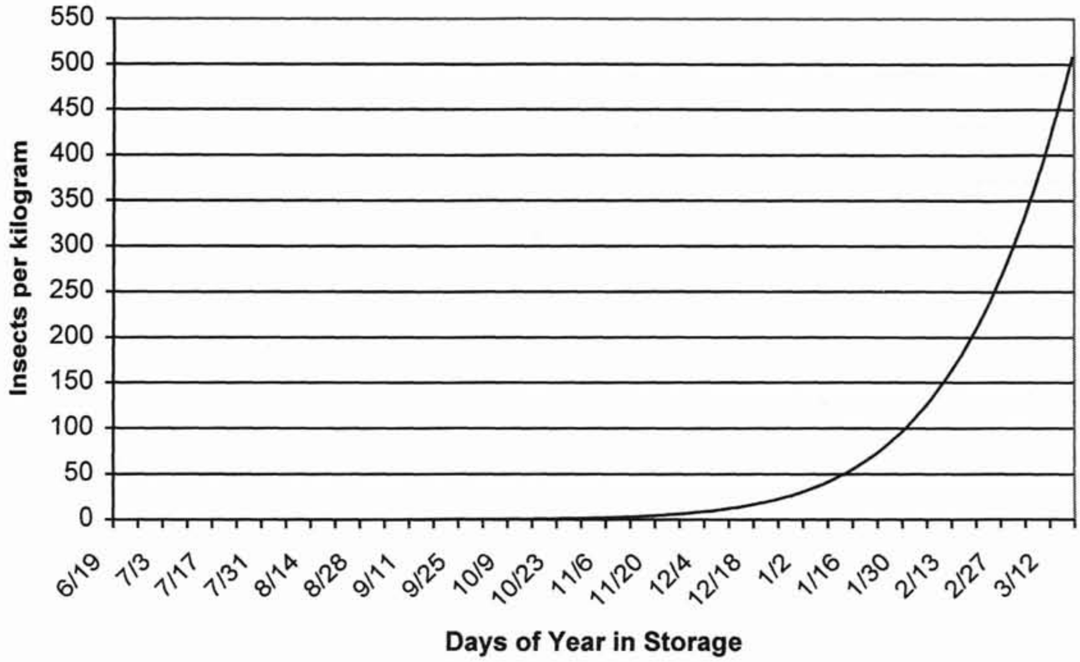

Figure 8. Average number of live insects per kilogram after a "no control" approach

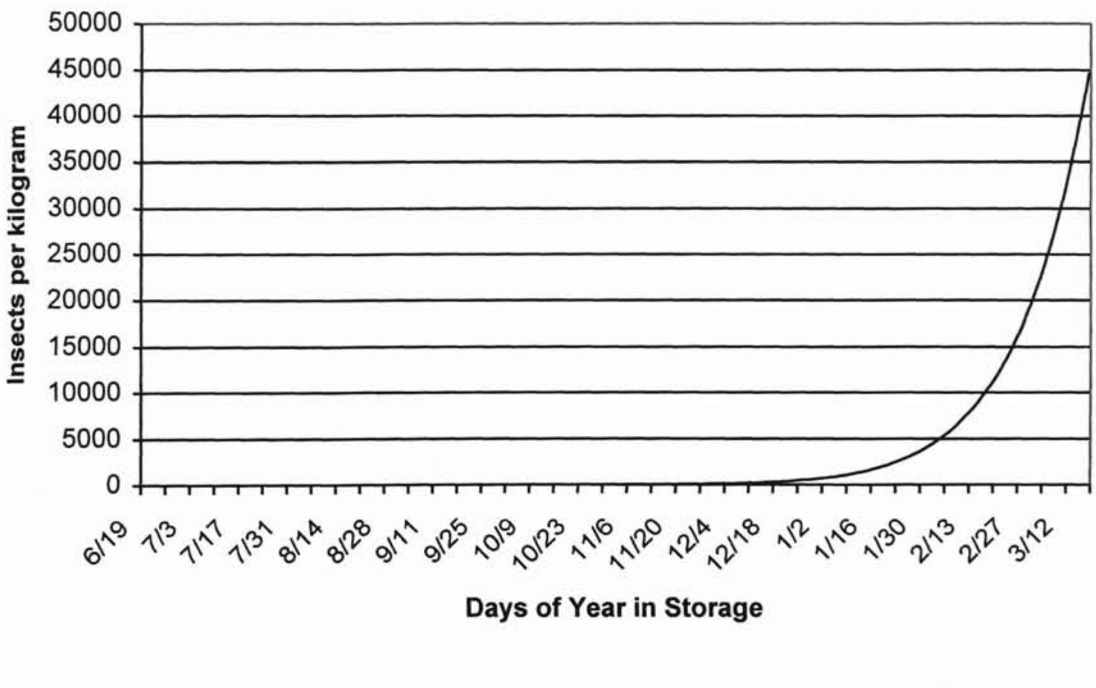

Figure 9. Average number of live insects per kilogram after a "no control" approach (MC 15%)

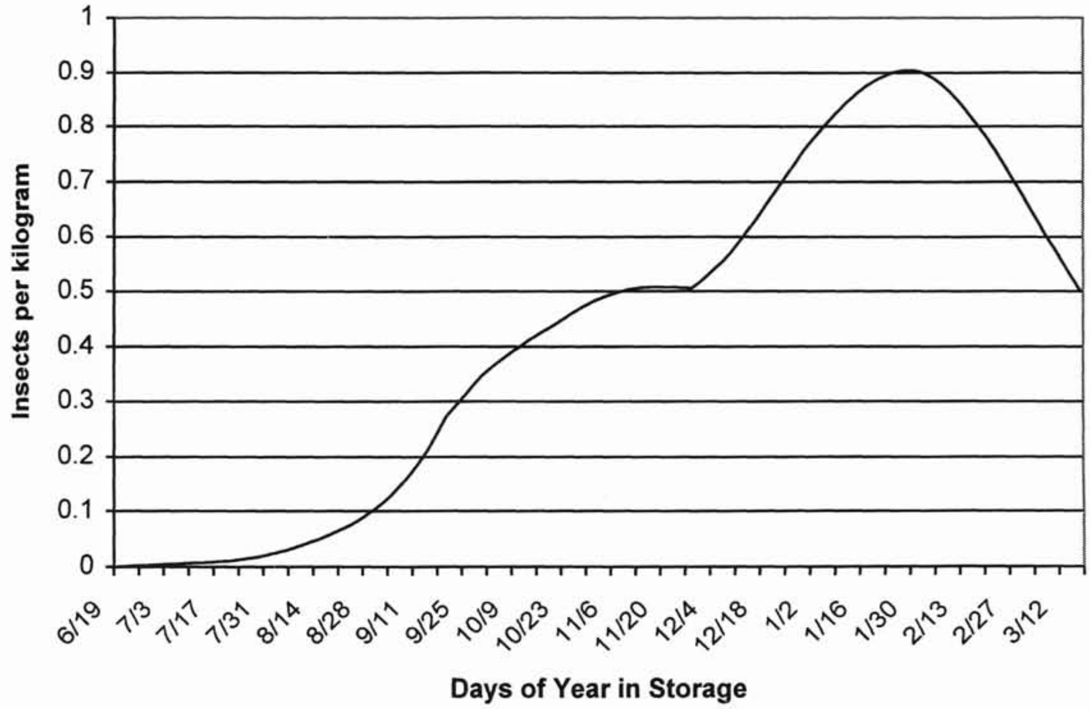

Figure 10. Average number of live insects per kilogram after manual aeration

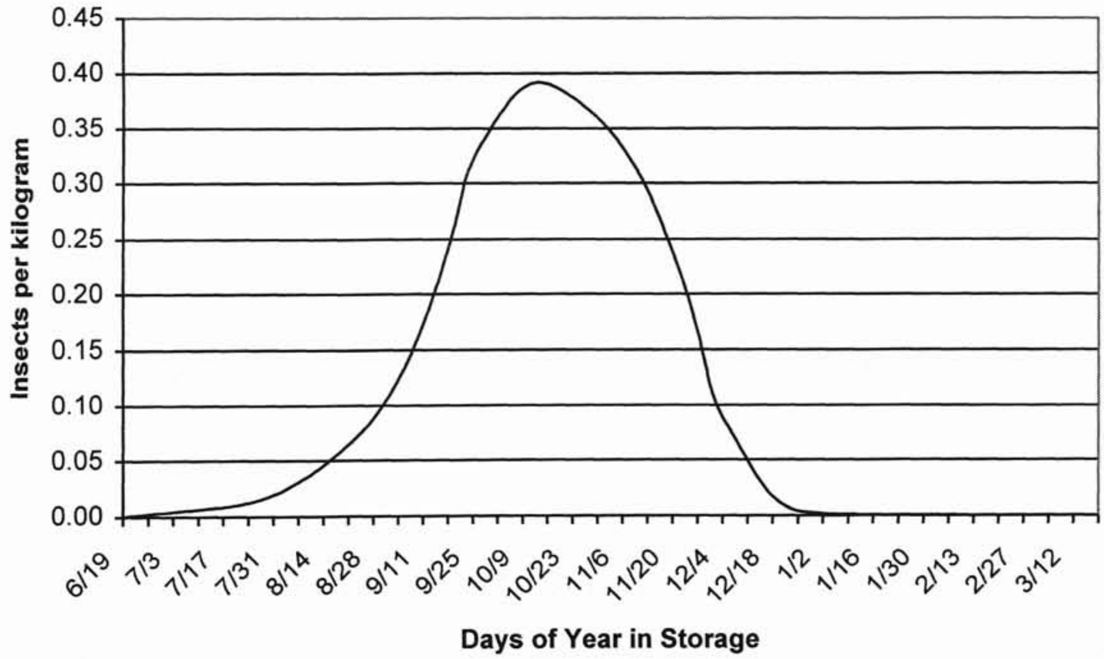

Figure 11. Average number of insects per kilogram after controlled aeration

0.5 insects per kilogram, or 0.05 insects per 100 grams. This number is not high enough to result in any damage or economic loss.

The third scenario (Figure 11) simulates controlled aeration, and predicts no insects at the end of the storage period. The graph shows that by using controlled aeration on September 20, lesser grain borers would not reproduce and live. Their mortality rate would exceed their reproduction rate.

The fourth scenario simulates fumigation once a year. The simulation was run 10 times, for 10 different possible dates for the fumigation: July 1 (approximately two weeks after storage), July 20, August 20, September 20, October 20, November 20, December 20, January 20, February 20 and March 1 (approximately two weeks prior selling). Fumigating prior selling the grain (March 1), resulted in less live insects compared to other days of fumigation. There was an average of 135 live insects per kilogram (Figure 12). This represents IDK of at least 14 per 100 grams after fumigating in March 1. Although the grain is not designated a "sample" grade, there will be a discount of $0.02/kernel, resulting in a discount of $0.28/bu. of wheat. Appendix C contains figures on the average number of live insects per kilogram corresponding to the other dates of fumigation.

For the fifth scenario (Figure 13), Reldan applied to the grain as a prevention method was simulated. By the end of the storage period, about 4 insects per kilogram were predicted to live. Although the grain is not designated a "sample" grade, it could mean a designation of "infested", in which case there will be a discount of $0.05/bu. of wheat. However, since the simulation is based on lesser grain borers only, this would be an underestimation.

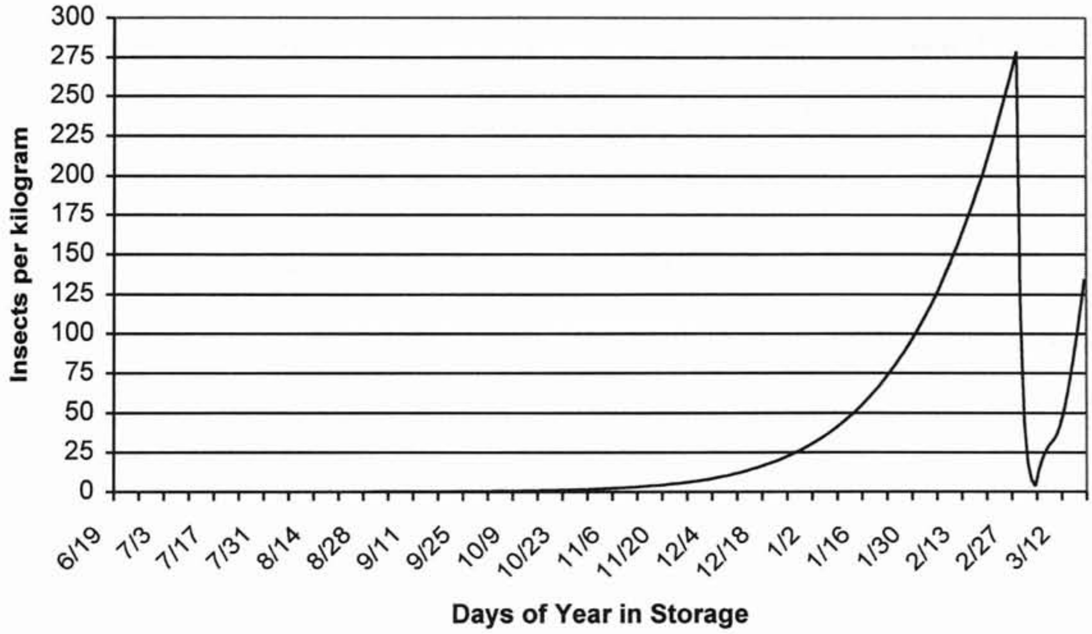

Figure 12. Average number of insects per kilogram after fumigating in March 1

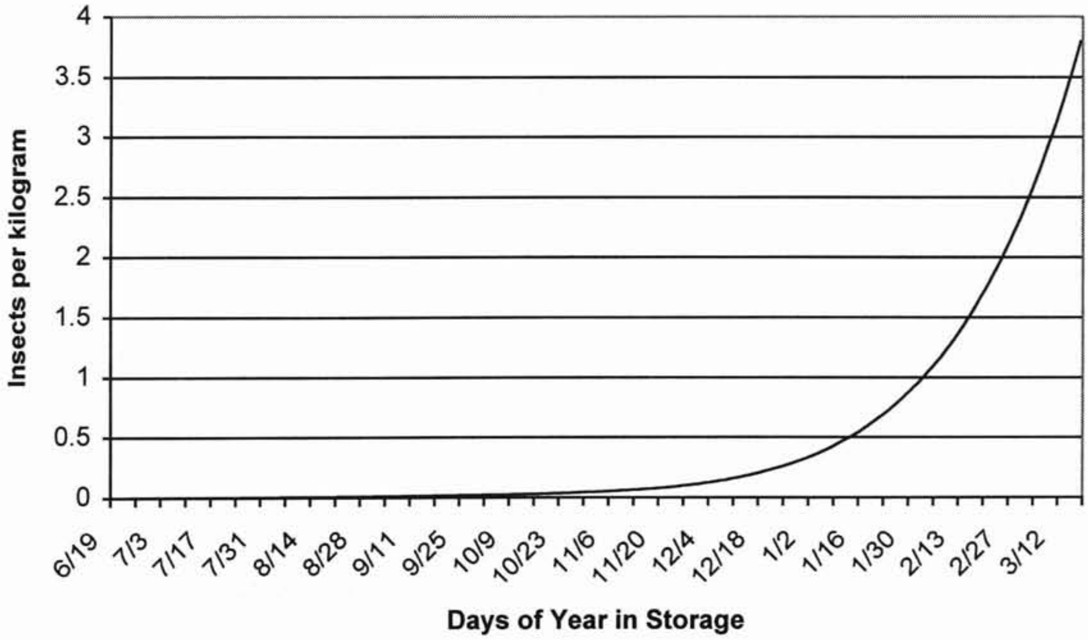

Figure 13. Average number of live insects per kilogram after Reldan application

The model predicts no insects at the end of the storage period for the remaining simulated scenarios: manual aeration and the application of a grain protectant (Figure 14), controlled aeration and the application of a grain protectant (Figure 15), and controlled aeration and fumigation (Figure 16). On this last scenario, several dates of fumigation were used. Results indicated no major effect on the ending number of live insects with respect to the date of fumigation. The graph shows controlled aeration and fumigation in November 20. The aeration methods applied appear to be detrimental on the growth of the lesser grain borer, never giving the insects an opportunity to intensify.

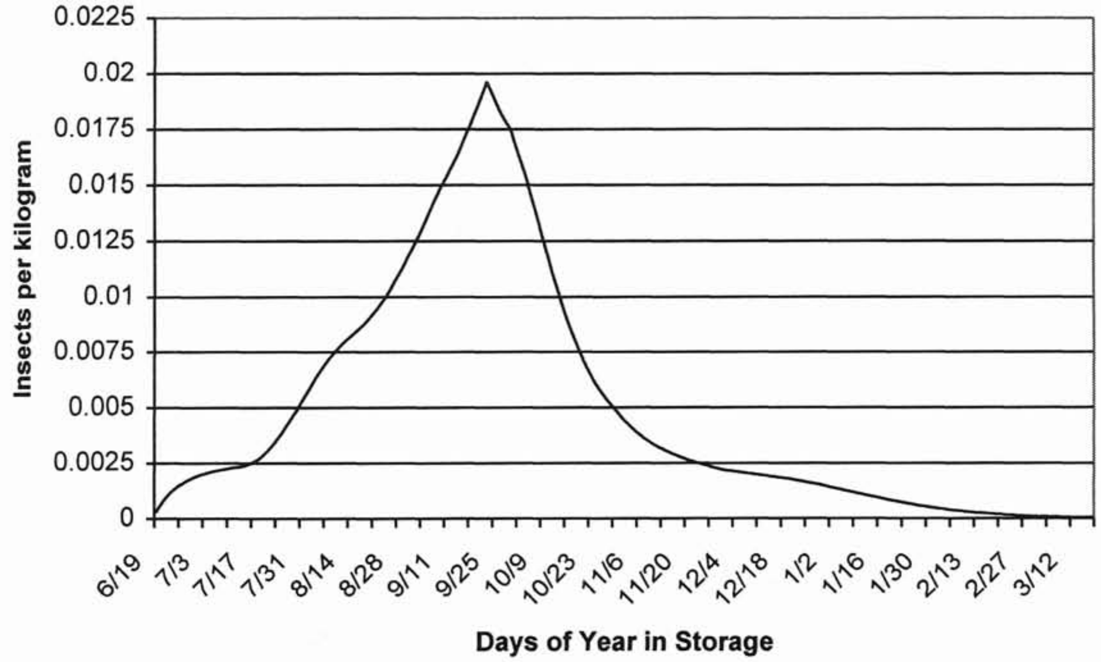

Figure 14. Average number of live insects per kilogram after manual aeration and Reldan application

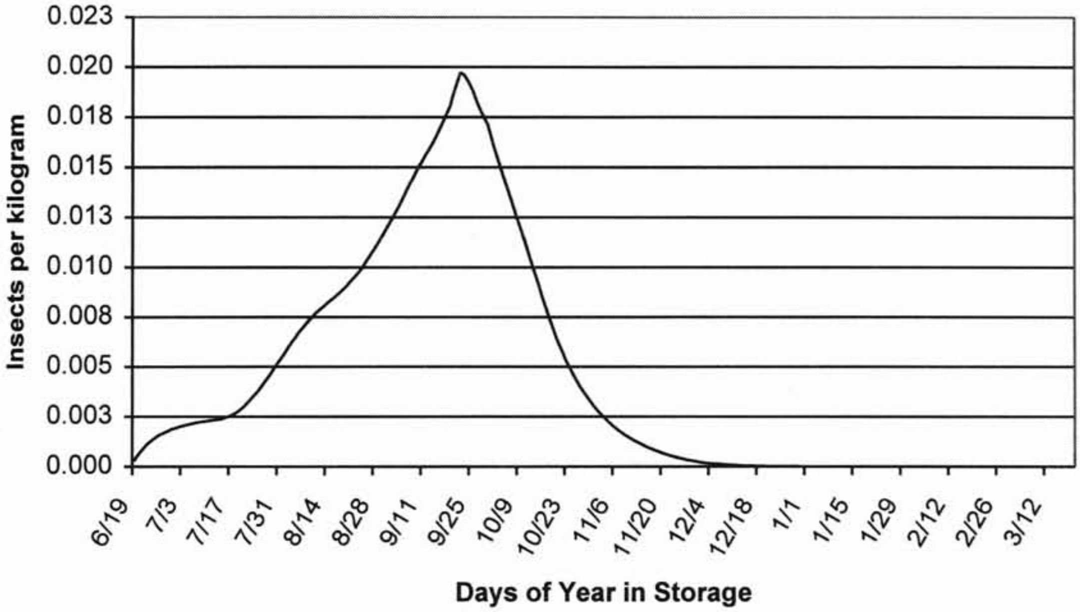

Figure 15. Average number of live insects per kilogram after controlled aeration and Reldan application

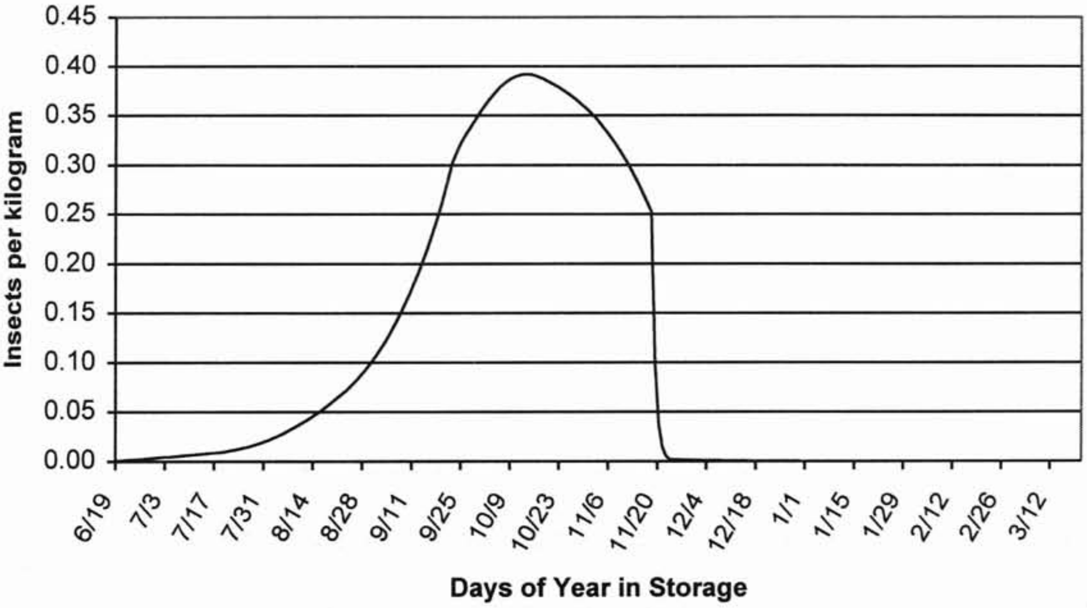

Figure 16. Average number of insects per kilogram after controlled aeration and fumigating on November 20

Interpretation of Results

Cost Results

Several patterns emerge. First, comparing the first bar (strategy) with the third bar, it is clear that for firms that fumigate, closed-loop fumigation is more economical than non-closed loop fumigation, even after accounting for installation and equipment costs. Because less fumigant is needed (about 1/3 less), chemical costs are lower. Although they are not explicitly considered here, any negative environmental effects will be reduced as well. The biggest cost savings with closed-loop fumigation compared with conventional fumigation in concrete storage facilities is that closed-loop fumigation does not require turning of grain, saving energy and labor costs. Moreover, because workers do not need to be in the facility while fumigant is applied, worker safety is greatly enhanced. Also, closed-loop fumigation is likely more effective in controlling insects because of the sustained concentration of gas in the facility.

Second, strategies using grain protectant (bars 8, 9, and 12) are among the more expensive strategies, since the protectant itself (assuming Reldan is used) costs about 2.2¢/bu. Costs of IPM strategies compare quite favorably with costs of strategies using a protectant, even in a situation in which insect infestation reaches the point at which partial fumigation is needed to supplement the IPM practices. For example, the ninth strategy --controlled aeration, sanitation, protectant -- costs about the same as the eleventh strategy, controlled aeration, sanitation, 1 sampling, ½ of bins fumigated using closed loop. Using a grain protectant also has potential to leave chemical residue, which may be rejected by flour mills, though this cost is not measured here.

Third, effective, accurate sampling is labor-intensive, making it the most costly component of IPM practices considered. However, if grain is sampled upon receipt (when transported from bin to bin, or elevator to elevator) and if other IPM practices such as sanitation and aeration for cooling are followed prior and during storage, sampling may not be required as part of an effective IPM strategy. It could be possible that if preventive measures such as sanitation are used the grain may not need be treated. If in-storage sampling is not required, sampling equipment and labor for sampling is not required, so costs of IPM strategies are likely to be lower than those of conventional strategies.

Effectiveness Analysis

The effectiveness analysis shows that choosing not to engage in any type of control method results in considerable economic losses. Even if the elevator manager chooses to fumigate once a year, s/he faces could face some economic losses due to pests, yet in lower magnitudes. Although cost analysis results indicate that fumigating once is less expensive compared to other strategies like manual and controlled aeration, the loss in market value due to pests is likely greater than for the aeration studies. This makes fumigating once a year not cost-effective. Manual aeration and controlled aeration, as well as the combination of these two strategies with other methods like the application of Reldan and fumigation once a year resulted in no economic losses, making these strategies cost-effective.

The strategies chosen for this project are representative of the ones a firm might choose to implement, depending on sampling, environmental conditions and/or previous experiences. It is not assumed (in the case of an IPM approach) that an elevator will use the same strategy year after year. The strategy that elevator managers ultimately adopt will be a result of several decisions contingent on previous circumstances.

CHAPTER FIVE

SUMMARY AND SUGGESTIONS FOR FURTHER RESEARCH

Objective one was accomplished using a spreadsheet model to calculate costs of thirteen IPM and conventional pest management strategies. Costs considered included labor, electricity, fumigant, and protectant. The final costs were computed on a dollar per bushel basis, and compared across the strategies. Costs were also computed for all strategies assuming that elevator managers had already purchased all the equipment. Sensitivity analysis for all the strategies was performed, using cost increments of 25, 50, 70, 100 and 200 percent for labor, electricity, fumigant and labor.

The costs of the strategies in the base model, from least to most expensive are as follows: controlled aeration and sanitation at 1.16¢/bu.; one closed-loop fumigation at 2.06¢/bu.; controlled aeration plus sanitation and one insect sampling at 2.60¢/bu.; one fumigation with turning at 2.67¢/bu.; mechanical cleaning plus controlled aeration and sanitation at 3.16¢/bu.; controlled aeration, sanitation and two insect samplings at 3.33¢/bu.; controlled aeration, sanitation and grain protectant application at 3.36¢/bu.; manual aeration in evening hours, sanitation and grain protectant application at 3.46¢/bu.; three closed-loop fumigations at 3.54¢/bu.; controlled aeration, sanitation, 1 insect sampling and half of the bins fumigated using closed-loop fumigation at 4.10¢/bu.; controlled aeration, sanitation, one insect sampling and half of the bins fumigated at 4.15¢/bu.; controlled aeration, sanitation, one closed-loop fumigation and grain protectant application at 5.41¢/bu.; and three fumigations with turning, at 7.15¢/bu.

These results suggest that:

1. Closed-loop fumigation is more economical than non-closed loop fumigation even after accounting for installation costs.
2. Strategies using the grain protectant Reldan are the most expensive strategies.
3. Effective, accurate sampling is labor intensive, making it the most costly component of the IPM strategies.

Sensitivity analysis indicated that parameters had greatest impact on the costs of the strategies that most heavily employed them.

Objective two was accomplished using an insect growth model to predict effectiveness of the strategies. Strategies evaluated were no control, manual aeration, controlled aeration, fumigating once a year, application of a grain protectant, manual aeration plus the application of a grain protectant, controlled aeration plus the application of a grain protectant, and controlled aeration plus fumigating once a year. Manual and controlled aerations alone, as well as the combination of these methods with others like applying protectant or fumigating once a year were effective, whereas choosing not to do anything or "fumigation-only" strategies resulted in economic losses.

Pesticides cause externalities, so their use is likely excessive (Feder 1979). Thus there are potential social benefits from reducing insecticide use. Also, reducing insecticide use should lessen potential problems with insect resistance. Both of these benefits should be considered in future research. Grain elevator managers have been reluctant to adopt IPM strategies. One reason may be that they do not understand the risks associated with available strategies. Economic risks associated with IPM and conventional insect control strategies should be evaluated in future research.

The effectiveness of other strategies such as closed-loop fumigation, mechanical cleaning, sanitation or even sampling as part of an IPM method is unknown. The effectiveness of theses strategies should be considered in further research.

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APPENDICES

APPENDIX A

Appendix A.1. Base Model Values for the Facility Description Worksheet.

Location	Hydro
Bin Type	Concrete
Number of bins	10
Bin Size	26,000 bu.
Units stored	25,000 bu.
Total units stored	250,000 bu.
Grain Price	$3.75/bu.
Initial Power Vac cost	$8000
Expected Power Vac life	10 yrs.
Closed loop fumigation system installation costs	$3125
Expected CL fumigation facility life	10 yrs.
Initial fumigation equipment cost	$3000
Initial fumigation monitoring device cost	$800
Annual fumigation monitor device recalibration cost	$50
Expected fumigation equipment life	10 yrs.
Equipment maintenance	5%
Equipment insurance	5%
Salvage Value	$0
Cost of capital	1%
PVIFA	6.145
Fan Horsepower	14.25 hp
Centrifugal Blower Horsepower	1 hp
Hourly labor cost	$16/hr.
Mechanical cleaning cost	$0.02/bu.
Sanitation costs	$0.005/bu.
Total grain protectant cost	$550
Grain protectant charge	$0.0220/bu.
Electricity cost	$0.07/kwhrs.
Fan Efficiency	74.8%
Fumigant type	tablets
Per flask	500 tablets
Flask/case	14 flasks
Tablets or pellets available	7000 tablets
Price per case	$300/case
Price per tablet or pellet	$0.04286/tablet
Dosage per 1000 bu.	120 tablets
Price of fumigant	$0.00514/bu.

Appendix A.2. Base Model Values for the Insect Sampling Worksheet.

Insect samples	10
Insect sampling labor	0.08 hrs.
Setup time	3 hrs.
Samplers	3 people
Insect Sampling labor charge	$0.00730/bu.
Sampling equipment cost	$0.00841/bu.

Appendix A.3. Base Model Values for the Aeration and Conditioning Worksheet.

This sheet assumes controlled aeration. Controlled aeration uses 50% less cooling hours that evening-only cooling. In the cost analysis sheet, the cost for both types of aeration will be calculated accordingly.

Moisture samples	10
Sampling labor	0.1 hrs.
Samplers	2 people
Conditioning labor	0.75 hrs.
Aeration season	Fall
Fans	1
Fan hours	40 hrs.
Shrink factor	0.001
Sampling labor charge	$0.00128/bu.
Conditioning labor charge	$0.00048/bu.
Electricity charge	$0.00213/bu.
Shrink loss charge	$0.004/bu.
Controlled Aeration Electricity charge	$0.00107/bu.

Appendix A.4. Base Model Values for the Fumigation Worksheet.

Number of in-season fumigations	1
Pre-unloading fumigation	1
Proportion of bins to be fumigated	0.5
Fumigant cost	$0.00514/bu.
Employees per fumigation crew	3 people
Training per employee	8 hrs.
Crew hours per fumigation	2 hrs.
Liability insurance	$0.0001/bu.
Fumigation Labor charge	$0.00384/bu.
Fumigation training charge	$0.00019/bu.
Fumigant charge	$0.00514/bu.
Fumigation equipment cost	$0.00403/bu.

Electricity and fumigant charges change if closed loop fumigation is used. An additional facility cost is added to the equipment used for fumigation.

Blower hours	48 hrs.
CL blower charge	$0.0001/bu.
CL facilities cost	$0.0089/bu.
CL fumigant charge	$0.0034/bu.

Appendix A.5. Base Model Values for the Fumigation Worksheet.

Grain turning	1
Man hours for turning grain	3 hrs.
Turning Labor charge	$0.00192/bu.
Grain turning electricity charge	$0.004/bu.
Turning shrink factor	0.00200
Grain turning shrink	$0.00750/bu.

Appendix A.6. Annual Operating Costs

One Fumigation with turning	$0.02773/bu.
Three fumigations with turning	$0.07253/bu.
One fumigation-Closed Loop	$0.02211/bu.
Three fumigations-Closed Loop	$0.03599/bu.
Controlled Aeration and sanitation	$0.01158/bu.
Controlled aeration, sanitation, 1 sampling	$0.02600/bu.
Controlled aeration, sanitation, 1 sampling, 1/2 of bins fumigated	$0.04213/bu.
Manual aeration in evening hours, sanitation, protectant	$0.03464/bu.
Controlled Aeration, sanitation, protectant	$0.03358/bu.
Controlled aeration, sanitation, 2 samplings	$0.03330/bu.
Controlled Aeration, sanitation, 1 sampling, 1/2 of bins fumigated, closed loop	$0.04156/bu.
Controlled aeration, sanitation, closed loop fumigation, protectant	$0.05470/bu.
Mechanical cleaning, controlled aeration, sanitation	$0.03158/bu.

APPENDIX B

Appendix B.1. Operating Cost Sensitivity of Strategies With a 25% Increase in Electricity Costs

STRATEGY	COSTS ($/bu.) Labor	Chemicals	Aeration	Turning	Equipment	Liability Insurance	Sanitation	Total Costs
Fumigation (with turning)	0.0046	0.0051	0.0000	0.0134	0.0040	0.0001	0.0000	0.0273
Three fumigations (with turning)	0.0123	0.0154	0.0000	0.0403	0.0040	0.0001	0.0000	0.0721
Fumigation- Closed Loop	0.0046	0.0034	0.0001	0.0000	0.0129	0.0001	0.0000	0.0212
Three fumigations-Closed Loop	0.0123	0.0103	0.0004	0.0000	0.0073	0.0001	0.0000	0.0361
Controlled aeration, sanitation	0.0018	0.0000	0.0051	0.0000	0.0000	0.0000	0.0050	0.0118
Controlled aeration, sanitation, 1 sampling	0.0078	0.0000	0.0051	0.0000	0.0084	0.0000	0.0050	0.0263
Controlled aeration, sanitation, 1 sampling, 1/2 of bins fumigated	0.0114	0.0026	0.0051	0.0058	0.0124	0.0001	0.0050	0.0424
Manual aeration in evening hours, sanitation, protectant	0.0018	0.0220	0.0064	0.0000	0.0000	0.0000	0.0050	0.0352
Controlled aeration, sanitation, protectant	0.0018	0.0220	0.0051	0.0000	0.0000	0.0000	0.0050	0.0338
Controlled aeration, sanitation, 2 samplings	0.0151	0.0000	0.0051	0.0000	0.0084	0.0000	0.0050	0.0336
Controlled aeration, sanitation, 1 sampling, 1/2 of bins fumigated closed-loop	0.0086	0.0017	0.0051	0.0000	0.0214	0.0001	0.0050	0.0418
Controlled aeration, sanitation, closed-loop fumigation, protectant	0.0064	0.0254	0.0051	0.0000	0.0129	0.0001	0.0050	0.0550
Mechanical cleaning, controlled aeration, sanitation	0.0018	0.0000	0.0051	0.0000	0.0200	0.0000	0.0050	0.0318

Appendix B.2. Operating Cost Sensitivity of Strategies With a 50% Increase in Electricity Costs

			COSTS ($/bu.)					
STRATEGY	**Labor**	**Chemicals**	**Aeration**	**Turning**	**Equipment**	**Liability Insurance**	**Sanitation**	**Total Costs**
Fumigation (with turning)	0.0046	0.0051	0.0000	0.0134	0.0040	0.0001	0.0000	0.0273
Three fumigations (with turning)	0.0123	0.0154	0.0000	0.0403	0.0040	0.0001	0.0000	0.0721
Fumigation- Closed Loop	0.0046	0.0034	0.0002	0.0000	0.0129	0.0001	0.0000	0.0213
Three fumigations-Closed Loop	0.0123	0.0103	0.0005	0.0000	0.0129	0.0001	0.0000	0.0361
Controlled aeration, sanitation	0.0018	0.0000	0.0054	0.0000	0.0000	0.0000	0.0050	0.0121
Controlled aeration, sanitation, 1 sampling	0.0078	0.0000	0.0054	0.0000	0.0084	0.0000	0.0050	0.0265
Controlled aeration, sanitation, 1 sampling, 1/2 of bins fumigated	0.0114	0.0026	0.0054	0.0058	0.0124	0.0001	0.0050	0.0427
Manual aeration in evening hours, sanitation, protectant	0.0018	0.0220	0.0070	0.0000	0.0000	0.0000	0.0050	0.0357
Controlled aeration, sanitation, protectant	0.0018	0.0220	0.0054	0.0000	0.0000	0.0000	0.0050	0.0341
Controlled aeration, sanitation, 2 samplings	0.0151	0.0000	0.0054	0.0000	0.0084	0.0000	0.0050	0.0338
Controlled aeration, sanitation, 1 sampling, 1/2 of bins fumigated closed-loop	0.0086	0.0017	0.0054	0.0000	0.0214	0.0001	0.0050	0.0421
Controlled aeration, sanitation, closed-loop fumigation, protectant	0.0064	0.0254	0.0054	0.0000	0.0129	0.0001	0.0050	0.0552
Mechanical cleaning, controlled aeration, sanitation	0.0018	0.0000	0.0054	0.0000	0.0200	0.0000	0.0050	0.0321

Appendix B.3. Operating Cost Sensitivity of Strategies With a 75% Increase in Electricity Costs

STRATEGY	COSTS ($/bu.)							
	Labor	Chemicals	Aeration	Turning	Equipment	Liability Insurance	Sanitation	Total Costs
Fumigation (with turning)	0.0046	0.0051	0.0000	0.0134	0.0040	0.0001	0.0000	0.0273
Three fumigations (with turning)	0.0123	0.0154	0.0000	0.0403	0.0040	0.0001	0.0000	0.0721
Fumigation- Closed Loop	0.0046	0.0034	0.0002	0.0000	0.0129	0.0001	0.0000	0.0213
Three fumigations-Closed Loop	0.0123	0.0103	0.0005	0.0000	0.0129	0.0001	0.0000	0.0362
Controlled aeration, sanitation	0.0018	0.0000	0.0056	0.0000	0.0000	0.0000	0.0050	0.0124
Controlled aeration, sanitation, 1 sampling	0.0078	0.0000	0.0056	0.0000	0.0084	0.0000	0.0050	0.0268
Controlled aeration, sanitation, 1 sampling, 1/2 of bins fumigated	0.0114	0.0026	0.0056	0.0058	0.0124	0.0001	0.0050	0.0429
Manual aeration in evening hours, sanitation, protectant	0.0018	0.0220	0.0075	0.0000	0.0000	0.0000	0.0050	0.0362
Controlled aeration, sanitation, protectant	0.0018	0.0220	0.0056	0.0000	0.0000	0.0000	0.0050	0.0344
Controlled aeration, sanitation, 2 samplings	0.0151	0.0000	0.0056	0.0000	0.0084	0.0000	0.0050	0.0341
Controlled aeration, sanitation, 1 sampling, 1/2 of bins fumigated closed-loop	0.0086	0.0017	0.0056	0.0000	0.0214	0.0001	0.0050	0.0424
Controlled aeration, sanitation, closed-loop fumigation, protectant	0.0064	0.0254	0.0056	0.0000	0.0129	0.0001	0.0050	0.0555
Mechanical cleaning, controlled aeration, sanitation	0.0018	0.0000	0.0056	0.0000	0.0200	0.0000	0.0050	0.0324

Appendix B.4. Operating Cost Sensitivity of Strategies With a 100% Increase in Electricity Costs

STRATEGY	COSTS ($/bu.) Labor	Chemicals	Aeration	Turning	Equipment	Liability Insurance	Sanitation	Total Costs
Fumigation (with turning)	0.0046	0.0051	0.0000	0.0134	0.0040	0.0001	0.0000	0.0273
Three fumigations (with turning)	0.0123	0.0154	0.0000	0.0403	0.0040	0.0001	0.0000	0.0721
Fumigation- Closed Loop	0.0046	0.0034	0.0002	0.0000	0.0129	0.0001	0.0000	0.0213
Three fumigations-Closed Loop	0.0123	0.0103	0.0006	0.0000	0.0129	0.0001	0.0000	0.0363
Controlled aeration, sanitation	0.0018	0.0000	0.0059	0.0000	0.0000	0.0000	0.0050	0.0126
Controlled aeration, sanitation, 1 sampling	0.0078	0.0000	0.0059	0.0000	0.0084	0.0000	0.0050	0.0271
Controlled aeration, sanitation, 1 sampling, 1/2 of bins fumigated	0.0114	0.0026	0.0059	0.0058	0.0124	0.0001	0.0050	0.0432
Manual aeration in evening hours, sanitation, protectant	0.0018	0.0220	0.0080	0.0000	0.0000	0.0000	0.0050	0.0368
Controlled aeration, sanitation, protectant	0.0018	0.0220	0.0059	0.0000	0.0000	0.0000	0.0050	0.0346
Controlled aeration, sanitation, 2 samplings	0.0151	0.0000	0.0059	0.0000	0.0084	0.0000	0.0050	0.0344
Controlled aeration, sanitation, 1 sampling, 1/2 of bins fumigated closed-loop	0.0086	0.0017	0.0059	0.0000	0.0214	0.0001	0.0050	0.0426
Controlled aeration, sanitation, closed-loop fumigation, protectant	0.0064	0.0254	0.0059	0.0000	0.0129	0.0001	0.0050	0.0558
Mechanical cleaning, controlled aeration, sanitation	0.0018	0.0000	0.0059	0.0000	0.0200	0.0000	0.0050	0.0326

Appendix B.5. Operating Cost Sensitivity of Strategies With a 200% Increase in Electricity Costs

STRATEGY	COSTS ($/bu.)							
	Labor	Chemicals	Aeration	Turning	Equipment	Liability Insurance	Sanitation	Total Costs
Fumigation (with turning)	0.0046	0.0051	0.0000	0.0134	0.0040	0.0001	0.0000	0.0273
Three fumigations (with turning)	0.0123	0.0154	0.0000	0.0403	0.0040	0.0001	0.0000	0.0721
Fumigation- Closed Loop	0.0046	0.0034	0.0003	0.0000	0.0129	0.0001	0.0000	0.0214
Three fumigations-Closed Loop	0.0123	0.0103	0.0009	0.0000	0.0129	0.0001	0.0000	0.0366
Controlled aeration, sanitation	0.0018	0.0000	0.0070	0.0000	0.0000	0.0000	0.0050	0.0137
Controlled aeration, sanitation, 1 sampling	0.0078	0.0000	0.0070	0.0000	0.0084	0.0000	0.0050	0.0281
Controlled aeration, sanitation, 1 sampling, 1/2 of bins fumigated	0.0114	0.0026	0.0070	0.0058	0.0124	0.0001	0.0050	0.0443
Manual aeration in evening hours, sanitation, protectant	0.0018	0.0220	0.0102	0.0000	0.0000	0.0000	0.0050	0.0389
Controlled aeration, sanitation, protectant	0.0018	0.0220	0.0070	0.0000	0.0000	0.0000	0.0050	0.0357
Controlled aeration, sanitation, 2 samplings	0.0151	0.0000	0.0070	0.0000	0.0084	0.0000	0.0050	0.0354
Controlled aeration, sanitation, 1 sampling, 1/2 of bins fumigated closed-loop	0.0086	0.0017	0.0070	0.0000	0.0214	0.0001	0.0050	0.0437
Controlled aeration, sanitation, closed-loop fumigation, protectant	0.0064	0.0254	0.0070	0.0000	0.0129	0.0001	0.0050	0.0568
Mechanical cleaning, controlled aeration, sanitation	0.0018	0.0000	0.0070	0.0000	0.0200	0.0000	0.0050	0.0337

Appendix B.6. Operating Cost Sensitivity of Strategies With a 25% Increase in Fumigant Costs

	COSTS ($/bu.)							
STRATEGY	**Labor**	**Chemicals**	**Aeration**	**Turning**	**Equipment**	**Liability Insurance**	**Sanitation**	**Total Costs**
Fumigation (with turning)	0.0046	0.0064	0.0000	0.0134	0.0040	0.0001	0.0000	0.0286
Three fumigations (with turning)	0.0123	0.0193	0.0000	0.0403	0.0040	0.0001	0.0000	0.0760
Fumigation- Closed Loop	0.0046	0.0043	0.0001	0.0000	0.0129	0.0001	0.0000	0.0221
Three fumigations-Closed Loop	0.0123	0.0129	0.0003	0.0000	0.0129	0.0001	0.0000	0.0386
Controlled aeration, sanitation	0.0018	0.0000	0.0048	0.0000	0.0000	0.0000	0.0050	0.0116
Controlled aeration, sanitation, 1 sampling	0.0078	0.0000	0.0048	0.0000	0.0084	0.0000	0.0050	0.0260
Controlled aeration, sanitation, 1 sampling, 1/2 of bins fumigated	0.0114	0.0032	0.0048	0.0058	0.0124	0.0001	0.0050	0.0428
Manual aeration in evening hours, sanitation, protectant	0.0018	0.0220	0.0059	0.0000	0.0000	0.0000	0.0050	0.0346
Controlled aeration, sanitation, protectant	0.0018	0.0220	0.0048	0.0000	0.0000	0.0000	0.0050	0.0336
Controlled aeration, sanitation, 2 samplings	0.0151	0.0000	0.0048	0.0000	0.0084	0.0000	0.0050	0.0333
Controlled aeration, sanitation, 1 sampling, 1/2 of bins fumigated closed-loop	0.0086	0.0022	0.0048	0.0000	0.0214	0.0001	0.0050	0.0420
Controlled aeration, sanitation, closed-loop fumigation, protectant	0.0064	0.0263	0.0048	0.0000	0.0129	0.0001	0.0050	0.0556
Mechanical cleaning, controlled aeration, sanitation	0.0018	0.0000	0.0048	0.0000	0.0200	0.0000	0.0050	0.0316

Appendix B.7. Operating Cost Sensitivity of Strategies With a 50% Increase in Fumigant

	COSTS ($/bu.)							
STRATEGY	**Labor**	**Chemicals**	**Aeration**	**Turning**	**Equipment**	**Liability Insurance**	**Sanitation**	**Total Costs**
Fumigation (with turning)	0.0046	0.0077	0.0000	0.0134	0.0040	0.0001	0.0000	0.0299
Three fumigations (with turning)	0.0123	0.0231	0.0000	0.0403	0.0040	0.0001	0.0000	0.0798
Fumigation- Closed Loop	0.0046	0.0052	0.0001	0.0000	0.0129	0.0001	0.0000	0.0229
Three fumigations-Closed Loop	0.0123	0.0155	0.0003	0.0000	0.0073	0.0001	0.0000	0.0412
Controlled aeration, sanitation	0.0018	0.0000	0.0048	0.0000	0.0000	0.0000	0.0050	0.0116
Controlled aeration, sanitation, 1 sampling	0.0078	0.0000	0.0048	0.0000	0.0084	0.0000	0.0050	0.0260
Controlled aeration, sanitation, 1 sampling, 1/2 of bins fumigated	0.0114	0.0039	0.0048	0.0058	0.0124	0.0001	0.0050	0.0434
Manual aeration in evening hours, sanitation, protectant	0.0018	0.0220	0.0059	0.0000	0.0000	0.0000	0.0050	0.0346
Controlled aeration, sanitation, protectant	0.0018	0.0220	0.0048	0.0000	0.0000	0.0000	0.0050	0.0336
Controlled aeration, sanitation, 2 samplings	0.0151	0.0000	0.0048	0.0000	0.0084	0.0000	0.0050	0.0333
Controlled aeration, sanitation, 1 sampling, 1/2 of bins fumigated closed-loop	0.0086	0.0026	0.0048	0.0000	0.0214	0.0001	0.0050	0.0424
Controlled aeration, sanitation, closed-loop fumigation, protectant	0.0064	0.0272	0.0048	0.0000	0.0129	0.0001	0.0050	0.0564
Mechanical cleaning, controlled aeration, sanitation	0.0018	0.0000	0.0048	0.0000	0.0200	0.0000	0.0050	0.0316

Appendix B.8. Operating Cost Sensitivity of Strategies With a 75% Increase in Fumigant Costs

	COSTS ($/bu.)							
STRATEGY	**Labor**	**Chemicals**	**Aeration**	**Turning**	**Equipment**	**Liability Insurance**	**Sanitation**	**Total Costs**
Fumigation (with turning)	0.0046	0.0090	0.0000	0.0134	0.0040	0.0001	0.0000	0.0312
Three fumigations (with turning)	0.0123	0.0270	0.0000	0.0403	0.0040	0.0001	0.0000	0.0837
Fumigation- Closed Loop	0.0046	0.0060	0.0001	0.0000	0.0129	0.0001	0.0000	0.0238
Three fumigations-Closed Loop	0.0123	0.0181	0.0003	0.0000	0.0129	0.0001	0.0000	0.0437
Controlled aeration, sanitation	0.0018	0.0000	0.0048	0.0000	0.0000	0.0000	0.0050	0.0116
Controlled aeration, sanitation, 1 sampling	0.0078	0.0000	0.0048	0.0000	0.0084	0.0000	0.0050	0.0260
Controlled aeration, sanitation, 1 sampling, 1/2 of bins fumigated	0.0114	0.0045	0.0048	0.0058	0.0124	0.0001	0.0050	0.0441
Manual aeration in evening hours, sanitation, protectant	0.0018	0.0220	0.0059	0.0000	0.0000	0.0000	0.0050	0.0346
Controlled aeration, sanitation, protectant	0.0018	0.0220	0.0048	0.0000	0.0000	0.0000	0.0050	0.0336
Controlled aeration, sanitation, 2 samplings	0.0151	0.0000	0.0048	0.0000	0.0084	0.0000	0.0050	0.0333
Controlled aeration, sanitation, 1 sampling, 1/2 of bins fumigated closed-loop	0.0086	0.0030	0.0048	0.0000	0.0214	0.0001	0.0050	0.0429
Controlled aeration, sanitation, closed-loop fumigation, protectant	0.0064	0.0280	0.0048	0.0000	0.0129	0.0001	0.0050	0.0573
Mechanical cleaning, controlled aeration, sanitation	0.0018	0.0000	0.0048	0.0000	0.0200	0.0000	0.0050	0.0316

Appendix B.9. Operating Cost Sensitivity of Strategies With a 100% Increase in Fumigant Costs

	COSTS ($/bu.)							
STRATEGY	**Labor**	**Chemicals**	**Aeration**	**Turning**	**Equipment**	**Liability Insurance**	**Sanitation**	**Total Costs**
Fumigation (with turning)	0.0046	0.0103	0.0000	0.0134	0.0040	0.0001	0.0000	0.0325
Three fumigations (with turning)	0.0123	0.0309	0.0000	0.0403	0.0040	0.0001	0.0000	0.0876
Fumigation- Closed Loop	0.0046	0.0069	0.0001	0.0000	0.0129	0.0001	0.0000	0.0247
Three fumigations-Closed Loop	0.0123	0.0207	0.0003	0.0000	0.0129	0.0001	0.0000	0.0463
Controlled aeration, sanitation	0.0018	0.0000	0.0048	0.0000	0.0000	0.0000	0.0050	0.0116
Controlled aeration, sanitation, 1 sampling	0.0078	0.0000	0.0048	0.0000	0.0084	0.0000	0.0050	0.0260
Controlled aeration, sanitation, 1 sampling, 1/2 of bins fumigated	0.0114	0.0051	0.0048	0.0058	0.0124	0.0001	0.0050	0.0447
Manual aeration in evening hours, sanitation, protectant	0.0018	0.0220	0.0059	0.0000	0.0000	0.0000	0.0050	0.0346
Controlled aeration, sanitation, protectant	0.0018	0.0220	0.0048	0.0000	0.0000	0.0000	0.0050	0.0336
Controlled aeration, sanitation, 2 samplings	0.0151	0.0000	0.0048	0.0000	0.0084	0.0000	0.0050	0.0333
Controlled aeration, sanitation, 1 sampling, 1/2 of bins fumigated closed-loop	0.0086	0.0034	0.0048	0.0000	0.0214	0.0001	0.0050	0.0433
Controlled aeration, sanitation, closed-loop fumigation, protectant	0.0064	0.0289	0.0048	0.0000	0.0129	0.0001	0.0050	0.0581
Mechanical cleaning, controlled aeration, sanitation	0.0018	0.0000	0.0048	0.0000	0.0200	0.0000	0.0050	0.0316

Appendix B.10. Operating Cost Sensitivity of Strategies With a 200% Increase in Fumigant Costs

STRATEGY	COSTS ($/bu.)							
	Labor	Chemicals	Aeration	Turning	Equipment	Liability Insurance	Sanitation	Total Costs
Fumigation (with turning)	0.0046	0.0154	0.0000	0.0134	0.0040	0.0001	0.0000	0.0376
Three fumigations (with turning)	0.0123	0.0463	0.0000	0.0403	0.0040	0.0001	0.0000	0.1030
Fumigation- Closed Loop	0.0046	0.0103	0.0001	0.0000	0.0129	0.0001	0.0000	0.0281
Three fumigations-Closed Loop	0.0123	0.0310	0.0003	0.0000	0.0129	0.0001	0.0000	0.0567
Controlled aeration, sanitation	0.0018	0.0000	0.0048	0.0000	0.0000	0.0000	0.0050	0.0116
Controlled aeration, sanitation, 1 sampling	0.0078	0.0000	0.0048	0.0000	0.0084	0.0000	0.0050	0.0260
Controlled aeration, sanitation, 1 sampling, 1/2 of bins fumigated	0.0114	0.0077	0.0048	0.0058	0.0124	0.0001	0.0050	0.0473
Manual aeration in evening hours, sanitation, protectant	0.0018	0.0220	0.0059	0.0000	0.0000	0.0000	0.0050	0.0346
Controlled aeration, sanitation, protectant	0.0018	0.0220	0.0048	0.0000	0.0000	0.0000	0.0050	0.0336
Controlled aeration, sanitation, 2 samplings	0.0151	0.0000	0.0048	0.0000	0.0084	0.0000	0.0050	0.0333
Controlled aeration, sanitation, 1 sampling, 1/2 of bins fumigated closed-loop	0.0086	0.0052	0.0048	0.0000	0.0214	0.0001	0.0050	0.0450
Controlled aeration, sanitation, closed-loop fumigation, protectant	0.0064	0.0323	0.0048	0.0000	0.0129	0.0001	0.0050	0.0616
Mechanical cleaning, controlled aeration, sanitation	0.0018	0.0000	0.0048	0.0000	0.0200	0.0000	0.0050	0.0316

Appendix B.11. Operating Cost Sensitivity of Strategies With a 25% Increase in Labor Costs

STRATEGY	COSTS ($/bu.) Labor	Chemicals	Aeration	Turning	Equipment	Liability Insurance	Sanitation	Total Costs
Fumigation (with turning)	0.0056	0.0051	0.0000	0.0139	0.0040	0.0001	0.0000	0.0288
Three fumigations (with turning)	0.0152	0.0154	0.0000	0.0417	0.0040	0.0001	0.0000	0.0765
Fumigation- Closed Loop	0.0056	0.0034	0.0001	0.0000	0.0129	0.0001	0.0000	0.0222
Three fumigations-Closed Loop	0.0152	0.0103	0.0003	0.0000	0.0129	0.0001	0.0000	0.0389
Controlled aeration, sanitation	0.0022	0.0000	0.0048	0.0000	0.0000	0.0000	0.0050	0.0120
Controlled aeration, sanitation, 1 sampling	0.0097	0.0000	0.0048	0.0000	0.0084	0.0000	0.0050	0.0279
Controlled aeration, sanitation, 1 sampling, 1/2 of bins fumigated	0.0142	0.0026	0.0048	0.0058	0.0124	0.0001	0.0050	0.0448
Manual aeration in evening hours, sanitation, protectant	0.0022	0.0220	0.0059	0.0000	0.0000	0.0000	0.0050	0.0351
Controlled aeration, sanitation, protectant	0.0022	0.0220	0.0048	0.0000	0.0000	0.0000	0.0050	0.0340
Controlled aeration, sanitation, 2 samplings	0.0188	0.0000	0.0048	0.0000	0.0084	0.0000	0.0050	0.0371
Controlled aeration, sanitation, 1 sampling, 1/2 of bins fumigated closed-loop	0.0106	0.0017	0.0048	0.0000	0.0214	0.0001	0.0050	0.0436
Controlled aeration, sanitation, closed-loop fumigation, protectant	0.0078	0.0254	0.0048	0.0000	0.0129	0.0001	0.0050	0.0561
Mechanical cleaning, controlled aeration, sanitation	0.0022	0.0000	0.0048	0.0000	0.0200	0.0000	0.0050	0.0320

Appendix B.12. Operating Cost Sensitivity of Strategies With a 50% Increase in Labor Costs

	COSTS ($/bu.)							
STRATEGY	**Labor**	**Chemicals**	**Aeration**	**Turning**	**Equipment**	**Liability Insurance**	**Sanitation**	**Total Costs**
Fumigation (with turning)	0.0066	0.0051	0.0000	0.0144	0.0040	0.0001	0.0000	0.0303
Three fumigations (with turning)	0.0182	0.0154	0.0000	0.0431	0.0040	0.0001	0.0000	0.0809
Fumigation- Closed Loop	0.0066	0.0034	0.0001	0.0000	0.0129	0.0001	0.0000	0.0232
Three fumigations-Closed Loop	0.0182	0.0103	0.0003	0.0000	0.0129	0.0001	0.0000	0.0418
Controlled aeration, sanitation	0.0026	0.0000	0.0048	0.0000	0.0000	0.0000	0.0050	0.0125
Controlled aeration, sanitation, 1 sampling	0.0117	0.0000	0.0048	0.0000	0.0084	0.0000	0.0050	0.0299
Controlled aeration, sanitation, 1 sampling, 1/2 of bins fumigated	0.0169	0.0026	0.0048	0.0058	0.0124	0.0001	0.0050	0.0476
Manual aeration in evening hours, sanitation, protectant	0.0026	0.0220	0.0059	0.0000	0.0000	0.0000	0.0050	0.0355
Controlled aeration, sanitation, protectant	0.0026	0.0220	0.0048	0.0000	0.0000	0.0000	0.0050	0.0345
Controlled aeration, sanitation, 2 samplings	0.0226	0.0000	0.0048	0.0000	0.0084	0.0000	0.0050	0.0408
Controlled aeration, sanitation, 1 sampling, 1/2 of bins fumigated closed-loop	0.0126	0.0017	0.0048	0.0000	0.0214	0.0001	0.0050	0.0455
Controlled aeration, sanitation, closed-loop fumigation, protectant	0.0093	0.0254	0.0048	0.0000	0.0129	0.0001	0.0050	0.0576
Mechanical cleaning, controlled aeration, sanitation	0.0026	0.0000	0.0048	0.0000	0.0200	0.0000	0.0050	0.0325

Appendix B.13. Operating Cost Sensitivity of Strategies With a 75% Increase in Labor Costs

STRATEGY	COSTS ($/bu.)							
	Labor	**Chemicals**	**Aeration**	**Turning**	**Equipment**	**Liability Insurance**	**Sanitation**	**Total Costs**
Fumigation (with turning)	0.0077	0.0051	0.0000	0.0149	0.0040	0.0001	0.0000	0.0318
Three fumigations (with turning)	0.0211	0.0154	0.0000	0.0446	0.0040	0.0001	0.0000	0.0852
Fumigation- Closed Loop	0.0077	0.0034	0.0001	0.0000	0.0129	0.0001	0.0000	0.0242
Three fumigations-Closed Loop	0.0211	0.0103	0.0003	0.0000	0.0129	0.0001	0.0000	0.0448
Controlled aeration, sanitation	0.0031	0.0000	0.0048	0.0000	0.0000	0.0000	0.0050	0.0129
Controlled aeration, sanitation, 1 sampling	0.0136	0.0000	0.0048	0.0000	0.0084	0.0000	0.0050	0.0318
Controlled aeration, sanitation, 1 sampling, 1/2 of bins fumigated	0.0196	0.0026	0.0048	0.0058	0.0124	0.0001	0.0050	0.0503
Manual aeration in evening hours, sanitation, protectant	0.0031	0.0220	0.0059	0.0000	0.0000	0.0000	0.0050	0.0360
Controlled aeration, sanitation, protectant	0.0031	0.0220	0.0048	0.0000	0.0000	0.0000	0.0050	0.0349
Controlled aeration, sanitation, 2 samplings	0.0264	0.0000	0.0048	0.0000	0.0084	0.0000	0.0050	0.0446
Controlled aeration, sanitation, 1 sampling, 1/2 of bins fumigated closed-loop	0.0145	0.0017	0.0048	0.0000	0.0214	0.0001	0.0050	0.0475
Controlled aeration, sanitation, closed-loop fumigation, protectant	0.0107	0.0254	0.0048	0.0000	0.0129	0.0001	0.0050	0.0590
Mechanical cleaning, controlled aeration, sanitation	0.0031	0.0000	0.0048	0.0000	0.0200	0.0000	0.0050	0.0329

Appendix B.14. Operating Cost Sensitivity of Strategies With a 100% Increase in Labor Costs

STRATEGY	COSTS ($/bu.) Labor	Chemicals	Aeration	Turning	Equipment	Liability Insurance	Sanitation	Total Costs
Fumigation (with turning)	0.0087	0.0051	0.0000	0.0153	0.0040	0.0001	0.0000	0.0333
Three fumigations (with turning)	0.0240	0.0154	0.0000	0.0460	0.0040	0.0001	0.0000	0.0896
Fumigation- Closed Loop	0.0087	0.0034	0.0001	0.0000	0.0129	0.0001	0.0000	0.0253
Three fumigations-Closed Loop	0.0240	0.0103	0.0003	0.0000	0.0129	0.0001	0.0000	0.0477
Controlled aeration, sanitation	0.0035	0.0000	0.0048	0.0000	0.0000	0.0000	0.0050	0.0133
Controlled aeration, sanitation, 1 sampling	0.0156	0.0000	0.0048	0.0000	0.0084	0.0000	0.0050	0.0338
Controlled aeration, sanitation, 1 sampling, 1/2 of bins fumigated	0.0223	0.0026	0.0048	0.0058	0.0124	0.0001	0.0050	0.0530
Manual aeration in evening hours, sanitation, protectant	0.0035	0.0220	0.0059	0.0000	0.0000	0.0000	0.0050	0.0364
Controlled aeration, sanitation, protectant	0.0035	0.0220	0.0048	0.0000	0.0000	0.0000	0.0050	0.0353
Controlled aeration, sanitation, 2 samplings	0.0301	0.0000	0.0048	0.0000	0.0084	0.0000	0.0050	0.0484
Controlled aeration, sanitation, 1 sampling, 1/2 of bins fumigated closed-loop	0.0165	0.0017	0.0048	0.0000	0.0214	0.0001	0.0050	0.0495
Controlled aeration, sanitation, closed-loop fumigation, protectant	0.0122	0.0254	0.0048	0.0000	0.0129	0.0001	0.0050	0.0605
Mechanical cleaning, controlled aeration, sanitation	0.0035	0.0000	0.0048	0.0000	0.0200	0.0000	0.0050	0.0333

Appendix B.15. Operating Cost Sensitivity of Strategies With a 200% Increase in Labor Costs

STRATEGY	COSTS ($/bu.) Labor	Chemicals	Aeration	Turning	Equipment	Liability Insurance	Sanitation	Total Costs
Fumigation (with turning)	0.0127	0.0051	0.0000	0.0173	0.0040	0.0001	0.0000	0.0392
Three fumigations (with turning)	0.0357	0.0154	0.0000	0.0518	0.0040	0.0001	0.0000	0.1071
Fumigation- Closed Loop	0.0127	0.0034	0.0001	0.0000	0.0129	0.0001	0.0000	0.0293
Three fumigations-Closed Loop	0.0357	0.0103	0.0003	0.0000	0.0129	0.0001	0.0000	0.0594
Controlled aeration, sanitation	0.0053	0.0000	0.0048	0.0000	0.0000	0.0000	0.0050	0.0151
Controlled aeration, sanitation, 1 sampling	0.0233	0.0000	0.0048	0.0000	0.0084	0.0000	0.0050	0.0416
Controlled aeration, sanitation, 1 sampling, 1/2 of bins fumigated	0.0331	0.0026	0.0048	0.0058	0.0124	0.0001	0.0050	0.0638
Manual aeration in evening hours, sanitation, protectant	0.0053	0.0220	0.0059	0.0000	0.0000	0.0000	0.0050	0.0382
Controlled aeration, sanitation, protectant	0.0053	0.0220	0.0048	0.0000	0.0000	0.0000	0.0050	0.0371
Controlled aeration, sanitation, 2 samplings	0.0452	0.0000	0.0048	0.0000	0.0084	0.0000	0.0050	0.0634
Controlled aeration, sanitation, 1 sampling, 1/2 of bins fumigated closed-loop	0.0245	0.0017	0.0048	0.0000	0.0214	0.0001	0.0050	0.0575
Controlled aeration, sanitation, closed-loop fumigation, protectant	0.0180	0.0254	0.0048	0.0000	0.0129	0.0001	0.0050	0.0663
Mechanical cleaning, controlled aeration, sanitation	0.0053	0.0000	0.0048	0.0000	0.0200	0.0000	0.0050	0.0351

Appendix B.16. Operating Cost Sensitivity of Strategies With a 25% Increase in Protectant Costs

STRATEGY	COSTS ($/bu.) Labor	Chemicals	Aeration	Turning	Equipment	Liability Insurance	Sanitation	Total Costs
Fumigation (with turning)	0.0046	0.0051	0.0000	0.0134	0.0040	0.0001	0.0000	0.0273
Three fumigations (with turning)	0.0123	0.0154	0.0000	0.0403	0.0040	0.0001	0.0000	0.0721
Fumigation- Closed Loop	0.0046	0.0034	0.0001	0.0000	0.0129	0.0001	0.0000	0.0212
Three fumigations-Closed Loop	0.0123	0.0103	0.0003	0.0000	0.0129	0.0001	0.0000	0.0360
Controlled aeration, sanitation	0.0018	0.0000	0.0048	0.0000	0.0000	0.0000	0.0050	0.0116
Controlled aeration, sanitation, 1 sampling	0.0078	0.0000	0.0048	0.0000	0.0084	0.0000	0.0050	0.0260
Controlled aeration, sanitation, 1 sampling, 1/2 of bins fumigated	0.0114	0.0026	0.0048	0.0058	0.0124	0.0001	0.0050	0.0421
Manual aeration in evening hours, sanitation, protectant	0.0018	0.0275	0.0059	0.0000	0.0000	0.0000	0.0050	0.0402
Controlled aeration, sanitation, protectant	0.0018	0.0275	0.0048	0.0000	0.0000	0.0000	0.0050	0.0391
Controlled aeration, sanitation, 2 samplings	0.0151	0.0000	0.0048	0.0000	0.0084	0.0000	0.0050	0.0333
Controlled aeration, sanitation, 1 sampling, 1/2 of bins fumigated closed-loop	0.0086	0.0017	0.0048	0.0000	0.0214	0.0001	0.0050	0.0416
Controlled aeration, sanitation, closed-loop fumigation, protectant	0.0064	0.0310	0.0048	0.0000	0.0129	0.0001	0.0050	0.0602
Mechanical cleaning, controlled aeration, sanitation	0.0018	0.0000	0.0048	0.0000	0.0200	0.0000	0.0050	0.0316

Appendix B.17. Operating Cost Sensitivity of Strategies With a 50% Increase in Protectant Costs

STRATEGY	COSTS ($/bu.) Labor	Chemicals	Aeration	Turning	Equipment	Liability Insurance	Sanitation	Total Costs
Fumigation (with turning)	0.0046	0.0051	0.0000	0.0134	0.0040	0.0001	0.0000	0.0273
Three fumigations (with turning)	0.0123	0.0154	0.0000	0.0403	0.0040	0.0001	0.0000	0.0721
Fumigation- Closed Loop	0.0046	0.0034	0.0001	0.0000	0.0129	0.0001	0.0000	0.0212
Three fumigations-Closed Loop	0.0123	0.0103	0.0003	0.0000	0.0129	0.0001	0.0000	0.0360
Controlled aeration, sanitation	0.0018	0.0000	0.0048	0.0000	0.0000	0.0000	0.0050	0.0116
Controlled aeration, sanitation, 1 sampling	0.0078	0.0000	0.0048	0.0000	0.0084	0.0000	0.0050	0.0260
Controlled aeration, sanitation, 1 sampling, 1/2 of bins fumigated	0.0114	0.0026	0.0048	0.0058	0.0124	0.0001	0.0050	0.0421
Manual aeration in evening hours, sanitation, protectant	0.0018	0.0310	0.0059	0.0000	0.0000	0.0000	0.0050	0.0436
Controlled aeration, sanitation, protectant	0.0018	0.0310	0.0048	0.0000	0.0000	0.0000	0.0050	0.0426
Controlled aeration, sanitation, 2 samplings	0.0151	0.0000	0.0048	0.0000	0.0084	0.0000	0.0050	0.0333
Controlled aeration, sanitation, 1 sampling, 1/2 of bins fumigated closed-loop	0.0086	0.0017	0.0048	0.0000	0.0214	0.0001	0.0050	0.0416
Controlled aeration, sanitation, closed-loop fumigation, protectant	0.0064	0.0344	0.0048	0.0000	0.0129	0.0001	0.0050	0.0637
Mechanical cleaning, controlled aeration, sanitation	0.0018	0.0000	0.0048	0.0000	0.0200	0.0000	0.0050	0.0316

Appendix B.18. Operating Cost Sensitivity of Strategies With a 75 % Increase in Protectant Costs

	COSTS ($/bu.)							
STRATEGY	**Labor**	**Chemicals**	**Aeration**	**Turning**	**Equipment**	**Liability Insurance**	**Sanitation**	**Total Costs**
Fumigation (with turning)	0.0046	0.0051	0.0000	0.0134	0.0040	0.0001	0.0000	0.0273
Three fumigations (with turning)	0.0123	0.0154	0.0000	0.0403	0.0040	0.0001	0.0000	0.0721
Fumigation- Closed Loop	0.0046	0.0034	0.0001	0.0000	0.0129	0.0001	0.0000	0.0212
Three fumigations-Closed Loop	0.0123	0.0103	0.0003	0.0000	0.0129	0.0001	0.0000	0.0360
Controlled aeration, sanitation	0.0018	0.0000	0.0048	0.0000	0.0000	0.0000	0.0050	0.0116
Controlled aeration, sanitation, 1 sampling	0.0078	0.0000	0.0048	0.0000	0.0084	0.0000	0.0050	0.0260
Controlled aeration, sanitation, 1 sampling, 1/2 of bins fumigated	0.0114	0.0026	0.0048	0.0058	0.0124	0.0001	0.0050	0.0421
Manual aeration in evening hours, sanitation, protectant	0.0018	0.0385	0.0059	0.0000	0.0000	0.0000	0.0050	0.0512
Controlled aeration, sanitation, protectant	0.0018	0.0385	0.0048	0.0000	0.0000	0.0000	0.0050	0.0501
Controlled aeration, sanitation, 2 samplings	0.0151	0.0000	0.0048	0.0000	0.0084	0.0000	0.0050	0.0333
Controlled aeration, sanitation, 1 sampling, 1/2 of bins fumigated closed-loop	0.0086	0.0017	0.0048	0.0000	0.0214	0.0001	0.0050	0.0416
Controlled aeration, sanitation, closed-loop fumigation, protectant	0.0064	0.0420	0.0048	0.0000	0.0129	0.0001	0.0050	0.0712
Mechanical cleaning, controlled aeration, sanitation	0.0018	0.0000	0.0048	0.0000	0.0200	0.0000	0.0050	0.0316

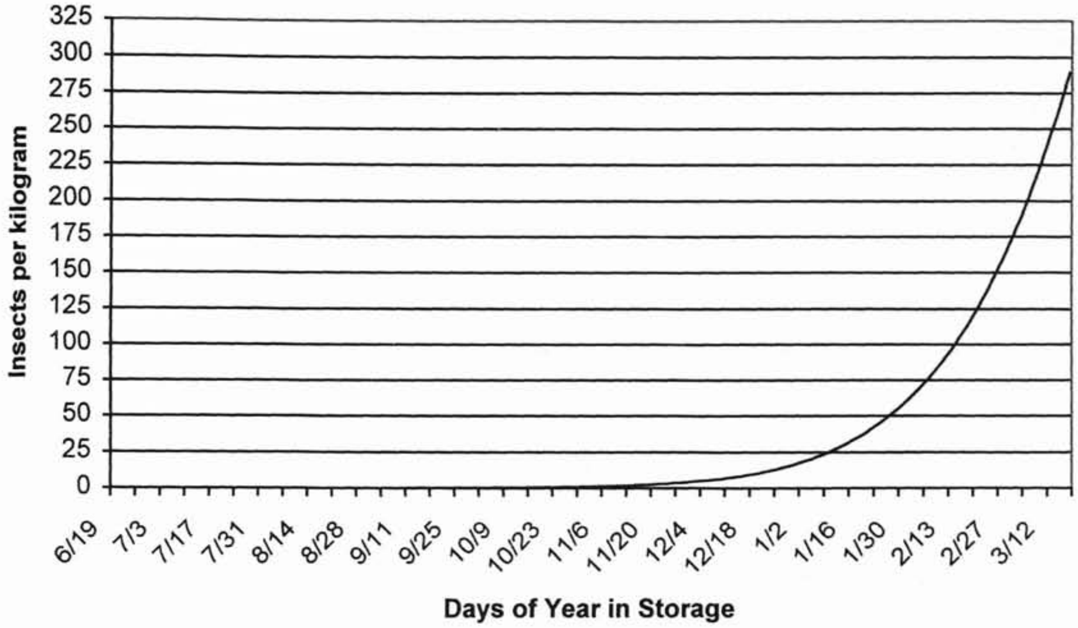
Appendix B.19. Operating Cost Sensitivity of Strategies With a 100% Increase in Protectant Costs

	COSTS ($/bu.)							
STRATEGY	**Labor**	**Chemicals**	**Aeration**	**Turning**	**Equipment**	**Liability Insurance**	**Sanitation**	**Total Costs**
Fumigation (with turning)	0.0046	0.0051	0.0000	0.0134	0.0040	0.0001	0.0000	0.0273
Three fumigations (with turning)	0.0123	0.0154	0.0000	0.0403	0.0040	0.0001	0.0000	0.0721
Fumigation- Closed Loop	0.0046	0.0034	0.0001	0.0000	0.0129	0.0001	0.0000	0.0212
Three fumigations-Closed Loop	0.0123	0.0103	0.0003	0.0000	0.0129	0.0001	0.0000	0.0360
Controlled aeration, sanitation	0.0018	0.0000	0.0048	0.0000	0.0000	0.0000	0.0050	0.0116
Controlled aeration, sanitation, 1 sampling	0.0078	0.0000	0.0048	0.0000	0.0084	0.0000	0.0050	0.0260
Controlled aeration, sanitation, 1 sampling, 1/2 of bins fumigated	0.0114	0.0026	0.0048	0.0058	0.0124	0.0001	0.0050	0.0421
Manual aeration in evening hours, sanitation, protectant	0.0018	0.0440	0.0059	0.0000	0.0000	0.0000	0.0050	0.0566
Controlled aeration, sanitation, protectant	0.0018	0.0440	0.0048	0.0000	0.0000	0.0000	0.0050	0.0556
Controlled aeration, sanitation, 2 samplings	0.0151	0.0000	0.0048	0.0000	0.0084	0.0000	0.0050	0.0333
Controlled aeration, sanitation, 1 sampling, 1/2 of bins fumigated closed-loop	0.0086	0.0017	0.0048	0.0000	0.0214	0.0001	0.0050	0.0416
Controlled aeration, sanitation, closed-loop fumigation, protectant	0.0064	0.0474	0.0048	0.0000	0.0129	0.0001	0.0050	0.0767
Mechanical cleaning, controlled aeration, sanitation	0.0018	0.0000	0.0048	0.0000	0.0200	0.0000	0.0050	0.0316

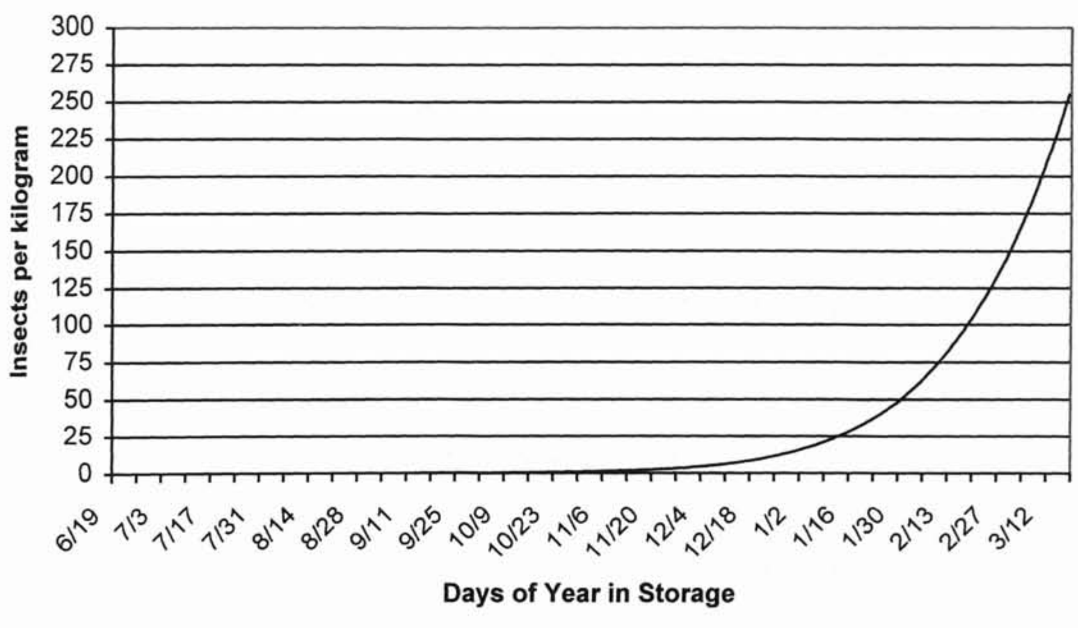
Appendix B.20. Operating Cost Sensitivity of Strategies With a 200% Increase in Protectant Costs

STRATEGY	COSTS ($/bu.) Labor	Chemicals	Aeration	Turning	Equipment	Liability Insurance	Sanitation	Total Costs
Fumigation (with turning)	0.0046	0.0051	0.0000	0.0134	0.0040	0.0001	0.0000	0.0273
Three fumigations (with turning)	0.0123	0.0154	0.0000	0.0403	0.0040	0.0001	0.0000	0.0721
Fumigation- Closed Loop	0.0046	0.0034	0.0001	0.0000	0.0129	0.0001	0.0000	0.0212
Three fumigations-Closed Loop	0.0123	0.0103	0.0003	0.0000	0.0129	0.0001	0.0000	0.0360
Controlled aeration, sanitation	0.0018	0.0000	0.0048	0.0000	0.0000	0.0000	0.0050	0.0116
Controlled aeration, sanitation, 1 sampling	0.0078	0.0000	0.0048	0.0000	0.0084	0.0000	0.0050	0.0260
Controlled aeration, sanitation, 1 sampling, 1/2 of bins fumigated	0.0114	0.0026	0.0048	0.0058	0.0124	0.0001	0.0050	0.0421
Manual aeration in evening hours, sanitation, protectant	0.0018	0.0660	0.0059	0.0000	0.0000	0.0000	0.0050	0.0786
Controlled aeration, sanitation, protectant	0.0018	0.0660	0.0048	0.0000	0.0000	0.0000	0.0050	0.0776
Controlled aeration, sanitation, 2 samplings	0.0151	0.0000	0.0048	0.0000	0.0084	0.0000	0.0050	0.0333
Controlled aeration, sanitation, 1 sampling, 1/2 of bins fumigated closed-loop	0.0086	0.0017	0.0048	0.0000	0.0214	0.0001	0.0050	0.0416
Controlled aeration, sanitation, closed-loop fumigation, protectant	0.0064	0.0694	0.0048	0.0000	0.0129	0.0001	0.0050	0.0987
Mechanical cleaning, controlled aeration, sanitation	0.0018	0.0000	0.0048	0.0000	0.0200	0.0000	0.0050	0.0316

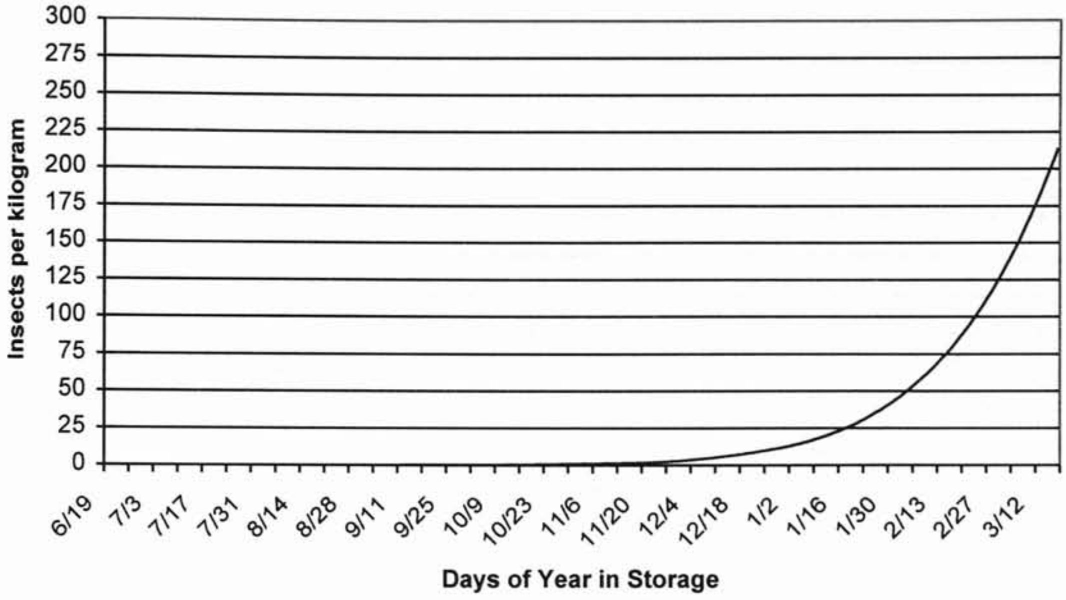
APPENDIX C.



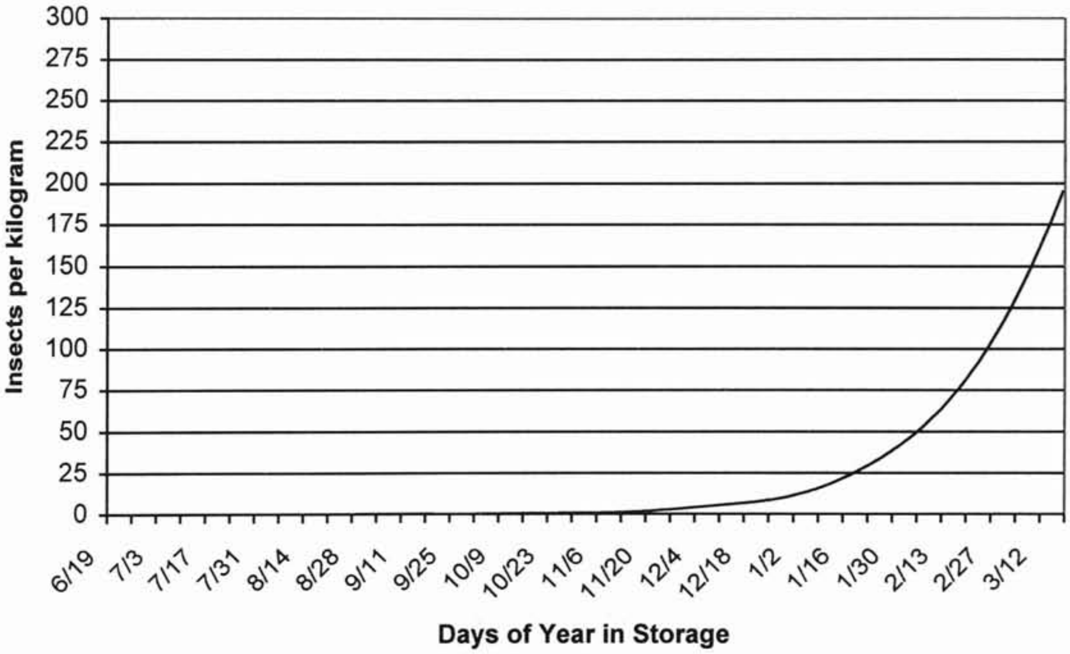
Appendix C.1. Average number of live insects per kilogram after fumigating in July 1



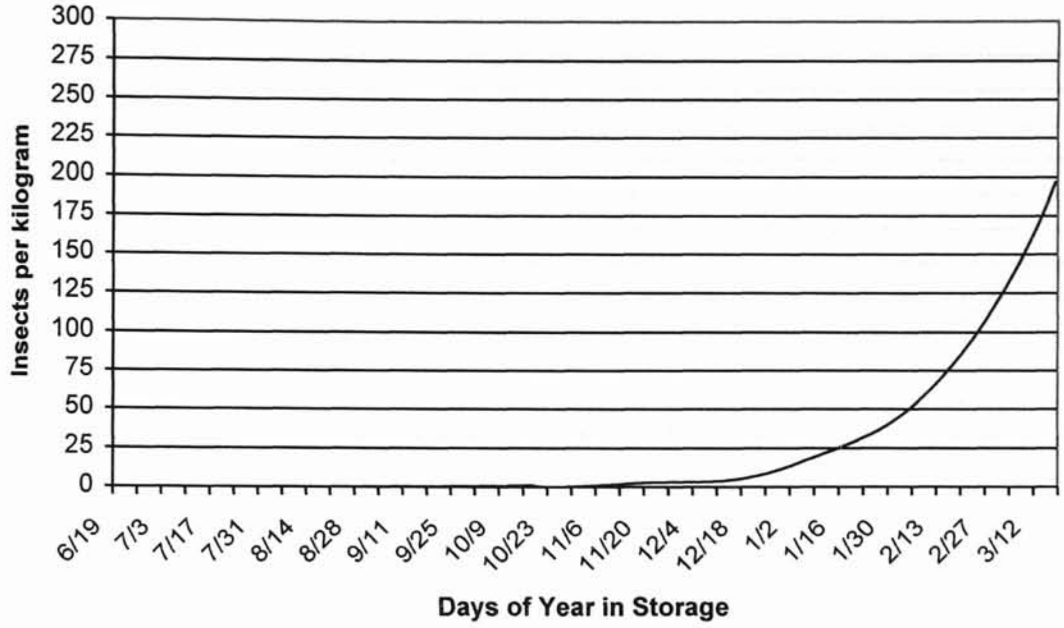
Appendix C.2. Average number of live insects per kilogram after fumigating on July 20



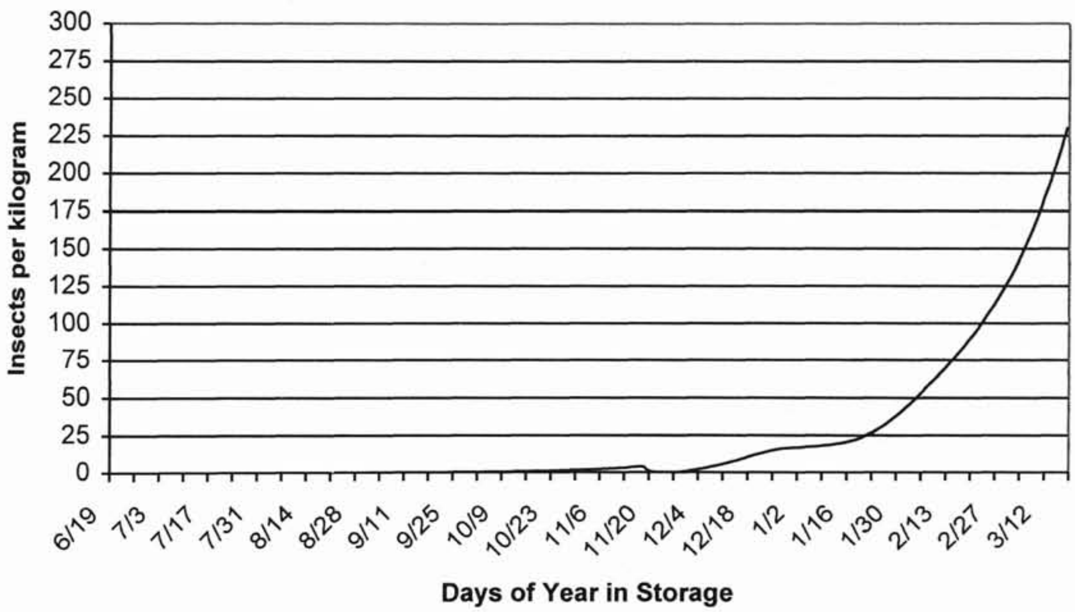
Appendix C.3. Average number of live insects per kilogram after fumigating on August 20



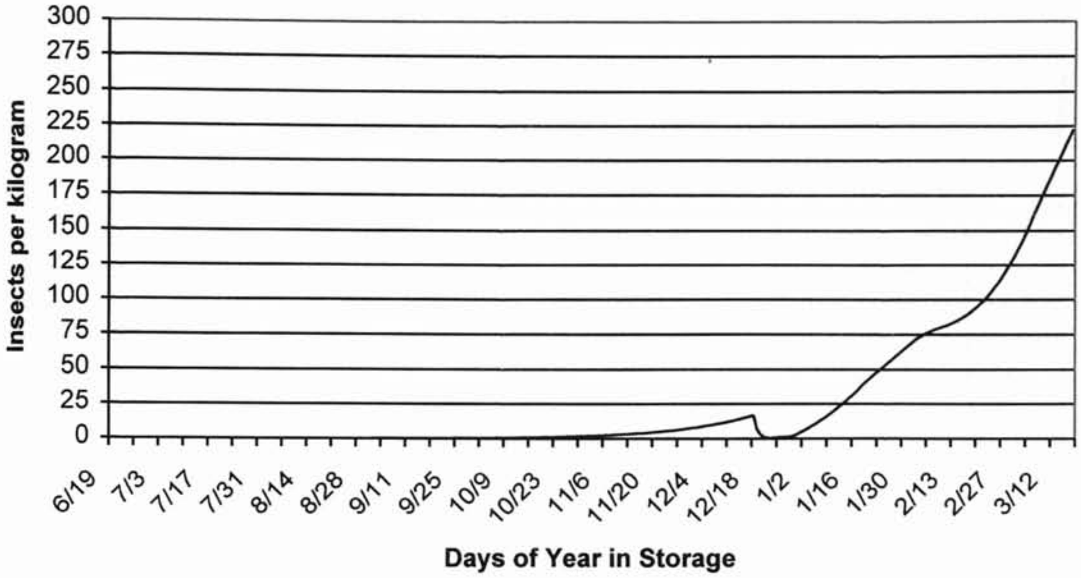
Appendix C.4. Average number of live insects per kilogram after fumigating in September 20



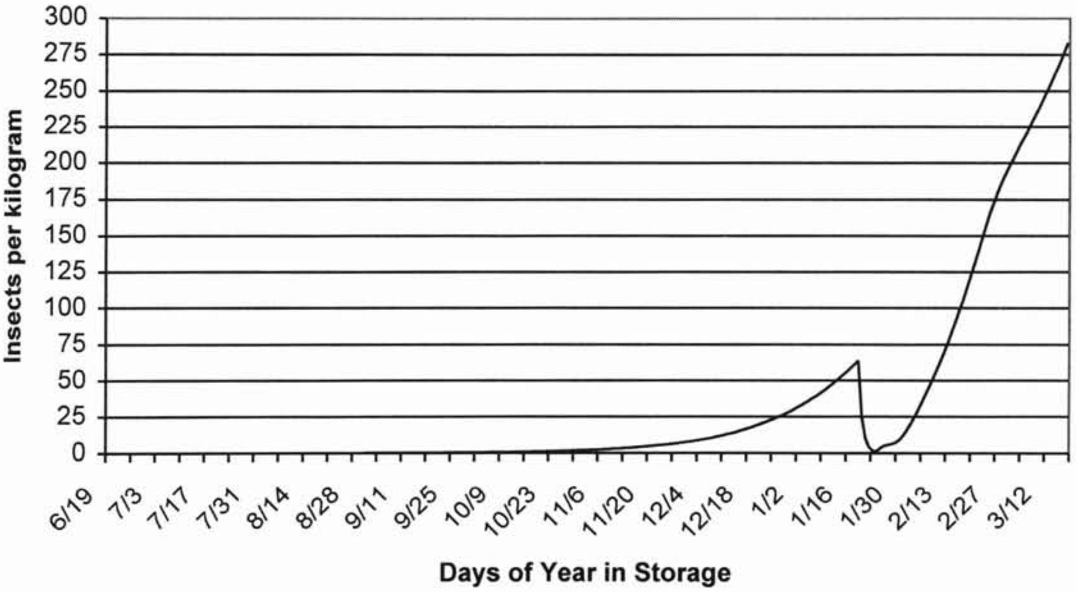
Appendix C.5. Average number of live insects per kilogram after fumigating in October 20



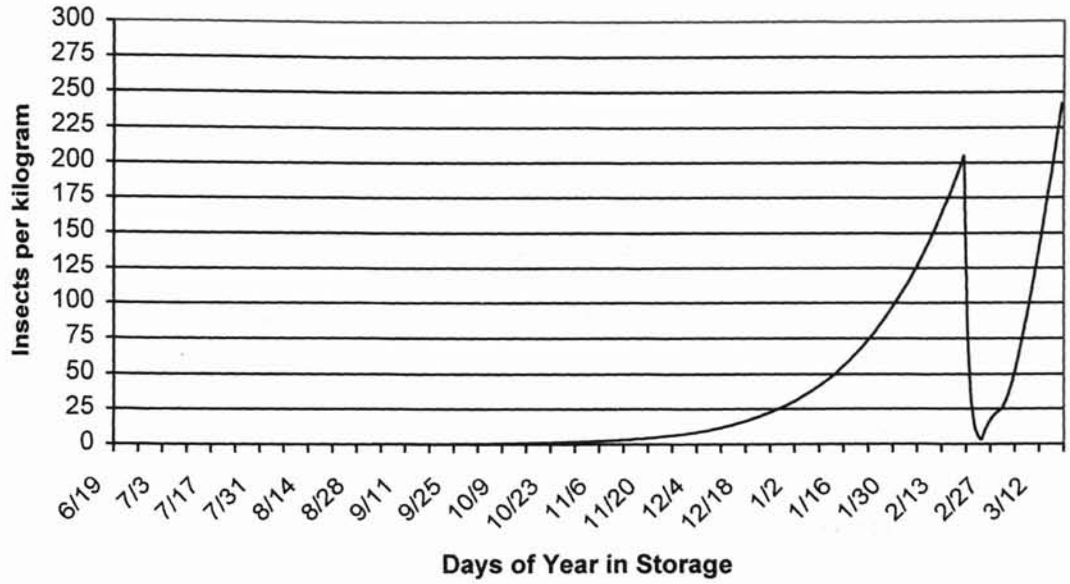
Appendix C.6. Average number of live insects per kilogram after fumigating in November 20



Appendix C.7. Average number of live insects per kilogram after fumigating on December 20



Appendix C.8. Average number of live insects per kilogram after fumigating in January 20



Appendix C.9. Average number of live insects per kilogram after fumigating in February 20

VITA 2

Tamara L Lukens

Candidate for the Degree of

Master of Science

Thesis: COST AND EFFECTIVENESS OF INTEGRATED PEST MANAGEMENT STRATEGIES COMPARED TO CHEMICAL-BASED METHODS IN STORED WHEAT

Major Field: Agricultural Economics

Biographical:

Personal Data: Born in Guayaquil, Ecuador on September 9, 1977. Daughter of Jeannine Flores and Jerry Barona.

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Experience: Employed by the Office of International Programs and by the Office of International Students and Scholars at Oklahoma State University as an undergraduate student. Employed as a graduate research assistant at Oklahoma State University; Department of Agricultural Economics, 2000-2002.