INSECT CONTROL UNDER UNCERTAINTY: ECONOMICAL STRATEGIES THAT ARE ROBUST TO VARYING WEATHER CONDITIONS AND INSECT IMMIGRATION RATES

By

SULING DUAN

Bachelor of Science in Turfgrass Management

Michigan State University

East Lansing, Michigan

2010

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
July, 2014

INSECT CONTROL UNDER UNCERTAINTY:

ECONOMICAL STRATEGIES THAT ARE ROBUST TO

VARYING WEATHER CONDITIONS AND INSECT

IMMIGRATION RATES

Thesis Approved:

Dr. Brian Adam

Thesis Adviser

Dr. Jeffrey Vitale

Dr. Rodney Holcomb

ACKNOWLEDGEMENTS

At the outset, I would like to thank my advisor Dr. Brian D. Adam, for his patience and guidance. I enjoy very much working under him and it was an excellent learning experience for me. I appreciate him for teaching me how to think about a problem, how to get a new idea to solve the problem and how to validate my idea. I would also like to thank him for helping me out with great patience in writing this thesis, for guiding me and giving me tips on structure, grammar, sentence and words. These lessons will benefit me all my life.

I would like to thank my committee members, Dr. Jeffrey Vitale and Dr. Rodney Holcomb for their timely advice, discussions and feedback. I often get inspiration and knowledge improvement from their intellectually courses.

Then, I will thank my husband Zhenan He for his totally understanding and supporting. He always supports and encourages me to work hard in my research field.

I am forever grateful to my parents for their love, financial and moral support and encouragement.

Name: SULING DUAN

Date of Degree: JULY, 2014

Title of Study: INSECT CONTROL UNDER UNCERTAINTY: ECONOMICAL STRATEGIES THAT ARE ROBUST TO VARYING WEATHER CONDITIONS AND INSECT IMMIGRATION RATES

Major Field: AGRICULTURAL ECONOMICS

Abstract: Insect control is a key concern for handlers of grain and grain-based products during storage. Traditionally, storage managers treat insects one or more times per year to control insects on a pre-determined schedule with limited evaluation of overall pest population dynamics, which can cause both unnecessary treatment costs and more rapid evolution of insect resistance to the fumigants. Some IPM strategies, such as sampling in storage bins, are intended to gain more accurate information of insect population in order to apply more appropriate insect control treatments. But IPM strategies depend on sampling, and choosing the frequency and timing of sampling is difficult. Also, sampling is costly. Storage managers need guidelines to select economical insect control strategies.

Here, an economic model is formulated and a simulation conducted to identify insect control strategies in wheat storage that are robust to changing weather conditions and alternative insect immigration rates. Costs of insect control include both treatment costs and costs of failing to control insects. Two different weather environments were considered, represented by Oklahoma City, Oklahoma, and Wichita, Kansas. The model shows how weather conditions, insect immigration rate and cost of insect control influence storage managers' insect management strategies. The insect control strategies considered include doing nothing, one or two routine fumigations, and fumigation based on sampling. Several sampling protocols were considered.

Simulation results show that under most situations for which insect immigration rate was known, the optimal strategy (one that achieves lowest cost of insect control) was one or two fumigations. In contrast, when insect immigration rate is not known, a strategy of one fumigation plus sampling after that became dominant for Oklahoma City. For Wichita, no one strategy became dominant, because fumigation was not needed in every year in that environment.

If cost of sampling was reduced by 50%, strategies using sampling became the least cost strategy under a greater range of scenarios. Also, if live insect discount was doubled, there was greater incentive to conduct more sampling after fumigating, to increase confidence that insects were, in fact, controlled.

TABLE OF CONTENTS

Chapter Page

LIST OF TABLES

Table Page

LIST OF FIGURES

Figure Page

CHAPTER I

INTRODUCTION

Background

Insect control is a key concern for handlers of grain and grain-based products during the storage, processing, and packing processes. Insect infestations and insect fragments in food product can cause product damage and human health hazards (Larsen at al. 2008), which can cause direct and indirect economic losses.

Traditionally, grain storage managers have relied on fumigations with specific insecticides. They often treat one or more times per year to control insects on a pre-determined schedule, which is called calendar-based fumigation. Calendar-based applications with limited evaluation of overall pest population dynamics can cause both unnecessary treatment costs and more rapid evolution of insect resistance to the fumigants, particularly phosphine. Phosphine is a commonly used fumigant for cereal grain storage, but some believe it may be declining in effectiveness for some applications because of insects developing resistance.

At the same time, consumers increasingly desire food products that are wholesome, chemical free and insect free. Suppliers face a challenge to find effective methods and techniques as alternatives to produce high quality agricultural products without substantially increasing costs.

Integrated pest management (IPM) programs are potential alternatives that reduce indiscriminate use and environmental impacts of pesticides. Unlike calendar-based fumigations, IPM is a balanced use of multiple control tactics – biological, chemical, and cultural – as it is most appropriate for a particular situation in light of careful study of all factors involved (Way, 1977). Grain storage managers can utilize a variety of insect controls within an IPM approach, such as obtaining insect population by sampling or monitoring to make combination use of several applications after an insect infestation has been detected. Some other IPM techniques like sanitation practices can help to reduce insect immigration in order to reduce the insect population.

However, managers may not easily accept IPM strategies because there are risks of failing to control insects. Many uncertainties exist, such as insect pressure in the surrounding environment, local weather conditions, or storage structures with varying levels of insect permeability. Although sampling and monitoring can be used to address these uncertainties, if sampling or monitoring fails to provide accurate information on insect population, food suppliers may face a large risk of making incorrect insect treatment choices, which can cause ineffective insect control.

If insect population is not controlled effectively while grain is in storage, live insect populations will damage it, resulting in large price discounts. For wheat, in particular, insect populations, particular lesser grain borer (*Rhyzopertha dominica*) cause insect-damaged kernels (IDK), and resulting large price discounts. Further, if the number of IDK exceeds 32 IDK per 1,000g sample, the wheat cannot be sold as human food, resulting in a large discount. For value-added processed products, such as flour, insect infestation causes damage in the form of undesirable taste or smell. The costs to suppliers of consumers disliking these tastes or smells, or discovering insects or insect fragments, can be very large. Food companies may suffer harm to their reputations in the market along with costs of product recalls.

On the other hand, if storage managers apply too many insect-control applications, treatment cost increases. Also, too many applications can build insect resistance to that chemical, which over time decreases the effectiveness of treatment.

Some IPM strategies such as sampling in storage bins intend to gain more accurate information of insect population in order to apply more appropriate insect control treatments. But IPM strategies require more management time and expertise, and it has not been clear that benefits of IPM are greater than its costs, so many firms have not adopted IPM (Adam et al., 2010).

IPM strategies depend on sampling and monitoring, and choosing the frequency and timing of sampling is difficult. Improper sampling increases the risk of failing to get accurate information. More frequent sampling can increase the quality and timeliness of that information, but it also increases expense in a low-margin industry. Balancing the cost of insect control strategies, including sampling, with the potential loss due to insect damage is important.

Decision making with IPM strategies is complicated because of the variety of choices. “Rules of thumb” are difficult to prescribe because individual firm conditions vary widely, and insect populations depend heavily on weather conditions that are dynamic and uncertain as well as on factors peculiar to each facility. For these same reasons, building a general economic model that can be used to analyze specific situations is difficult. Food suppliers may hesitate to adopt IPM methods when facing too many uncertainties. They need accurate information about cost and effectiveness of IPM and non-IPM alternatives to make good insect control decisions.

A study is necessary to provide managers economically-based guidelines to choose proper methods for controlling insects. This study examines a range of costs that grain storage managers who store wheat face in their insect control decisions, and attempts to identify key factors affecting their decisions. It combines these in a general economic model that includes both treatment costs and costs of failing to control insects, considering varying weather conditions and insect population pressure. A key goal of this research is to identify insect control strategies that are robust to varying weather conditions and insect immigration rates (a key component of insect pressure), both of which have large effects on insect population.

If strategies that are robust to varying weather and insect immigration rates can be identified, grain storage managers can have greater confidence in choosing insect control strategies even with limited information. This can reduce costs of providing safe, wholesome food.

Objectives

The general objective is to identify insect control strategies for stored wheat that are robust to varying weather conditions and insect immigration rates.

The specific objectives are:

1) Determine treatment cost for appropriate insect control strategies.
2) Determine insect damage cost for each strategy over a range of weather conditions and immigration rates.
3) Determine optimal insect control strategies that are robust to varying weather conditions and insect immigration rates.

Conceptual Assumptions

The key factor that influences treatment strategies is insect population. However, insect population is uncertain. Insect growth and insect immigration is mainly affected by humidity and temperature conditions. Insect populations grow exponentially without any treatment, and economic loss due to insect infestation can be very high. Failing to control insects effectively can lead to large discounts in the product price because of reduced quality, reduction in quantity as insects destroy grain, and loss of key markets. For example, a lot of wheat may be designated as unfit for human consumption, or buyers may reject shipments of wheat with more insects or insect damage than a specified minimum amount.

For wheat in storage, damage includes live insect discount and an Insect Damaged Kernels (IDK) discount. Treatment cost includes cost of chemicals, labor, and application. For IPM methods, key costs are extra management required and cost of sampling and monitoring. A big part of these costs is labor cost.

If treatment is applied, insect population will be reduced and the damage will decrease. But there is a cost of treatment. The total cost of insect management is the sum of both damage and treatment cost. As number of treatments increases, treatment cost increases while damage decreases.

IPM strategies are based on information about insect population from sampling or monitoring while non-IPM strategies rely on calendar-based applications. Sampling and monitoring can help determine insect population more precisely, but there is also risk that sampling may fail to detect insect populations that eventually cause damage or discounts.

Cost of insect damage and cost of insect treatment move in opposite directions. The optimal result occurs at the point where additional cost of insect damage and additional cost of insect treatment are equal. It is possible that the optimal strategy is to treat insects more than once in a period of time. It is also possible that the optimum strategy is no treatment at all because insect population is not large enough to cause loss. The optimal strategy is assumed here to be the strategy with the lowest total cost among all treatment strategies.

Outline of Work

An economic model is constructed to identify insect control strategies in wheat storage that are robust to changing weather conditions and alternative insect immigration rates. Two different weather environments are considered in a simulation analysis: Oklahoma City, Oklahoma, and Wichita, Kansas. Oklahoma City is in the Southern Plains of the U.S., and although some might consider Wichita in the Central Plains, it is only 160 miles north of Oklahoma City. Even though the distance between them is not large, the weather conditions are sufficiently different between them to cause differences in insect population growth. The model shows how weather conditions, insect immigration rate and cost of insect management influence food supplier's insect management strategies. The insect control strategies considered include doing nothing, one or two routine fumigations, and fumigation based on sampling. Several sampling protocols are considered.

A simplified version of an insect growth model from Flinn and Hagstrum (1990) is used to estimate insect population for grain storage. Insect immigration rate is an important component of this model.

An economic engineering approach is used to estimate the specific cost components – labor, management, materials, chemical, and investment. Sampling cost is the main treatment cost for IPM strategies, composed mainly of labor cost. The cost of failing to control insects, including discounts, will also be measured. Insect population estimates are used to calculate insect damage costs, or discounts.

CHAPTER II

LITERATURE REVIEW

Insects in Stored Product

Tribolium castaneum (Herbst), the red flour beetle and *Tribolium confusum* (du Val), the confused flour beetle are two of the major beetle pests of stored and processed products, especially for milled grain (Arthur and Campbell, 2008). For wheat storage, the most economically-damaging insect pest is the lesser grain borer (LGB) in the US (Arthur et al. 2009)

Insect activities directly cause grain damages such as: boring holes into the kernels and reducing grain quality through weight, nutritional, or quality loss; spreading and encouraging mold germination; adding to the fatty acid content of the grain; and leaving quantities of uric acid that cause grain rancidity (Mason and McDonough, 2012). For instance, the red flour beetle and the confused flour beetle produce pheromones and toxic Quinone compounds that will cause a foul odor and taste in the food products (Krischik and Burkholder, 1991).

The presence of insects in a grain sample (two live insects in 1,000 grams of wheat) causes the grain to be graded as “infested”, and results in significant cash discounts for the grain sellers (Mason and McDonough, 2012). Actual monetary losses due to stored-grain insects are generally considered to be in the range of 5 to 10% of the bulk commodities stored in the USA (Flinn et al. 2007). In 1990, postharvest losses by insects in the United States were estimated to be $500 million (Harein and Meronuck, 1991).

Integrated Pest Management

Unlike calendar-based treatment, IPM concepts stress judicious use of pesticide with the objective of maximizing its efficiency. After obtaining information on insect population, chemical efficacy, treatment cost, and risk of failure to control insects, integrated pest management tactics can help managers to make better decisions regarding insect management strategies (Fields and White, 2002). Uncertainty about insect population is one of the significant barriers of decision-making. If the insect population threshold is not well defined, unnecessary treatments can increase costs and environmental impacts. Also, inadequate information of insect population increases both risk of failing to control insects and cost of extra treatments.

There are many ways to obtain insect population including: sampling or monitoring information, expert systems, consultants, and the predictions of computer simulation models (Hagstrum and Flinn, 2012). However, these methods may not provide accurate information. Sampling storage grain is taking a sample from the grain for live insect observation. When sampling a grain product, managers have to decide which sampling device to use; the size, location, and number of samples to take; and the time and frequency of sampling (Hagstrum and Subramanyam, 2000). Pheromone trapping programs have been widely used to monitor insect population and distribution. However, pheromone trapping on insect monitoring usually provide inaccurate information on insect population because insects' footprints and harborage are hard to assess due to the lack of uniform distribution (Campbell, et al., 2002). When Campbell et al (2002) used pheromone trapping with contour mapping and mark-recapture to assess the spatial distribution and movement patterns of some species of stored-product insects; it was determined that trap type, trap location and the number of traps were difficult to decide because different decisions could cause different results of spatial distribution of pest infestation.

In addition, IPM strategies are costly. The cost of sampling includes the amortized cost of an investment in a PowerVac sampling machine, labor used to set up and take down the sampling equipment, and labor used in sampling (Adam, et al., 2010). Also, insect monitoring programs are some components of costs, which mainly include cost of traps, cost of mark and cost of data collecting. There might also be risk of losing flour traps leading to both economic costs and costs in term of information loss (Campbell, et al., 2002). Adam et al (2010) compared cost of insect control in hard red winter wheat storage for sampling-based IPM and calendar-based approaches and estimated that if fumigation eventually became necessary in all the bins, sampling was just an extra cost. So IPM has more risk of failure to control insects thus it may not be economically profitable to be accepted by suppliers.

However, IPM also may have benefits that are not easily quantified, such as increased environmental and worker safety and reduction of pesticide residual. Successful IPM programs need to define the balance between the costs of doing additional IPM and the gains in information obtained and the potential economic benefits of reducing the amount of chemical use (Campbell, et al., 2002).

Cost and Risk Analysis on IPM and non-IPM

The goal of both IPM and non-IPM approaches is to manage insect population and damage in a storage structure most cost effectively (Adam and Alexander, 2012). In other words, the goal is to minimize the total insect cost, which includes insect treatment cost and insect damage cost.

Treatment cost increases while damage cost decreases (Adam and Alexander, 2012). The authors show that both costs are directly or indirectly affected by insect population. Flinn, Hagstrum, and Phillips (2007) developed an exponential insect growth model to calculate insect population based on starting insect numbers, weather conditions, and immigration rate. Adam et al (2010) used that insect growth model together with an economic-engineering model to measure economic cost of treatments to control insects, including both treatment costs and failure-to-control costs.

Also, there are published economic models of cost and risk attempting to identify a strategy with minimum risk-adjusted cost. For example, Tilley et al (2007) measured risk as deviations below target mortality (Target MOTAD) in their study of cost and risk of heat and chemical treatment. In addition, two previous studies (Adam, et al., 2006, Adam, et al., 2010) found that for elevators in the Central and Southern Plains calendar-based fumigation is likely a lower cost strategy than sampling-based fumigation, an IPM strategy. Their simulation showed that in warmer, more humid climates, insects grow quickly enough that fumigation is always necessary and the results of sampling seldom or never change that prescription, but simply add unnecessary costs. The results also showed, though, that sampling-based IPM is economical in cooler climates, if managers can reduce immigration rate of insects in at least a portion of their storage bins and store the grain a shorter amount of time.

However, those results were based on limited weather data. If the data overestimated temperatures and humidity in a typical growing season, it is possible that considering additional years would decrease the probability that fumigation would be required, increasing the relative attractiveness of a sampling-based IPM approach. This study builds on Adam et al (2010), using a simulation analysis to identify best strategies for insect control with a longer period of weather data to determine if their finding is consistent for alternative time periods.

CHAPTER III

PROCEDURES AND METHODOLOGY

Conceptual Framework

Costs and Benefits

Suppose that a grain storage manager's goal is to identify a treatment or a set of treatments to maximize his expected profit. To obtain that goal, a manager needs information on weather conditions to make a decision. The best information about weather is historical weather. With 29 previous years' weather data about temperature and humidity, we assume each year's historic weather is equally likely in predicting next year's weather, as in a uniform distribution.

If each year is a random sample from a uniform distribution of marketing years, sampling years from that uniform distribution has the effect of sampling from a more normal-looking distribution of temperature and humidity conditions. The more normal-looking distribution is because many of the individual years have temperature and humidity patterns similar to those of other years, so more observations may be concentrated near the average of temperature and humidity than toward the extremes. As a result, we use a set of historical weather observations as representative of the future distribution of temperature and humidity. For a given immigration rate scenario, the objective, which is optimized by choosing strategy j, is

(3.1) $$Max_j \; E(\pi) = \int [f(\pi) d\pi | ImmR]$$

In order to focus on costs of insect control, we assume that revenues and other costs do not vary. Thus, to maximize expected profit, the firm maximizes a constant expected revenue minus a random insect control cost.

(3.2) $$E(\pi) = E(R - C) = E(R) - E\ (C) = R - E\ (C)$$

where $E(\pi)$ is the expected profit, $E(R)$ is the expected revenue of the elevator, which is equal to R as constant, and $E(C)$ is the expected cost of insect control in the storage period.

Insect control cost is composed of two parts: 1) treatment costs (*TC*), and 2) insect damage cost (*DC*), or costs due to insect infestation, so that

(3.3) $$C = TC + DC$$

The insect damage cost includes discounts due to damaged grain (IDKd), which is IDK discount, and discounts due to live insects at time of marketing (LVd), which is live insect discount, so that

(3.4) $$DC = IDKd + LVd.$$

If no treatment is applied, there is no treatment cost but likely a cost of damage by insect infestation. Otherwise, any treatment application will incur treatment cost. Treatment cost for insect control is the sum of costs of all treatments, so that

(3.5) $$TC = \sum_1^i k_i \mathrm{cost}_i$$

where TC is treatment cost, k_i is number of treatments i and $cost_i$ is cost for treatment i.

From equations (3.3), (3.4) and (3.5), insect control cost for each strategy *j* during each storage period is:

(3.6) $$C_j = \sum_1^d \sum_1^i k_{id} \mathrm{cost}_i + \sum_1^d IDKd\big(\widetilde{N}_T\big) + LVd\ (\widetilde{N}_T)$$

where C is cost of insect control strategy, k_i is number of treatments for applications i at time d and $cost_i$ is cost for treatment i, $IDKd(\widetilde{N}_T)$ and $LVd(\widetilde{N}_T)$ are both functions of random insect population $\widetilde{N}_T$ at time of marketing (end of storage period) T, $\widetilde{N}_T$ is random insect population based on temperature and humidity, $\widetilde{N}_T = f(\widetilde{Tem}, \widetilde{Hum})$.

Optimization

Insect population is the key factor in total cost of insect management, affecting both treatment choices and product damage loss from insect infestation. TC and DC should be inversely related. Any application adds to treatment cost but can reduce insect population, which in turn reduces damage loss. Unnecessary treatments increase the total cost of insect management by increasing treatment cost without reducing damage loss. Too little treatment reduces treatment cost, but raises damage loss. Normally, risk of damage loss from too little insect control outweighs risk of spending too much on treatment, because insect populations grow exponentially if not adequately controlled.

A profit-maximizing company will spend more on treatment if it can reduce damage costs by at least as much as treatment costs. Since an IPM insect control strategies use sampling to prescribe treatments, uncertainty about insect population could lead to excessive or inadequate insect control, both raising costs above the static optimum.

The optimization objective is to determine the types of treatments (i) and the proper timing of those applications (d) in order to get the minimum total insect management cost.

(3.7) Objective: $min_j\ E\ (C_j)\ =\ TC_j + E\ (IDKd_j(\widetilde{N}_T)) + E\ (LVd_j(\widetilde{N}_T))$

Subject to: $N_d\ = (N_{d-1} + G_d + ImmR_d) * (1 - F_K * TR_d)$

$TR_d = 0\ or\ 1$

$SP_d = 0\ or\ 1$

$FC_j = \text{Vcost}_{fum} * \sum_1^d TR_d + \text{Fcost}_{fum}$

$SC_j = \text{Vcost}_{sp} * \sum_1^d SP_d + \text{Fcost}_{sp}$

$TC_j = FC + SC$

where $E(C_j)$ is the expected cost of insect control strategy j, TC_j is the treatment cost associated with the jth insect control strategy, $IDKd_j$ is the discount due to damaged kernels and LVd_j is the discount due to live insects at time of marketing associated with the jth insect control strategy. N_d is insect number per kg on day d, G_d is insect growth per kg from day $d-1$ to day d, $ImmR_d$ is insect immigration rate into the grain storage structure from day d-1 to d (G_d and $ImmR_d$ are explained as below) and F_K represents the kill factor of the treatment. TR_d is set to be one at certain time (d) to represent fumigating on that day. SP_d is set to be one at certain time (d) to represent sampling on that day. FC_j is fumigation cost and SC_j is sampling cost. $\sum_1^T TR_d$ and $\sum_1^T SP_d$ represents the number of fumigations or samples. T is number is days in storage period. Vcost_i and Fcost_i are variable and fixed cost of treatment *i* (fumigation or sampling).

Insect Population: Insect Growth Model

The first step is to predict insect population. Insect population on a particular day is determined by population on the previous day, insect growth from the previous day to the current day and insect immigration into the storage facility since the previous day. Flinn, Hagstrum, and Phillips (2007) describe an exponential insect growth model that is simplified for use here. In their model, 10 weather variables, including daily temperature and humidity, are used to model insect growth in a grain storage bin. This study uses a simplified version of Flinn, Hagstrum, and Phillips (2007)'s model, with temperature and humidity as the only weather variables determining insect growth. The full model uses 10 weather variables in addition to equations modeling temperature exchange between the exterior and the interior of the grain bin, but the simplified model was calibrated to match the full model's predictions of insect population in a 24-ft. diameter concrete grain silo. The simplified model is:

$$G_d = N_d * \alpha Exp\left(\beta \frac{Tem_d * Hum_d}{100}\right) \quad (3.8)$$

where G_d is insect growth per kg from day d to day $d+1$, N_d is insect number per kg of day d, Tem_d and Hum_d are average Temperature and average Humidity of day d, α is an adjusted parameter on exponential and β is an adjusted parameter as Intrinsic Rate of Insect growth.

We adjusted α and β to most closely match the insect numbers at the end of storage from Flinn et al. (2007) model. In this study, the best calibration with the Flinn et al. (2007) model is with $\alpha = 0.044328728$ and $\beta = 0.00035$.

Immigration rate of insects into the storage facility depends on weather conditions, facility-specific factors such as integrity of the storage structure and cleanliness of the facility and grounds, and characteristics of the natural habitat surrounding the facility grounds (Campbell et al. 2002). These factors are simplified here into three different immigration rates: High, Medium (Normal) and Low (Table 3.1).

Table 3.1 Insect Immigration Rate Factors

Immigration Rate	Immigration Rate Factor
High	0.0001
Medium (Normal)	0.00001
Low	0.000001

Source: Adam et al. 2010

Equation 3.9 expresses insect immigration rate as a function of temperature and immigration rate factor.

(3.9) $$ImmR_d = MAX\ (0, (1 * Exp(Tem_d * ImmRF)\ - 1)/10)$$

where $ImmR_d$ is immigration rate into a grain storage structure from day d to day $d + 1$, Tem_d is average Temperature of day d and $ImmRF$ is the immigration rate factor.

As a result, daily insect population is,

(3.10) $$N_d = N_{d-1} + G_{d-1} + ImmR_{d-1}$$

where N_d is insect number per kg of day d, G_{d-1} is insect growth per kg from day $d - 1$ to day d, and $ImmR_{d-1}$ is immigration rate into grain storage structure from day $d - 1$ to day d. In the model, starting insect population (N_0) is assumed to be 0.000002 per kg.

Objective 1: Determine treatment cost for appropriate insect control strategies.

Treatment cost: Economic Engineering Model

The second step is to estimate treatment cost of each insect control strategy. An economic engineering model developed by Adam et al. (2010) for estimating costs of insect control treatments in a grain storage facility was adapted here. Table 3.2 illustrates the possible types of treatment costs that may be incurred. The magnitude of each possible cost depends on the specific approach. Variable costs include labor, chemical and material costs, and value of product lost, since those costs depend on the amount of grain treated or the number of treatments. Fixed costs, those not varying with amount of grain treated, include equipment costs, liability insurance, and training costs.

Table 3.2 Insect Treatment Cost Components

Possible costs	Formula
Labor cost (various kinds)	Wage ($/hr)*hours*number of workers
Costs paid to vendors (e.g. training workshop fees)	(Training hours per worker*hourly labor cost + registration fee)*number of workers
Electricity cost	Electricity cost ($/kwh)*operation time (h)*power (kw)
Equipment cost	Amortized equipment cost ($/yr) + maintenance cost (% of equipment cost, $/yr)
Chemical cost	Chemical price ($/unit)*units used

These cost components are combined in various configurations depending on the particular treatment used. For example, cost of fumigation includes fumigation equipment cost, fumigation labor charge, fumigation training cost, fumigant chemical charge, and turning charge including grain lost from turning (Table 3.3). All costs are calculated as cost per tonnes stored, which is total cost spent for each component divided by total amount of storage. We assume all ten bins are full, at 760 tonnes per bin.

Table 3.3 Economic-engineering Costs of Fumigating One Time in Stored Wheat

Fumigation cost components	Rate	$/tonne
Fixed		
Liability insurance	$200/yr	$0.0263/t
Fumigation training (training hours/employee) × # employees × labor cost + training fee)	$434/yr	$0.0570/t
Fumigation equipment ($3800 amortized at 10% over 10 yrs + insurance + maintenance)	$998/yr	$0.1311/t
Variable		
Labor 2 people, 3 h per bin, @$16/h	$96/fumigation/bin	$0.1261/t
Fumigant (120 tablets/27.19 t) × $0.04286/tablet		$0.1892/t
Grain lost in turning 0.25% × grain price ($150/t)		$0.3750/t
Turning electricity 0.10/kWh × 250 kWh/bin (3 h × 83 kW/h)	$25/bin	$0.0327/t
Average cost (10 bins each 760 t)		$0.937/t

Source: Adam et al. (2010)

Fumigation equipment cost can be calculated as: ((initial equipment cost/PVIFA) + maintenance costs per year + insurance costs per year) /tonnes stored. Initial equipment cost includes initial purchase cost of all safety and application equipment needed to apply fumigants within regulatory guidelines. Expected equipment life is approximate life of the equipment. PVIFA is present value interest factor for an annuity of *n* years at *i* percent interest, calculated as $[1-(1/(1-i))^n]/i$.

The fumigation equipment maintenance factor is estimated percent of initial equipment cost spent on annual equipment up-keep and consumables, expressed as a decimal. Maintenance cost per year is the equipment maintenance factor multiplied by initial equipment cost. Similarly, equipment insurance factor is the estimated percent of initial equipment cost spent on insurance annually, expressed as a decimal. Insurance cost per year is equipment insurance factor multiplied by initial equipment cost.

Fumigation labor charge is calculated as (person hours per fumigation*hourly labor cost*# fumigation*# bins)/tonnes stored, where hourly labor cost represents hourly wage plus taxes and benefits such as insurance and bonuses paid by the employer. For the base case a wage rate based on minimal management abilities was used. Person-hours required per fumigation include hours used to seal the facility, administer and prepare fumigant, check concentrations, and operate the equipment, from the time the process starts until the storage facility is completely aerated.

Fumigation training charge can be calculated as (training hours per employee*hourly labor cost + registration fee)*# of employees) / tonnes stored. Training hours per employee is number of hours required per employee for certification, continuing education, and safety training.

Fumigant cost can be calculated as (price per tablet or pellet*(dosage per tonne)) /tonnes stored.

Turning is often required for effective fumigation. Grain is transported on a moving belt from one storage bin to another while fumigant (such as aluminum phosphide tablets) is added into the moving grain (Adam et al. 2010). Turning cost includes cost of electricity and value of grain lost in turning (Table 3.3). During turning, grain weight lost is assumed to be 0.25% based on Adam et al. (2010). Electricity cost is calculated as: electricity cost ($/kWh)*operation time (h)*power usage rate (kW/h) (Table 3.2).

The cost of sampling includes fixed cost of a PowerVac sampling machine, labor used to set up and take down the sampling equipment, and labor for sampling (Table 3.4) (Adam, et al.

2010). PowerVac cost is: ((initial POWERVAC cost/PVIFA) + maintenance costs per year + insurance costs per year)/tonnes stored.

Table 3.4 Economic-Engineering Costs of One Sampling for Insects in Stored Wheat

Sampling cost components	Rate	$/tonne
Fixed		
PowerVac ($8,000 amortized at 10% over useful life of 10 yrs + insurance + maintenance)	$2,102/yr	$0.276/t
Variable		
Setup/takedown labor		
3 people, 3 h each, @$16/h	$144/sampling	$0.0189/t
Sampling labor		
3 people @$16/h, 0.08 h/sample, 10 samples/bin	$38/fumigation/bin	$0.0504/t
Average cost (10 bins each 760 t)		$0.345/t

Source: Adam et al. (2010)

The amortized fixed cost of fumigation is $0.214/t/yr and variable cost is $0.723/t (Table 3.2). Fixed cost for sampling or fumigation is incurred if the elevator ever needs to purchase equipment for those operations. Here, it is assumed that the elevator has purchased that equipment or, if sampling or fumigation is contracted, that the contract rate includes the contractor's fixed cost. Thus, cost is $0.214/t if no fumigation occurs, $0.937/t if one fumigation is done, and $1.66/t if two fumigations are done in a year. Similarly, since fixed sampling cost is $0.2760/t and variable sampling cost is $0.0693/t (Table 3.3), sampling cost is $0.2760/t if no sampling is done, $0.3454/t if one sampling is done, and $0.4147/t if two samplings are done in a year. If monthly sampling is contracted, the rate is assumed to be $0.0845/t/month, including fixed and variable costs as well as profit.

Methods besides fumigation, such as aeration, can help control insects in storage bins. An automatic aeration controller can run fans automatically when the outside air temperature is lower than the grain temperature by some specified amount. Aeration works by slowing insect growth and development by reducing temperature. Since many elevators in Oklahoma do not have aeration capabilities, we assume no aeration occurs during the storage period and use natural temperature data to predict insect growth and immigration.

Objective 2: Determine insect damage cost for each strategy over a range of weather conditions and immigration rates.

Insect Damage

Insect populations could grow to levels that cause damage if there is insufficient control, or if the control is ineffective. For wheat, the economic damage is in the form of a discount for live insects, and a discount for IDK, with discount rates set by the buyer. Buyers may impose additional discounts of their own; these would typically be specified in a purchase contract. The seller may incur additional costs of re-transporting or sale at a lower price if a load is rejected because of insects or insect damage, or demurrage if a truck or rail car is delayed because of a required fumigation. Weight loss due to insect damage may occur, but its economic cost is small compared to the other costs mentioned, so it is ignored here.

Federal grain standards for wheat assign an "infested" designation when two or more live grain-damaging insects are observed in a sample of grain to be sold. In practice, an "infested" discount is likely to be applied when only one insect is observed, sometimes even when the insect is not considered a grain-damaging insect. Much more costly, grain buyers may refuse to accept a shipment of grain if they detect even one insect in a sample.

In this study, it is assumed that grain to be sold is penalized with a discount of $1.837/t (Adam et al., 2010) if there is one or more live grain-damaging insects in a 1000g sample,

$$LVd_T = 1.837 \; if \; N_T \geq 1 \quad (3.11)$$

$$or$$

$$LVd_T = 0$$

where LVd_T is live insect discount and N_T is insect population at the end of a storage period of length T. However, sensitivity analysis is conducted to determine the effect on optimal insect control strategies of alternative assumptions about discounts or rejection for infestation. Specifically, higher insect damage costs are considered, as well as a constraint that number of live adult insects must be less than one in a 1kg sample.

In addition, adult LGB lay their eggs in a crevice of a wheat kernel. After an egg hatches, the larva eats the inside of the kernel until it emerges as an adult, resulting in an 'Insect Damaged Kernel' (IDK). Such damage is permanent, and IDK never decreases, even if treatment kills all insects and no new IDK result.

Equation 3.12 expresses IDK on day d+1 as a function of previous IDK and insect growth.

$$IDK_{d+1} = IDK_d + max\ (0, G_d/10)\ * F_{IDK} \quad (3.12)$$

where IDK_d is insect damage kernel on day d, G_d is insect growth per kg on day d, and F_{IDK} is an IDK factor ($F_{IDK} = 3.2$). The starting IDK, IDK_0, is assumed to be zero because there are no insects present at the beginning.

Table 3.5 shows a typical schedule of IDK discount by a terminal elevator to country elevator. In this model, the prediction of insect damage kernels at time of sale (IDK_T) is used to calculate IDK discount ($IDKd_T$).

Table 3.5 Discount for Insect Damage Kernels ($IDKd_T$)

# of insect-damaged kernels (IDK_T) per 100gram sample	Discount ($/t)
$1 \leq IDK_T < 5$	0
$5 \leq IDK_T \leq 20$	$0.367 * IDK_T$
$20 \leq IDK_T \leq 31$	$0.735 * (IDK_T - 20) + 0.367 * 20$
$31 \leq IDK_T < 70$	14.70 cleaning charge
$70 \leq IDK_T < 100$	22.05 cleaning charge
$100 \leq IDK_T < 140$	33.07 cleaning charge
$140 \leq IDK_T$	$0.367 * (IDK_T - 140) + 33.07$

Source: Central Oklahoma terminal elevator

We used cost data provided from Adam et al (2010) and Dr. Reed, an adjusted cost with double live insect damage, and an adjusted cost with sampling cost halved to estimate cost and benefit for each scenario of doing nothing, routine fumigation, sampling-based fumigation and a combination of routine and sampling-based fumigation.

Objective 3: Determine optimal insect control strategies that are robust to varying weather conditions and insect immigration rates.

Optimization Model Statement

We use 29 years of historic weather data as representative of the future distribution of temperature and humidity to find insect control strategies (combinations of treatments) that maximize the storage firm's expected profit.

We do this in a simulation analysis by first choosing the lowest cost strategy as an optimal strategy for each storage period. Since we assume revenue is constant, the lowest cost strategy gains maximum net profit. Then for each strategy, we calculate average cost over 29 year Finally, we choose strategies with lowest average cost, under each immigration rate scenario (same as equation 3.1).

(3.1) $$Max_j\ E(\pi) = \int [f(\pi) d\pi | ImmR]$$

To complete objective 3, the general optimization model is revised from equation 3.7:

(3.13) Objective: $$min_j\ E\ (C_j)\ =\ TC_j + E\ (IDKd_j(\widetilde{N}_T)) + E\ (LVd_j(\widetilde{N}_T))$$

Subject to:
$$N_d\ = (N_{d-1} + G_d + ImmR_d) * (1 - F_K * TR_d)$$
$$G_d\ = N_d * \alpha Exp\left(\beta \frac{Tem_d * Hum_d}{100}\right)$$
$$ImmR_d = MAX\ (0, (1 * Exp(Tem_d * ImmRF) - 1)/10)$$
$$TR_d\ = 0\ or\ 1$$
$$SP_d\ = 0\ or\ 1$$
$$FC_j\ = \text{Vcost}_{fum} * \sum_1^T TR_d + \text{Fcost}_{fum}$$
$$SC_j\ = \text{Vcost}_{sp} * \sum_1^T SP_d + \text{Fcost}_{sp}$$
$$TC_j\ = FC_j + SC_j$$

Adult insect population is the number of adult insects on day *d*, N_d, depends on number of adult insects on day d-1 (N_{d-1}), change in insect population from day d-1 to d (G_d), insect immigration rate into the grain storage structure from day d-1 to d ($ImmR_d$), and the amount of insects remaining after a treatment such as fumigation.

TR_d and SP_d is a dummy variable representing treatment choice, with 0 = no treatment and 1 = treatment. Fumigation cost, FC_j or sampling cost, SC_j or both of them can be zero, depending on the strategy chosen.

F_K represents the kill factor of the treatment. Generally, a highly-effective fumigation kills 90% of insects in the pupae and adult stage and 99.9% of eggs and larvae over a 5-day period (Mah, 2004). We assume that all the fumigation treatments are highly effective, as 99% effective (F_K = 0.99). Starting insect population (N_0) is assumed to be 0.000002 per Kg.

Table 3.6 lists all the insect control strategies under consideration here.

Table 3.6 List of Insect Control Strategies Considered

Strategies	Description
I	Doing Nothing
Calendar-based Strategies	
II	One Routine Fumigation on December 4th
III	Two Routine Fumigation that firstly on Oct 31 and then on Mar 31
Sampling-based Strategies	
IV	One sampling-based fumigation
V	Monthly Sampling with 0.5 insects/kg threshold at every end of the month from September to March
VI	Monthly Sampling with a 0.75 insects/kg threshold on every 19th of the month from September to April
Combination Strategies	
VII	Routine Fumigation on Oct 31, then one sample on Mar 31
VIII	Routine Fumigation on Oct 31, Monthly Sampling with 0.5 insects/kg threshold at every end of the month from November to March
IX	Routine Fumigation on Oct 31, Two Samples with 0.5 insects/kg threshold on February 28 and March 31

Doing nothing

The total cost when using no treatment is used as a point of comparison. If no sampling and fumigations are applied, $TR_d = 0$ and $SP_d = 0$, and since treatment costs are zero as $TC_j = FC_j + SC_j = 0$, the total cost will include live insect and IDK discounts, as

(3.14) $$C_N = \sum_1^d IDKd\left(\widetilde{N}_T\right) + LVd\ (\widetilde{N}_T)$$

Routine fumigation

Figure 3.1 shows the relationship between insect numbers, N_d, which is determined by TR (fumigation). Fumigation reduces insect growth, which in turn reduces live insect and IDK discounts. Meanwhile, TR increases fumigation cost in result increases. Since there is no sample, in the set of constraints in equation 3.13, $SP_d = 0$ and $SC = 0$. TR_d is set to be one when fumigation is scheduled and treatment cost occurs. Treatment cost is equal to fumigation cost, $TC_j = FC_j$.

For one fumigation, we set up TR = 1 on each day and then compare the total cost at the end. The day on which the lowest cost (considering both treatment cost and discounts due to insects) occurs is the optimal choice among all fumigation dates considered. For some immigration rates (particularly high immigration), fumigating one time may not be sufficient to reduce damage cost; spending a small amount on treatment cost may not be optimal. Conversely, for some immigration rates (particularly low immigration), no fumigation is necessary to eliminate insect damage so fumigation may not be better than doing nothing.

The results will show whether the optimal fumigation time range contains the selected routine fumigating schedule. Adam, et al. (2010), assuming a storage period from June 20 to April 19, analyzed fumigating on December 20 for calendar-based fumigation and sampling on December 20th to determine whether to fumigate or not in a sampling-based fumigation strategy. However, there may be reasons to try different dates for sampling than for treatment. This study will adjust the fumigation date earlier to Dec 4, based on the result of the window range of optimal fumigation dates. Also, it will consider two fumigation dates: one on Oct 15 and one on March 15.

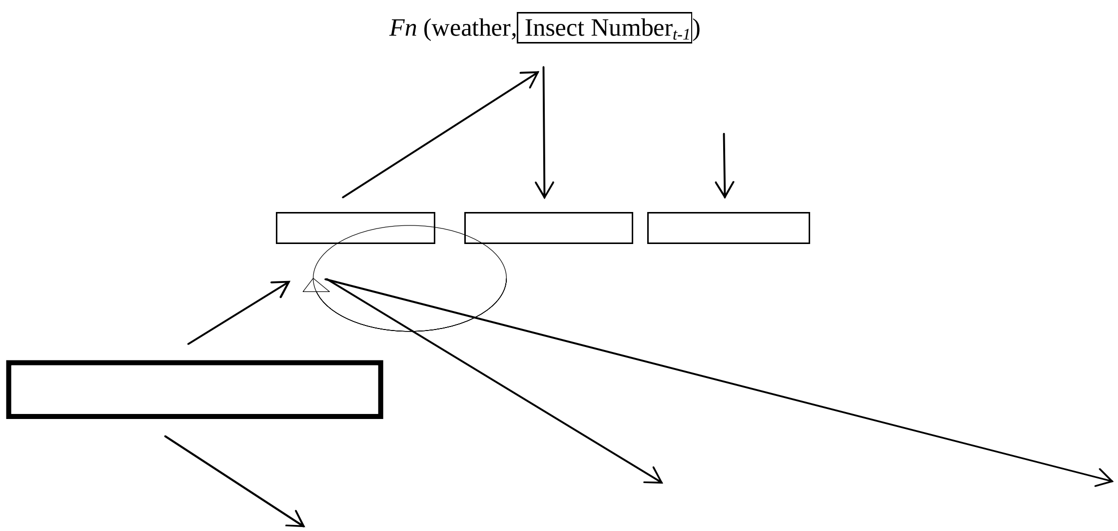

Figure 3.1 Relationship between Variables in the Model for One Fumigation Optimization

Sampling-based fumigation

In the sampling-based decision model, a dummy variable SP_d is added to the model: 0 = not to sample, 1 = sample in equation 3.13. Similarly (Figure 3.2), SP is to set up to choose the date of sampling, when $SP_d = 1$, sampling cost occurs. Choice of fumigation is TR=1 if N_d is greater than sampling threshold, $TR_d = 1 \ \ if \ \ N_d > \theta$ in equation 3.13, where θ is Sampling threshold to determine fumigant or not.

Treatment cost is equal to fumigation cost, $TC_j = FC_j + SC_j$. Sampling may indicate that no fumigation should occur. In that case, variable fumigation cost is zero and there will be only fixed cost of fumigation. SP_d could equal to 1 for any one *d*, *d = 1 to T*, with the optimal date for sampling the *d* that gives the lowest total cost for that particular year.

For monthly sampling, we set up $SP_m = 1$, where *m=1,2,…j*, Since fumigating one time may be not enough to reduce the damage cost for a high immigration rate, the model could suggest no, one or two fumigations during the storage. During the storage period from Jun 20th to April 18th, we started sampling in September.

Sampling threshold and time is an important determinant for a successful insect management. Adam at al. (2010) suggested that the criterion must be low enough so that no grain damage would occur before sampling was conducted, but high enough so that there is some possibility fumigation would not always be prescribed. They suggested 0.5 insects/kg as a reasonable criterion.

A threshold that is too low might lead to unnecessary fumigations, while a high threshold might lead to excessive insect damage. If the sampling date is too late, fumigation based on that information might allow too much insect damage.

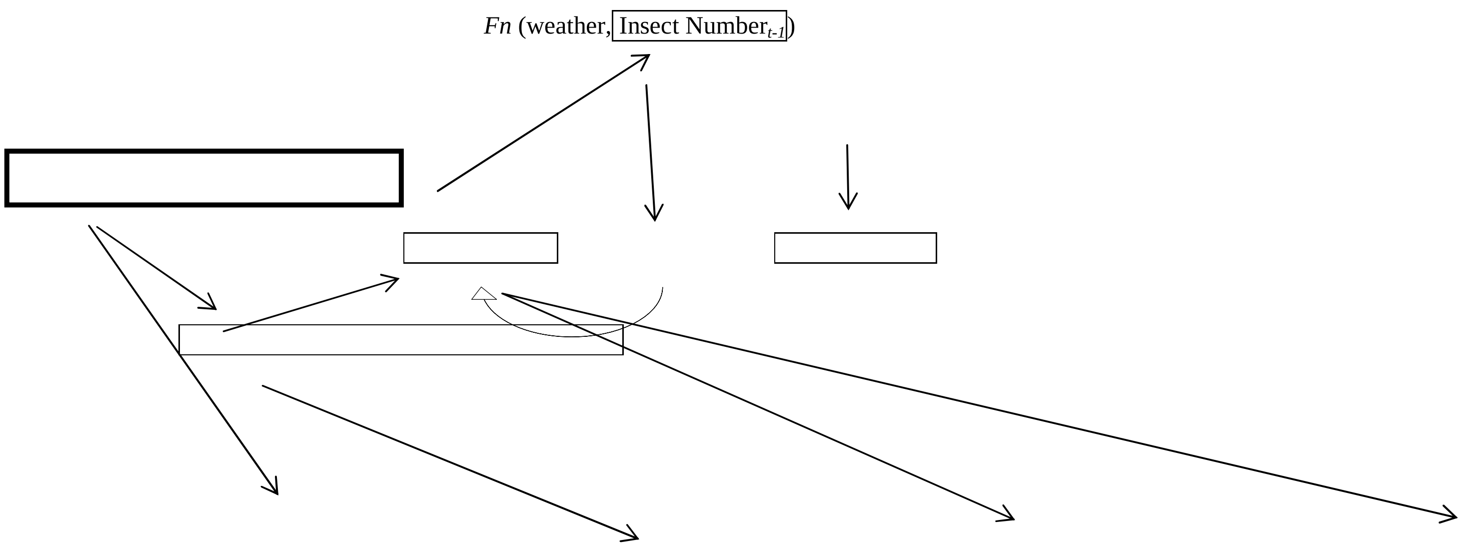

Figure 3.2 Relationship between Variables in the Model for One Sampling Optimization

Sampling more frequently (monthly, for example) would provide more reliable information on insect population. Cost of sampling monthly might be higher, but it could potentially reduce the cost of failing to control insects.

We consider two scenarios for more frequent sampling: 1) Sample with threshold of 0.5 insects/kg at the end of each month from September to March during the storage period, 2) Sample with threshold of 0.75 insects/kg on the 19th of each month from September to April on the end of each month. We also consider the effect of reducing sampling cost by 50%.

Routine and sampling-based fumigation combination

With a high insect immigration rate, we discovered that at least one fumigation is necessary. Therefore, we considered a strategy that combines a routine fumigation on October 31 with sampling-based fumigation afterwards. With this strategy, the sampling component took the form of one sample on March 31, one sample on Feb 28 and one on March 31, or monthly samples from November 30 to March 31.

The reason for multiple year objective estimation is to determine if considering varying weather conditions across years influences the optimal decision compared with using a single year's weather. The difference is that the objective in multiple estimation models should be the average of single objectives (overlaps of single years' best strategies). It is possible for there to be no overlaps for certain locations and immigration rates.

The insect immigration rate is unknown and it is very possible that a storage facility has several bins with different insect immigration rates. We will expand these base results for cost and damage estimation for a single insect immigration rate (assuming all bins have the same insect immigration rate) to more realistic scenarios in which a storage facility's bins vary in their insect immigration rates. Assuming there are ten bins in a storage facility, we consider the following insect immigration rate scenarios: 1) 1/3 of the bins have a low immigration rate, 1/3 have a normal immigration rate, and 1/3 have a high immigration rate; 2) 40% of bins have a low immigration rate, 40% have a normal immigration rate, and 20% of bins have a high immigration rate, and 3) 50% of the bins have low immigration rate and 50% have a normal immigration rate. Particularly, we are interested in determining the costs a manager would incur by choosing the best strategy while assuming 100% of the bins have a normal immigration rate, when the actual proportions are one of these three possibilities.

Data

This study simulates grain storage for ten months, from harvest in June until marketing in April. Dr. Paul Flinn, retired from USDA-ARS-CGAHR, provided weather data, as well as an EXCEL version of the insect growth model (Flinn et al.). Twenty-nine years (1961 to 1990) of temperature and humidity are taken from daily observations in two locations: Oklahoma City, OK (OKC) and, for comparison, Wichita, KS. The temperature of OKC is higher than Wichita and the relative humidity of OKC is lower than Wichita (Figures 3.3 and 3.4).

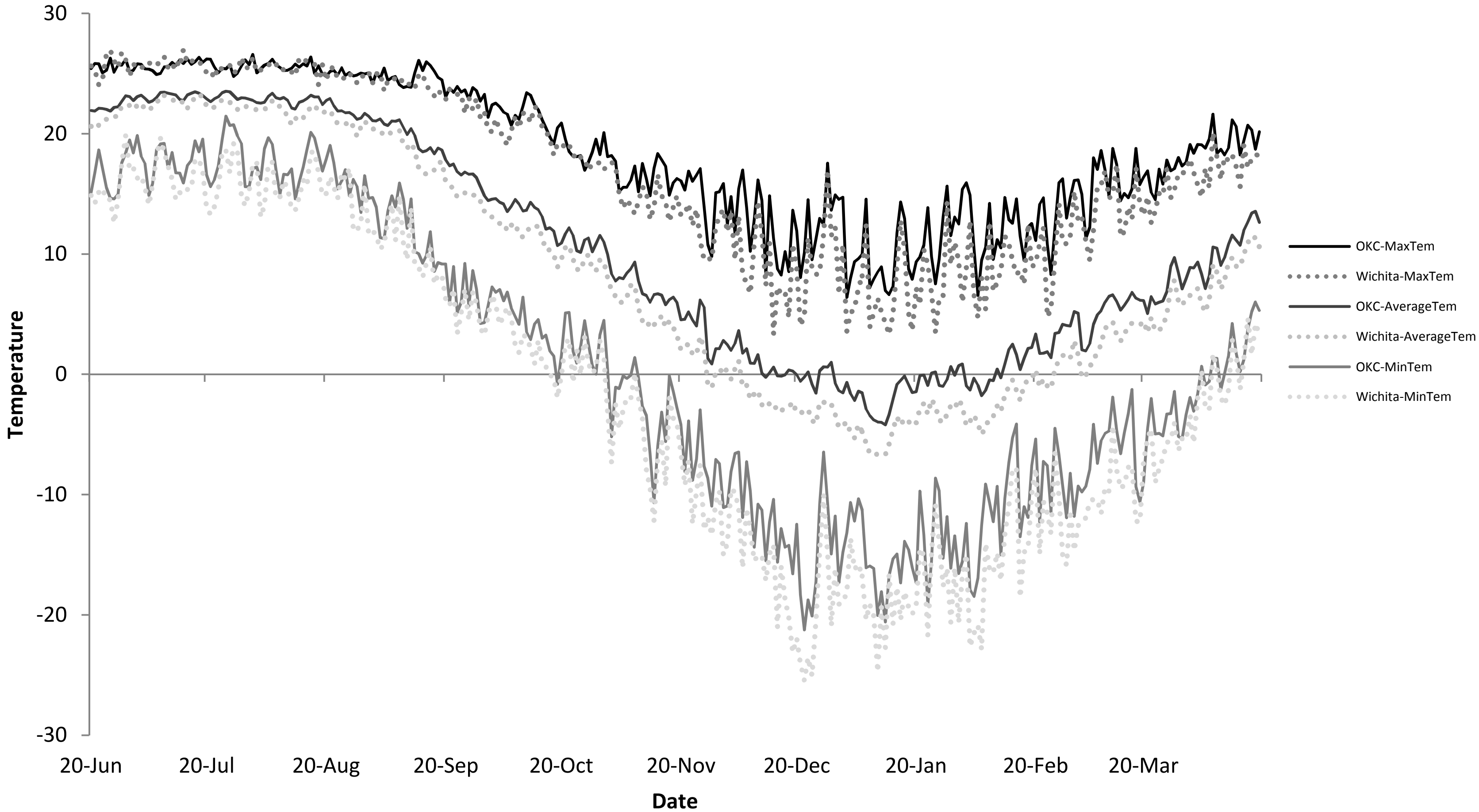

Figure 3.3 Comparison of Daily Temperature (C^o) of 29-year Average, Maximum and Minimum between Oklahoma City and Wichita from 1961 to 1990

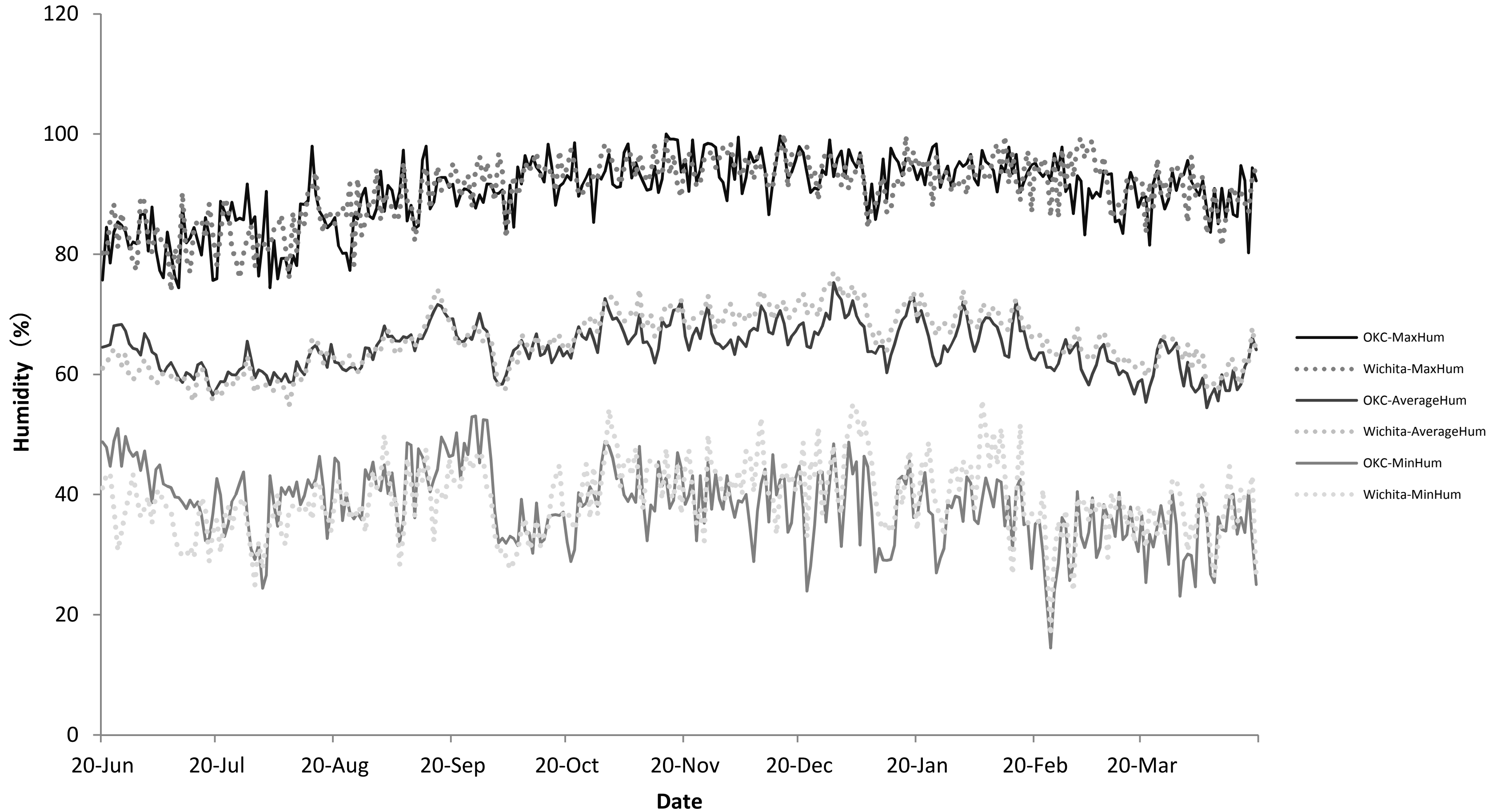

Figure 3.4 Comparison of Relative Humidity of 29-year Average, Maximum and Minimum between Oklahoma City and Wichita from 1961 to 1990

The data for cost components for routine fumigation and sampling-based fumigation are from Adam et al. (2010). For monthly sampling, Dr. Carl Reed, who owns a private grain storage management consulting company, provided cost of contracting for monthly sampling. We used the software MATLAB to optimize the models.

CHAPTER IV

RESULTS

Objective 1: Determine treatment cost for appropriate insect control strategies.

Objective 2: Determine insect damage cost for each strategy over a range of weather conditions and immigration rates.

Table 4.1 summarizes costs of the sets of treatments considered. Both treatment cost and damage costs are included. For the strategy "doing nothing," the only costs are live insect discount, IDK discount, or both.

For the strategy "one routine fumigation," in years when no damage occurs, the cost is $0.937/tonne, but in years when live insect discount is incurred, the cost increases to $2.74/tonne or $4.61/tonne. For the strategy "two fumigations," the cost is simply the treatment cost, $1.66/tonne, with no live insect or IDK discounts.

For "sampling-based fumigation," a range of costs results depending on weather. Cost of sampling one time is $0.559/tonne. One fumigation conducted as a result of sampling raised the cost to $1.282/tonne if no insect discounts occured, and up to $3.12/tonne if insect discounts occurred even after a fumigation ($4.96/tonne with a doubled live insect discount).

If sampling is conducted monthly, sampling by itself costs $0.592/tonne (if sampling is conducted on 19th of every month, one extra sampling is done and cost is $0.676/tonne). The other lines show the effect of varying weather conditions which might lead to one or two fumigations, or live insect discount, IDK discounts, or both.

Table 4.1. Summary of Cost ($/tonne/storage period) for Insect Control Treatments

Strategy/outcome	Standard discounts and sampling cost	Doubled live insect discounts	Sampling cost halved
Doing nothing			
Live insect discount	1.84	3.67	-
Live insect and IDK discounts*	3.69~97.2	5.53~99.0	-
One routine fumigation			
One fumigation, No damage	0.937	-	-
One fumigation, Live insect discount	2.77	4.61	-
One fumigation, IDK discount*	2.77~98.1	-	-
One fumigation, Live insect and IDK discounts*	4.61~94.0	6.45~95.84	-
Two routine fumigation			
No damage	1.66	-	-
Sampling-based fumigation			
No treatment, no discount	0.559	-	0.387
No treatment, live insect discount	2.40	4.23	2.23
No treatment, live insect and IDK discounts*	4.25~97.76	6.09~99.6	4.08~97.6
One fumigation, no discount	1.28	-	1.11
One fumigation, live insect discount	3.12	4.96	2.95
One fumigation, IDK discount*	3.12~10.8	-	2.95~10.6
One fumigation, live insect and IDK discounts*	4.26~ 98.5	6.10~100	4.09~98.3
(Standard sampling cost = 0.345)			

***Monthly Sampling-based fumigation** (Two scenarios: a. end of month, b. 19th of month**)*

Strategy/outcome	Standard: *end*	Standard: *19th*	Doubled: *end*	Doubled: *19th*	Halved: *end*	Halved: *19th*
No treatment, no discount	0.806	0.890	-	-	0.510	0.552
No treatment, live insect discount	2.64	-	4.48	-	2.35	-
One fumigation, no discount	1.53	1.61	-	-	1.23	1.28
One fumigation, live insect discount	3.37	-	5.20	-	3.07	-
Two fumigations, no discount	2.25	2.34	-	-	1.96	2.00
(Standard sampling cost = a.0.592 and b. 0.676)						

***One fumigation + sampling based fumigation** (Three scenarios: fumigation on Oct 31st with: a) sample on Mar 31, b) sample on Feb 28 & Mar31, c) end-of-month samples from Nov to Mar)*

Strategy/outcome	Standard: a)	Standard: b)	Standard: c)	Doubled: a)	Doubled: b)	Doubled: c)	Halved: a)	Halved: b)	Halved: c)
One fumigation, no discount	1.28	1.35	1.36	-	-	-	1.11	1.14	1.15
One fumigation, live insect discount	3.12	3.19	3.20	4.96	5.03	5.03	2.95	2.98	2.99
One fumigation, plus one indicated by sampling, no discount	2.01	2.07	2.08	-	-	-	1.83	1.87	1.87
(Sampling cost for the three scenarios: a) 0.345, b) 0.415 and c) 0.423)									

*varies depending on location, weather and immigration rate

**one extra sampling is conducted in the 19th of every month

For an approach of conducting one fumigation on October 31 and then either: a) sampling once on March 31; b) sampling at the end of February and March; or c) sampling at the end of every month from November to March;, the costs ranged from $1.11~1.36/tonne for sampling cost alone to $5.03/tonne when live insect discount. No insect damage cost occurred when an additional fumigation was indicated by sampling: the total cost for that was from $1.83~2.08/tonne.

Doing Nothing

Figures 4.1 and 4.2 show total costs with a low immigration rate if there was no treatment during the storage period from 1961 to 1990. The costs were composed of live insect discount and IDK discount, although IDK discounts were 0 in both OKC and Wichita for all the years due to the low immigration rate. Live insect discount of $1.837/tonne occurred in each year in OKC.

In Wichita, though, live insect discounts occurred only in approximately half of the storage periods. For 12 out of 29 years, there were no costs of insects at all. Those years were: 1961/62, 1963/64, 1964/65, 1966/67, 1967/68, 1968/69, 1969/70, 1970/71, 1974/75, 1976/77, 1977/78, and 1978/79. The best strategy for those years was to do nothing.

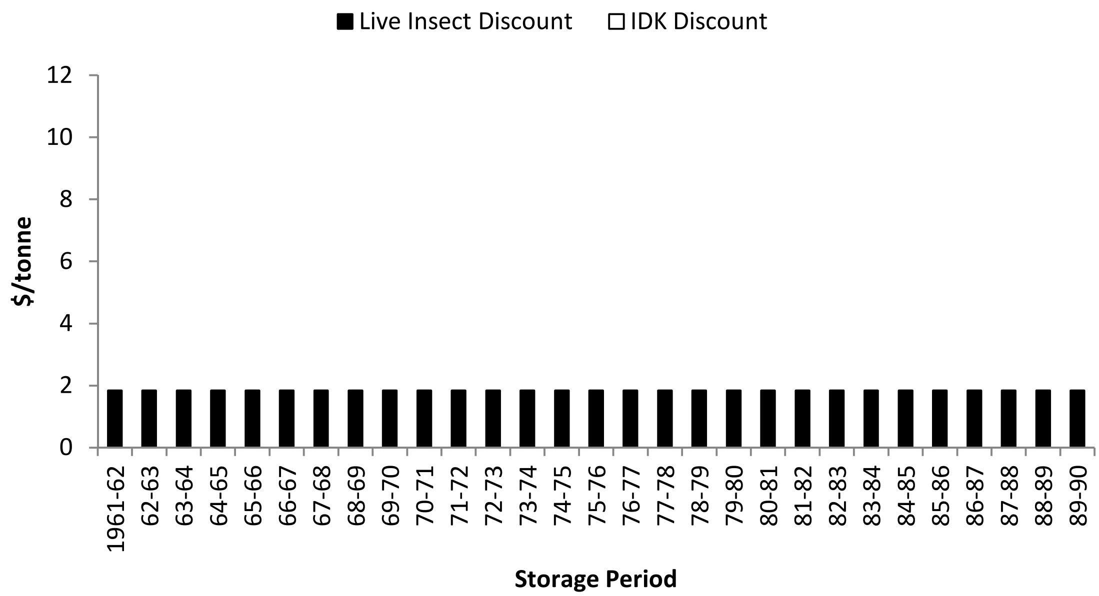

Figure 4.1 Total Cost of Doing Nothing: Low Immigration Rate, Oklahoma City, 1961 to 1990

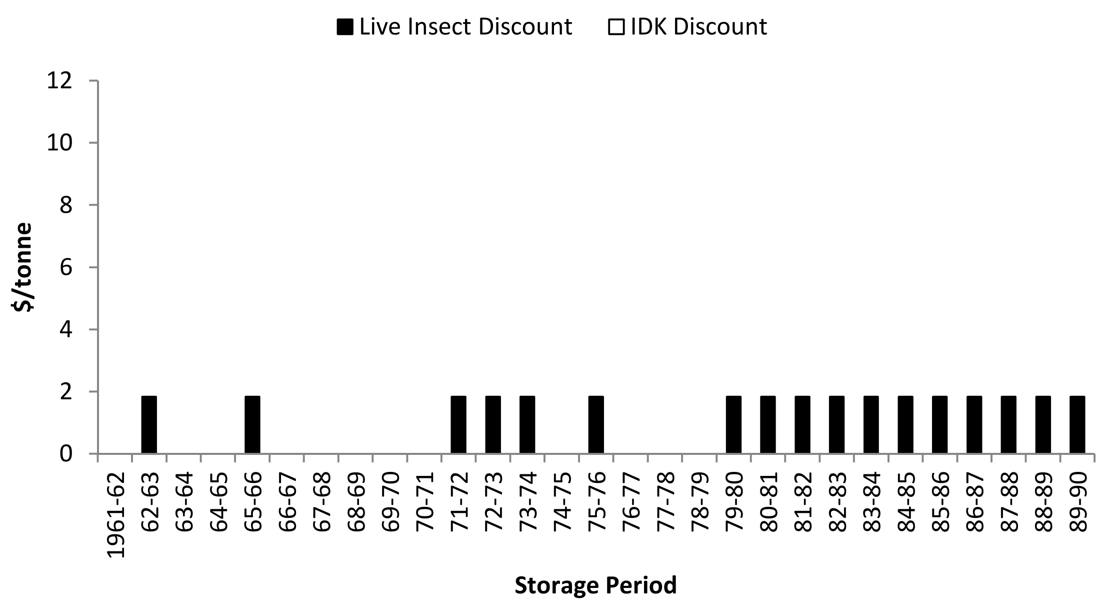

Figure 4.2 Total Cost of Doing Nothing: Low Immigration Rate, Wichita, 1961 to 1990

Figures 4.3 and 4.4 show total cost with a normal immigration rate if there was no treatment during the storage period from 1961 to 1990. With a normal immigration rate, a live insect discount of $1.837/tonne occurred every year in both Oklahoma City and Wichita. An additional IDK discount occurred every year in OKC. The highest IDK discount in OKC was $9.56/tonne (1986/87), and the lowest was $2.16/tonne (1977/78).

IDK discounts in Wichita were typically lower than in OKC. IDK discounts were zero in 15 out of 29 years (1961/62, 1963/64, 1964/65, 1966/67, 1967/68, 1968/69, 1969/70, 1970/71, 1974/75, 1975/76, 1976/77, 1977/78, 1978/79, 1981/82, and 1983/84). Among the remaining years, the highest IDK discount in Wichita was $2.75/tonne (1973/74) and the lowest was $1.85/tonne (1988/89).

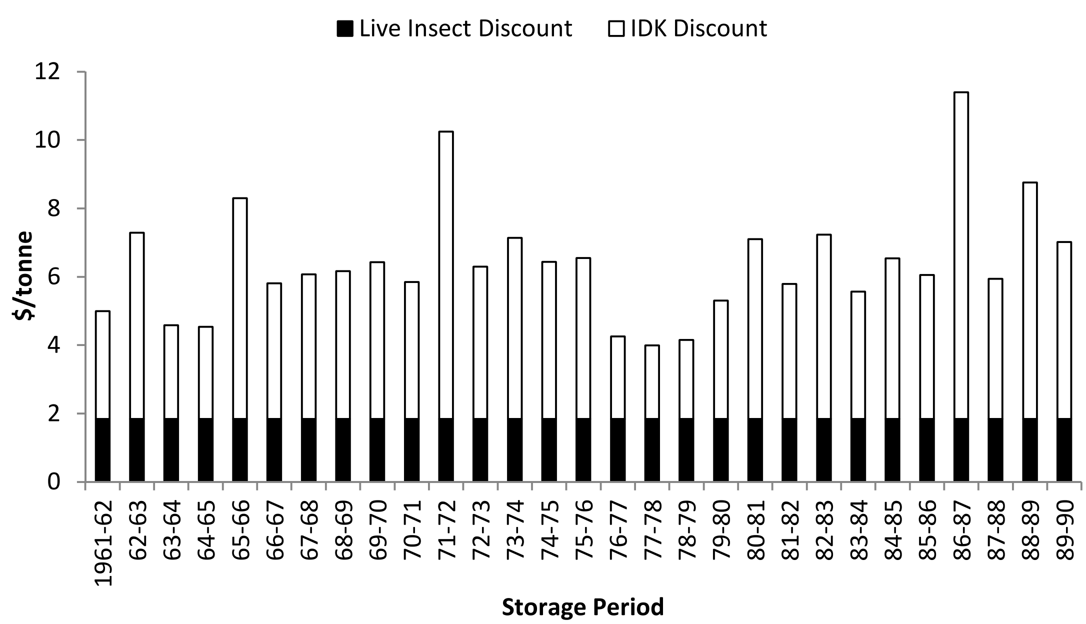

Figure 4.3 Total Cost of Doing Nothing: Normal Immigration Rate, Oklahoma City, 1961 to 1990

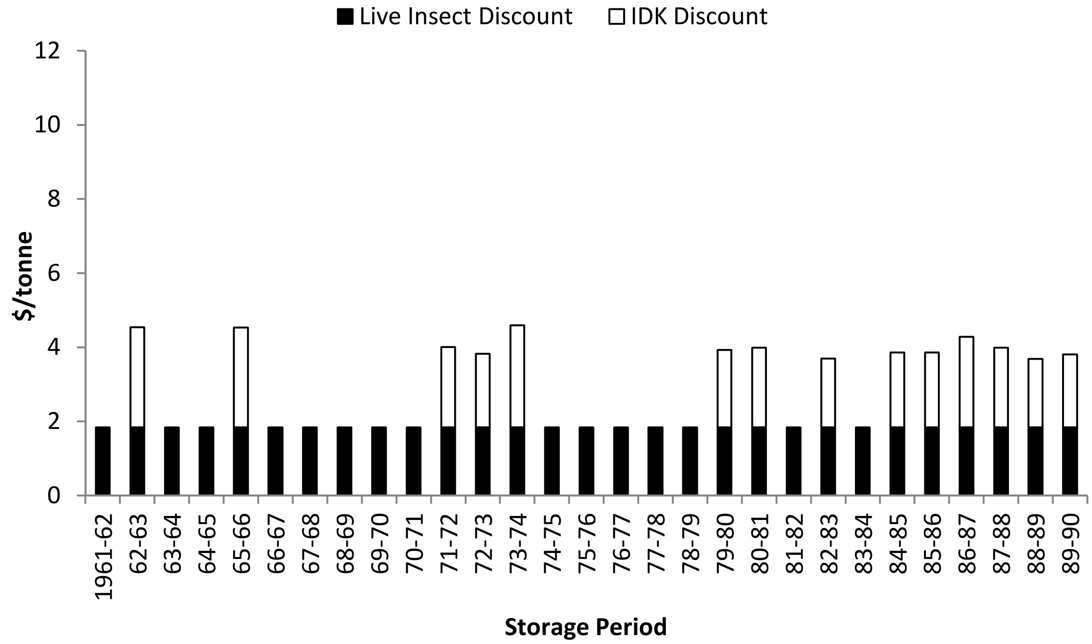

Figure 4.4 Total Cost of Doing Nothing: Normal Immigration Rate, Wichita, 1961 to 1990

Figures 4.5 and 4.6 show total cost with a high immigration rate if there was no treatment during the storage period from 1961 to 1990. In this case, the highest value in the y-axis is 10 times the highest value for the low and normal immigration rate graphs. As with a normal immigration rate, a live insect discount of $1.837/tonne occurred every year in both Oklahoma City and Wichita.

The magnitude of the IDK discount was significantly higher than with a normal immigration rate and occurred every year in both OKC and Wichita. The highest IDK discount in OKC was $95.35/tonne (1986/87) and the lowest was $21.51/tonne (1977/78). The IDK discount in Wichita was typically lower than in OKC. The highest IDK discount in Wichita was $27.47/tonne (1973/74) and the lowest was $6.72/tonne (1976/77). The insect-related costs under a high immigration rate were roughly ten times those under a normal immigration rate.

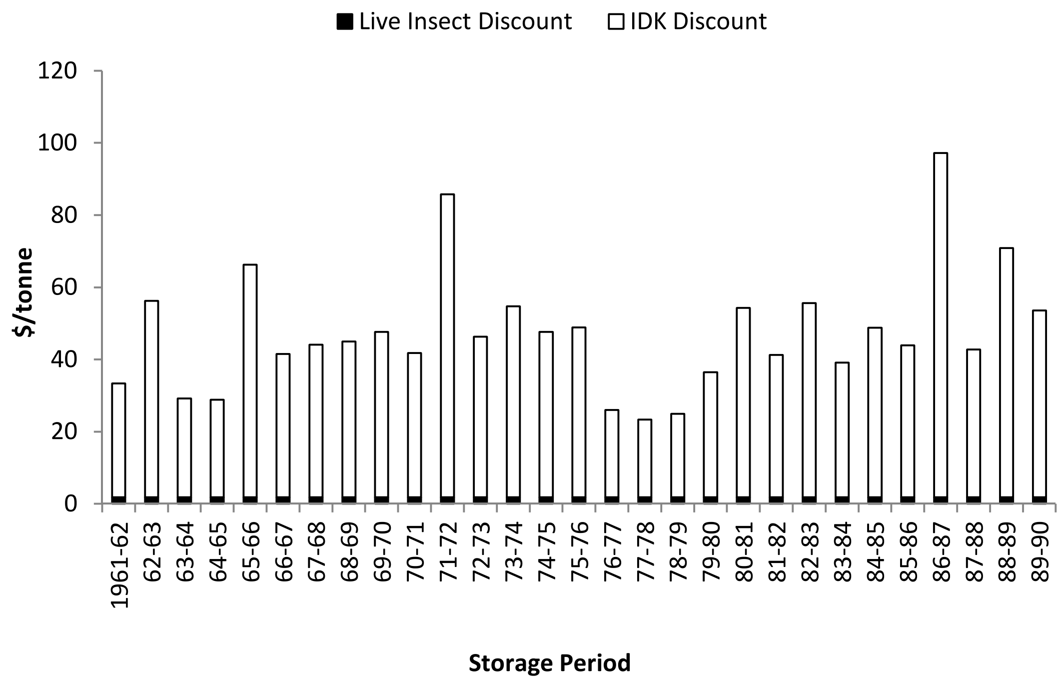

Figure 4.5 Total Cost of Doing Nothing: High Immigration Rate, Oklahoma City, 1961 to 1990

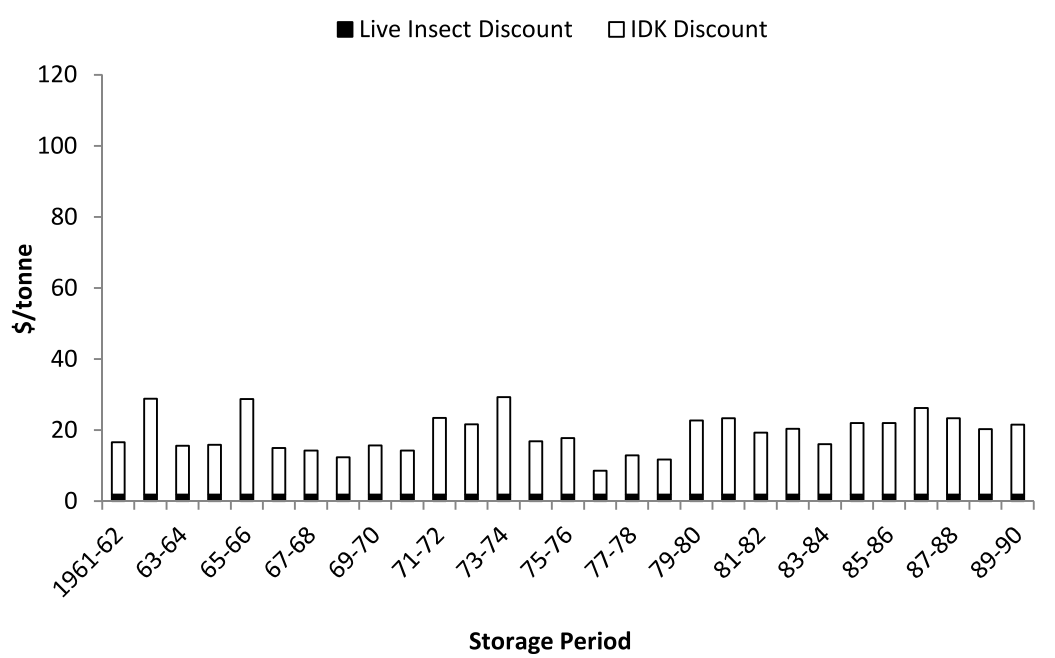

Figure 4.6 Total Cost of Doing Nothing: High Immigration Rate, Wichita, 1961 to 1990

For the other treatments and approaches to be considered, we are looking for dates for which resulting costs are lowest; these may be candidates for the most robust treatments and treatment dates.

Routine Fumigation

One Routine fumigation

Figures 4.7-4.12 show the cost of conducting one routine fumigation during each storage period. Each day of the storage period is considered as a possibility to be that one day; each point in a particular line on the graph represents the total cost (both treatment cost and insect damage cost) of fumigating on that day. As before, the highest value in the y-axis for high immigration rate is 10 times the highest value for normal and low immigration rate.

With a low immigration rate (Figures 4.7 and 4.8), the total cost can be separated into only two different ranges. First, in every year in OKC and 17 out of 29 years in Wichita, fumigating at the beginning of each storage period would result in an IDK discount of zero. The cost of $2.774/tonne contained the live insect discount and treatment cost (table 4.1). This period is too early to fumigate, since live insect discount occurs.

Then, in the second range, the total cost started decreasing to $0.937/tonne, which equals the cost of fumigation. This cost is an optimal value with fumigation on any of those dates the optimal strategy. In OKC, the earliest date the 2nd range began was June 27 (in the 1987/88 storage period). In Wichita, the earliest date 2nd range began was June 21 during the 1988/89 storage period.

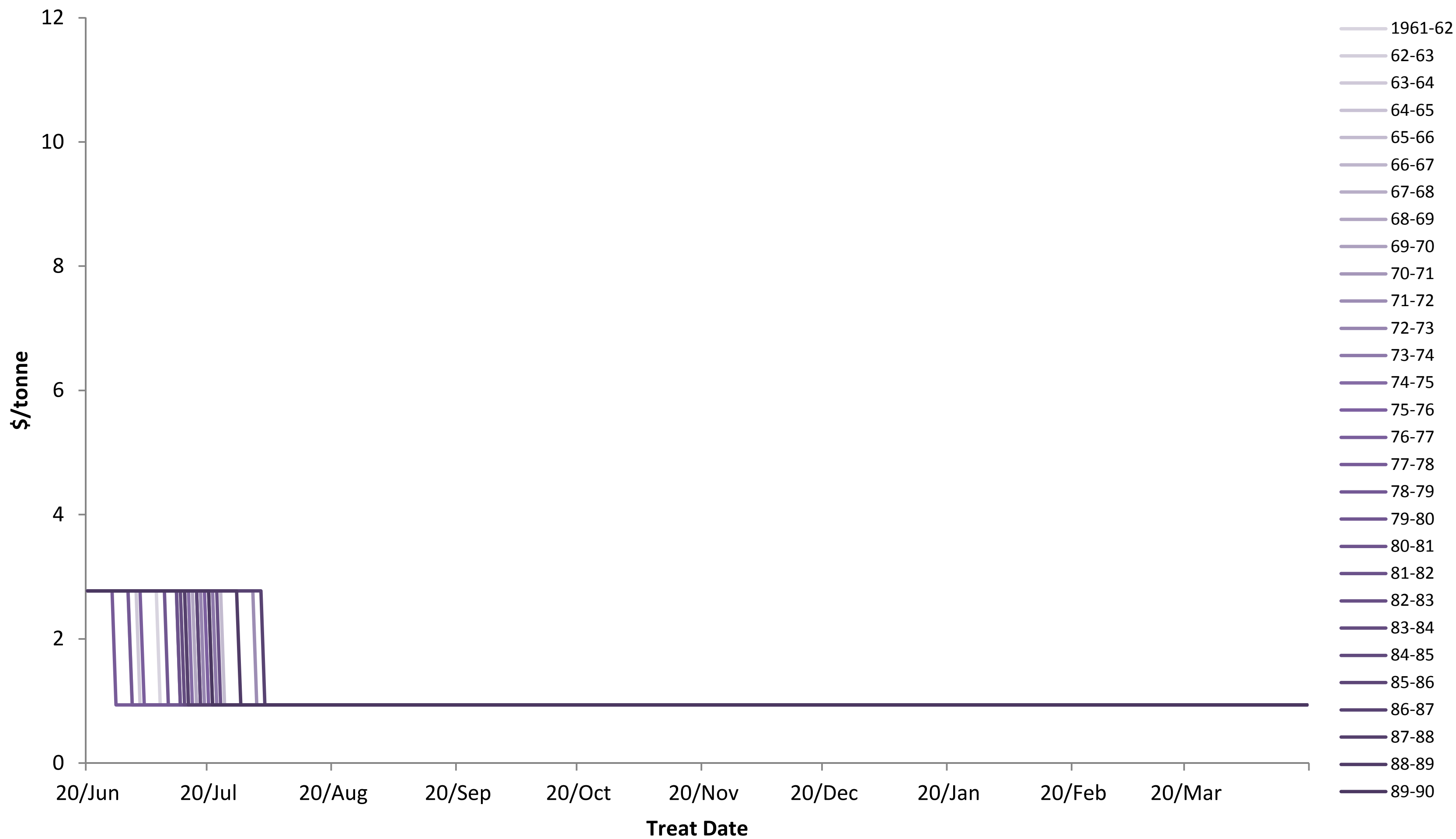

Figure 4.7 Annual Cost of Fumigating Once per Year with Low Immigration Rate in OKC from 1961 to 1990 (Crop Years, June 20 – April 18 or 19)

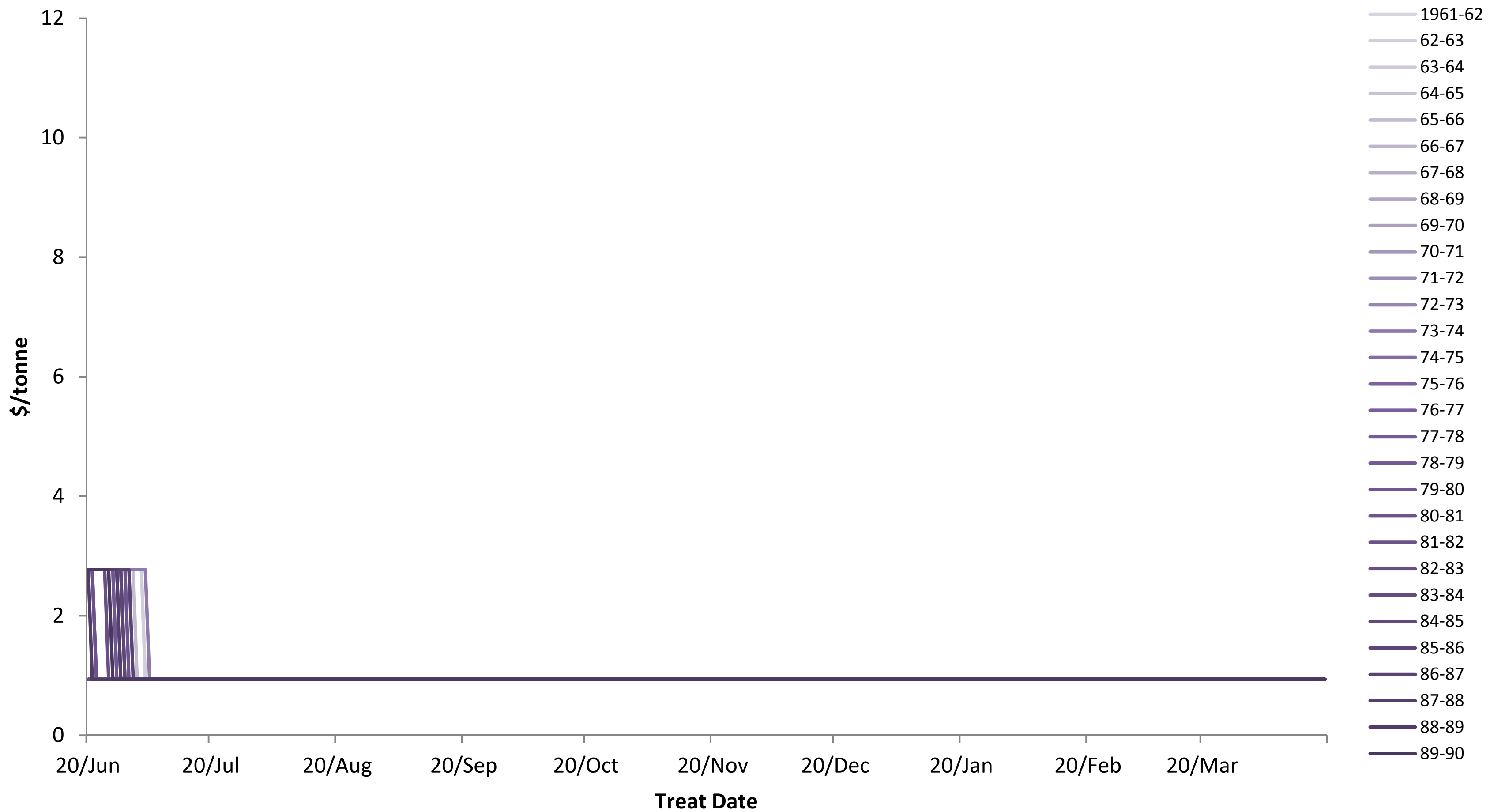

Figure 4. Annual Cost of Fumigating Once per Year with Low Immigration Rate in Wichita from 1961 to 1990 (Crop Years, June 20 – April 18 or 19)

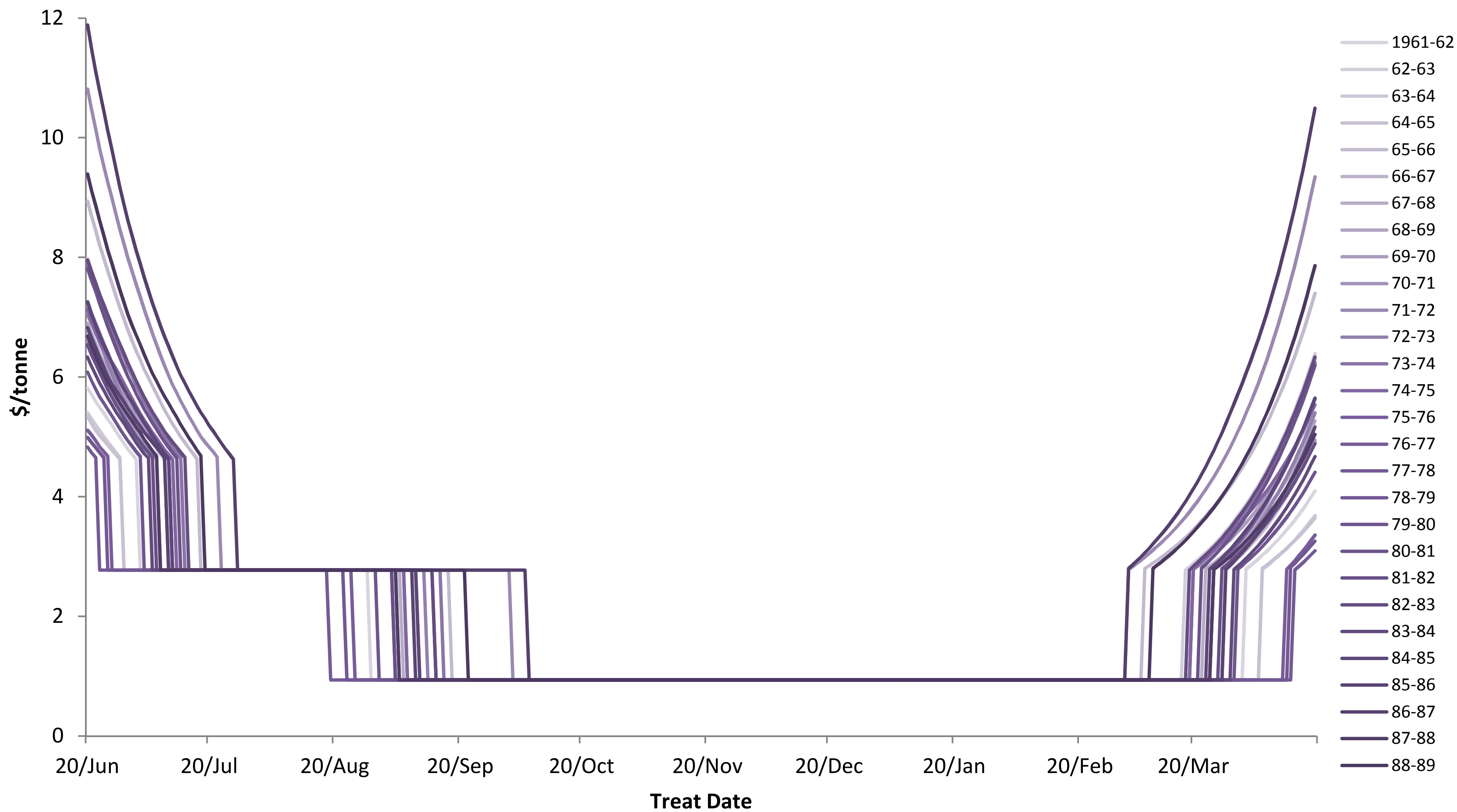

Figure 4.9 Annual Cost of Fumigating Once per Year with Normal Immigration Rate in OKC from 1961 to 1990 (Crop Years, June 20 – April 18 or 19)

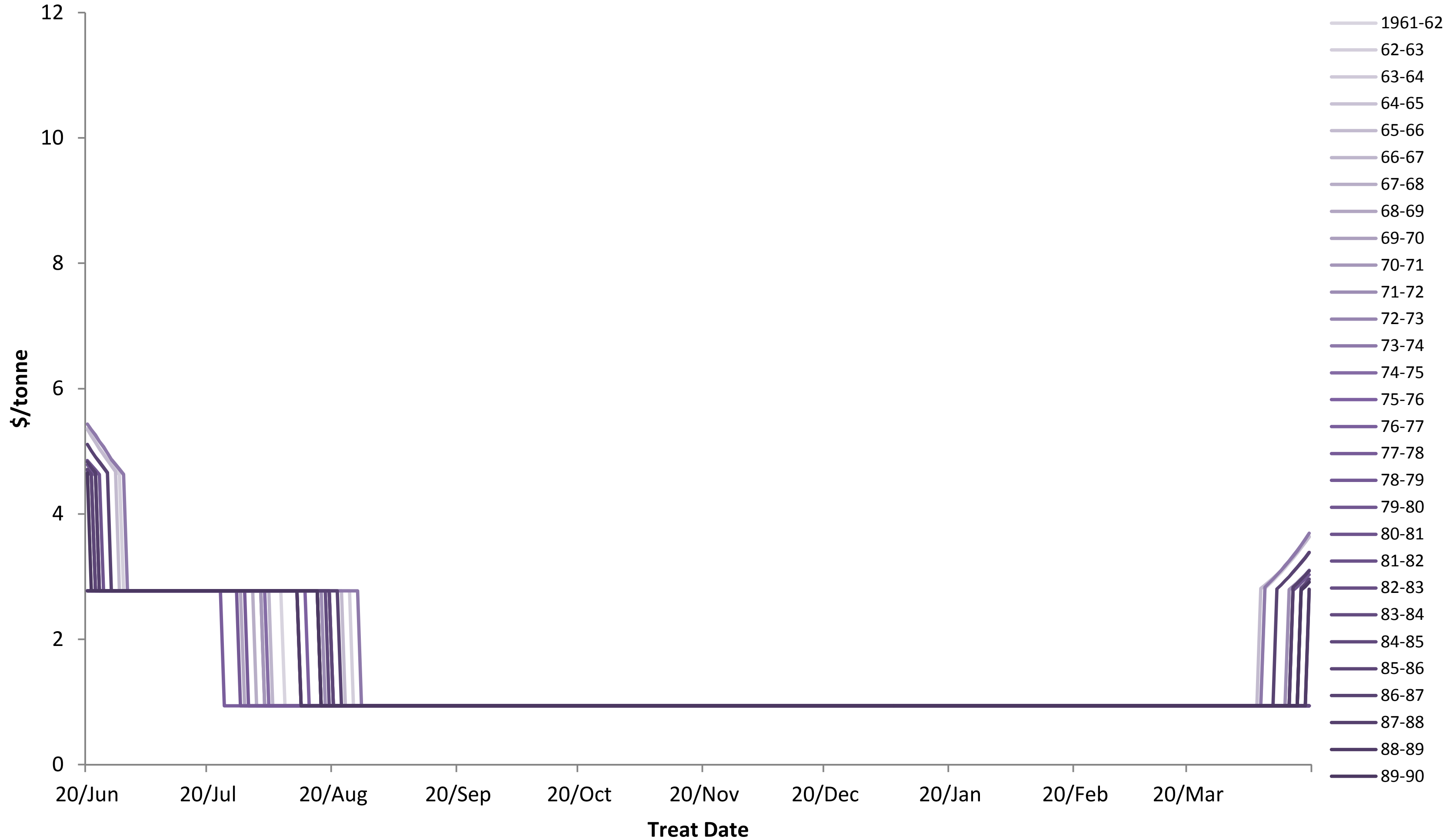

Figure 4.10 Annual Cost of Fumigating Once per Year with Normal Immigration Rate in Wichita from 1961 to 1990 (Crop years, June 20 – April 18 or 19)

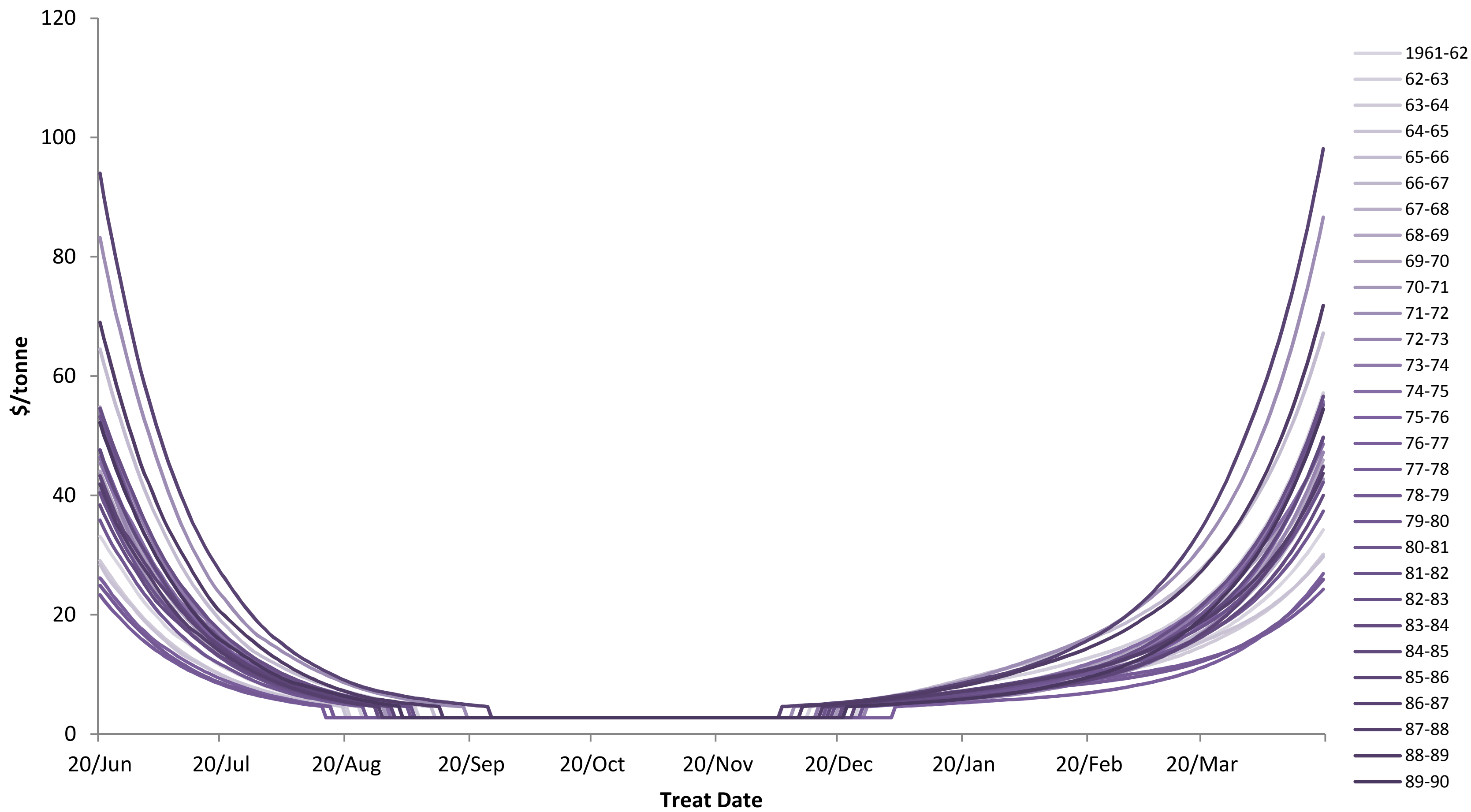

Figure 4.11 Annual Cost of Fumigating Once per Year with High Immigration Rate in OKC from 1961 to 1990 (Crop years, June 20 – April 18 or 19)

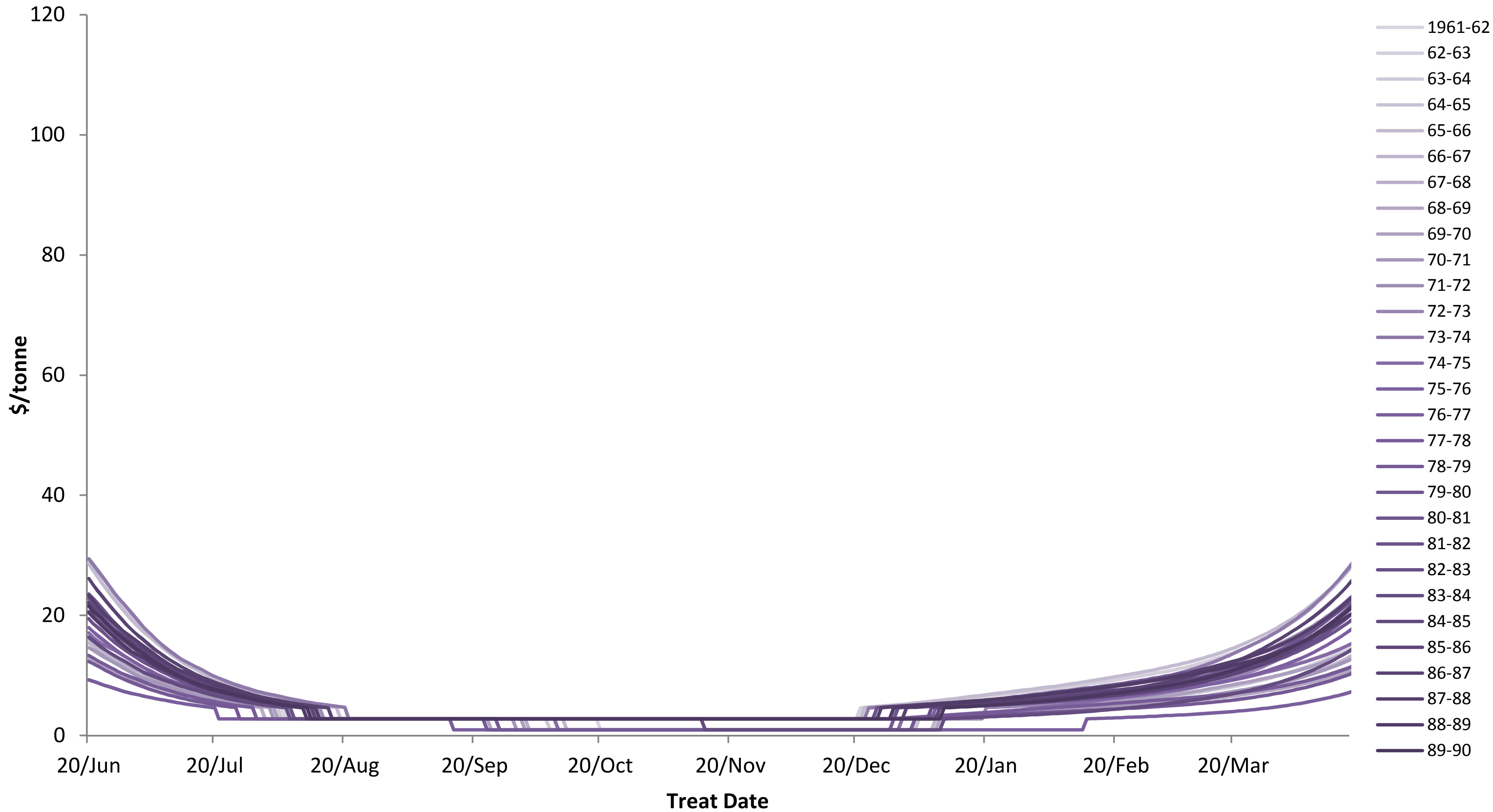

Figure 4.12 Annual Cost of Fumigating Once per Year with High Immigration Rate in Wichita from 1961 to 1990 (Crop years, June 20 – April 18 or 19)

In Wichita in the 12 storage periods 1961/62, 1963/64, 1964/65, 1966/67, 1967/68, 1968/69, 1969/70, 1970/71, 1974/75, 1976/77, 1977/78, and 1978/79 the total costs were \$0.937/tonne for one fumigation. This is consistent with the result shown in figure 4.2 that for these years, the optimal strategy would have been to do nothing; there were no costs of insects at all, so that fumigation causes extra cost.

With a normal immigration rate (Figures 4.9 and 4.10), the total cost can be separated into four different ranges. Fumigating from approximately June 20 to the end of July (dates vary depending on years) is very inefficient because the insect population has a long time during the hot summer to rebound, causing both live insect and IDK discounts before the grain is sold.

The 2nd cost range, beginning from a range (depending on the years) between June 23 and July 27 for OKC and beginning from a range between June 20 and July 29 for Wichita, was \$2.77/tonne or higher, including live insect discount and treatment cost but no IDK discount.

Third, for many of the 29 years fumigation once was sufficient to avoid live insect and IDK discounts, so that the only cost was a fumigation treatment cost of \$0.937/tonne. Depending on the year, this lowest cost result could be achieved by fumigating as early as August 19 in OKC and July 24 in Wichita, or as late as April 13 in OKC and April 19 in Wichita.

However, the “window” of lowest cost for all years was from October 7 through March 3 of the following year in OKC, and from August 27 through April 7 of the following year in Wichita. Fumigating on any day within these windows was early enough in all years to prevent insect population from growing enough to damage wheat, yet late enough to prevent insect population from rebounding sufficiently to result in a live insect discount.

Because of the relatively cooler temperatures in Wichita, the low-cost window there was wider than in OKC most of the individual years, and the window that included all years was also wider in Wichita than in OKC.

In the fourth cost range, fumigation conducted after March in OKC and April in Wichita was more likely to result in IDK discounts, in addition to treatment cost. Depending on the year, this range began with fumigation as early as March 3 or as late as April 13 in OKC, and as early as April 7 or as late as April 19 in Wichita. Especially in OKC, costs increased rapidly once they began increasing, since insect population increases exponentially with favorable weather conditions.

For a high immigration rate (Figures 4.11 and Figure 4.12), there was no year in OKC for which one fumigation, at any time, was sufficient to avoid either live insect or IDK discounts. Fumigating between September 25 and December 5, though, attained lower costs than fumigating on other dates.

For Wichita, in 13 of the 29 years one fumigation (between November 14 and December 20) was sufficient to avoid discounts. However, just as in OKC, in 16 of the 29 years live insect and IDK discounts resulted no matter when the fumigation was conducted, although the total costs were lower in Wichita than in OKC.

Two Routine Fumigations

Table 4.2 summarizes the cost of conducting two routine fumigations, one on October 31 and one on March 31. The costs in every storage period, in both OKC and Wichita, were $1.66/tonne. Fumigating twice eliminated both live insect and IDK discounts, regardless of the immigration rate. However, the second fumigation was unnecessary in some years in both locations under low and normal immigration rates, and in some years, even with a high immigration rate, in Wichita.

Table 4.2 Cost ($/tonne) Summary of Two Routine Fumigations on October 31 and March 31

	OKC			Wichita		
Storage Period [b]	Low Immigration	Normal Immigration	High Immigration	Low Immigration	Normal Immigration	High Immigration
1961/62	1.66[N/O]	1.66[N/O]	1.66	1.66[N/O]	1.66[N/O]	1.66[N/O]
1962/63	1.66[N/O]	1.66[N/O]	1.66	1.66[N/O]	1.66[N/O]	1.66
1963/64	1.66[N/O]	1.66[N/O]	1.66	1.66[N/O]	1.66[N/O]	1.66[N/O]
1964/65	1.66[N/O]	1.66[N/O]	1.66	1.66[N/O]	1.66[N/O]	1.66[N/O]
1965/66	1.66[N/O]	1.66[N/O]	1.66	1.66[N/O]	1.66[N/O]	1.66
1966/67	1.66[N/O]	1.66[N/O]	1.66	1.66[N/O]	1.66[N/O]	1.66[N/O]
1967/68	1.66[N/O]	1.66[N/O]	1.66	1.66[N/O]	1.66[N/O]	1.66[N/O]
1968/69	1.66[N/O]	1.66[N/O]	1.66	1.66[N/O]	1.66[N/O]	1.66[N/O]
1969/70	1.66[N/O]	1.66[N/O]	1.66	1.66[N/O]	1.66[N/O]	1.66[N/O]
1970/71	1.66[N/O]	1.66[N/O]	1.66	1.66[N/O]	1.66[N/O]	1.66[N/O]
1971/72	1.66[N/O]	1.66[N/O]	1.66	1.66[N/O]	1.66[N/O]	1.66
1972/73	1.66[N/O]	1.66[N/O]	1.66	1.66[N/O]	1.66[N/O]	1.66
1973/74	1.66[N/O]	1.66[N/O]	1.66	1.66[N/O]	1.66[N/O]	1.66
1974/75	1.66[N/O]	1.66[N/O]	1.66	1.66[N/O]	1.66[N/O]	1.66[N/O]
1975/76	1.66[N/O]	1.66[N/O]	1.66	1.66[N/O]	1.66[N/O]	1.66
1976/77	1.66[N/O]	1.66[N/O]	1.66	1.66[N/O]	1.66[N/O]	1.66[N/O]
1977/78	1.66[N/O]	1.66[N/O]	1.66	1.66[N/O]	1.66[N/O]	1.66[N/O]
1978/79	1.66[N/O]	1.66[N/O]	1.66	1.66[N/O]	1.66[N/O]	1.66[N/O]
1979/80	1.66[N/O]	1.66[N/O]	1.66	1.66[N/O]	1.66[N/O]	1.66
1980/81	1.66[N/O]	1.66[N/O]	1.66	1.66[N/O]	1.66[N/O]	1.66
1981/82	1.66[N/O]	1.66[N/O]	1.66	1.66[N/O]	1.66[N/O]	1.66
1982/83	1.66[N/O]	1.66[N/O]	1.66	1.66[N/O]	1.66[N/O]	1.66
1983/84	1.66[N/O]	1.66[N/O]	1.66	1.66[N/O]	1.66[N/O]	1.66[N/O]
1984/85	1.66[N/O]	1.66[N/O]	1.66	1.66[N/O]	1.66[N/O]	1.66
1985/86	1.66[N/O]	1.66[N/O]	1.66	1.66[N/O]	1.66[N/O]	1.66
1986/87	1.66[N/O]	1.66[N/O]	1.66	1.66[N/O]	1.66[N/O]	1.66
1987/88	1.66[N/O]	1.66[N/O]	1.66	1.66[N/O]	1.66[N/O]	1.66
1988/89	1.66[N/O]	1.66[N/O]	1.66	1.66[N/O]	1.66[N/O]	1.66
1989/90	1.66[N/O]	1.66[N/O]	1.66	1.66[N/O]	1.66[N/O]	1.66

N/O: not optimal: unnecessary fumigation occurs

Sampling-based Fumigation

<u>One sample</u>

Figures 4.13 to 4.18 show the cost of taking one sample during each storage period, with a fumigation conducted if the number of insects in the sample exceeds the threshold of 0.5

insects/kg. As with “One Routine Fumigation,” each day of the storage period is considered as a possibility to be the day that the sample is taken. Comparing these figures with figures 4.7 to 4.12, the cost shape for sampling-based fumigation is different than for one routine fumigation.

With a low immigration rate (Figures 4.13 and 4.14), depending on the year, two possible results occurred. After incurring a sampling cost, for samples that exceeded the threshold, fumigation occurred, and the total cost was $1.28/tonne, with no live insect or IDK discounts. For OKC, if the sampling did not exceed the threshold, fumigation did not occur, and the insect population grew to a level that incurred a live insect discount, for a total cost of $2.40/tonne.

With later dates for the sample to be taken, total cost dropped from $2.40/tonne to $1.28/tonne. The date in each year on which that drop occurred represents the starting dates when sampling indicated fumigation should occur. Sampling on dates earlier than that resulted in no fumigation (because the sample didn’t exceed the threshold), so the insect population grew unchecked to level that incurred a live insect discount. The earliest date sampling indicated fumigation should occur was on February 8 (in the 1986/87 storage period) and the latest date was March 27 (in the 1977/78 storage period).

For Wichita, in 17 of 29 years, the sample exceeded the threshold and fumigation was conducted, for a total cost of $1.28/tonne. If the sample did not exceed the threshold, fumigation did not occur; this happened in 12 out of 29 years. In eleven of those years, the insect population grew to a level that incurred a live insect discount, for a total cost of $2.40/tonne. Ine the other year, though, (1976/77) no live insect discount resulted and the total cost was $0.345/tonne.

For Wichita, the earliest date that sampling led to fumigation was March 14 (in the 1973/74 year) and the latest date was April 4 (1987/84). In general, sampling late was more likely to signal fumigation, which sampling earlier was more likely to signal no fumigation. In most years, this “no fumigation” signal led to a live insect discount.

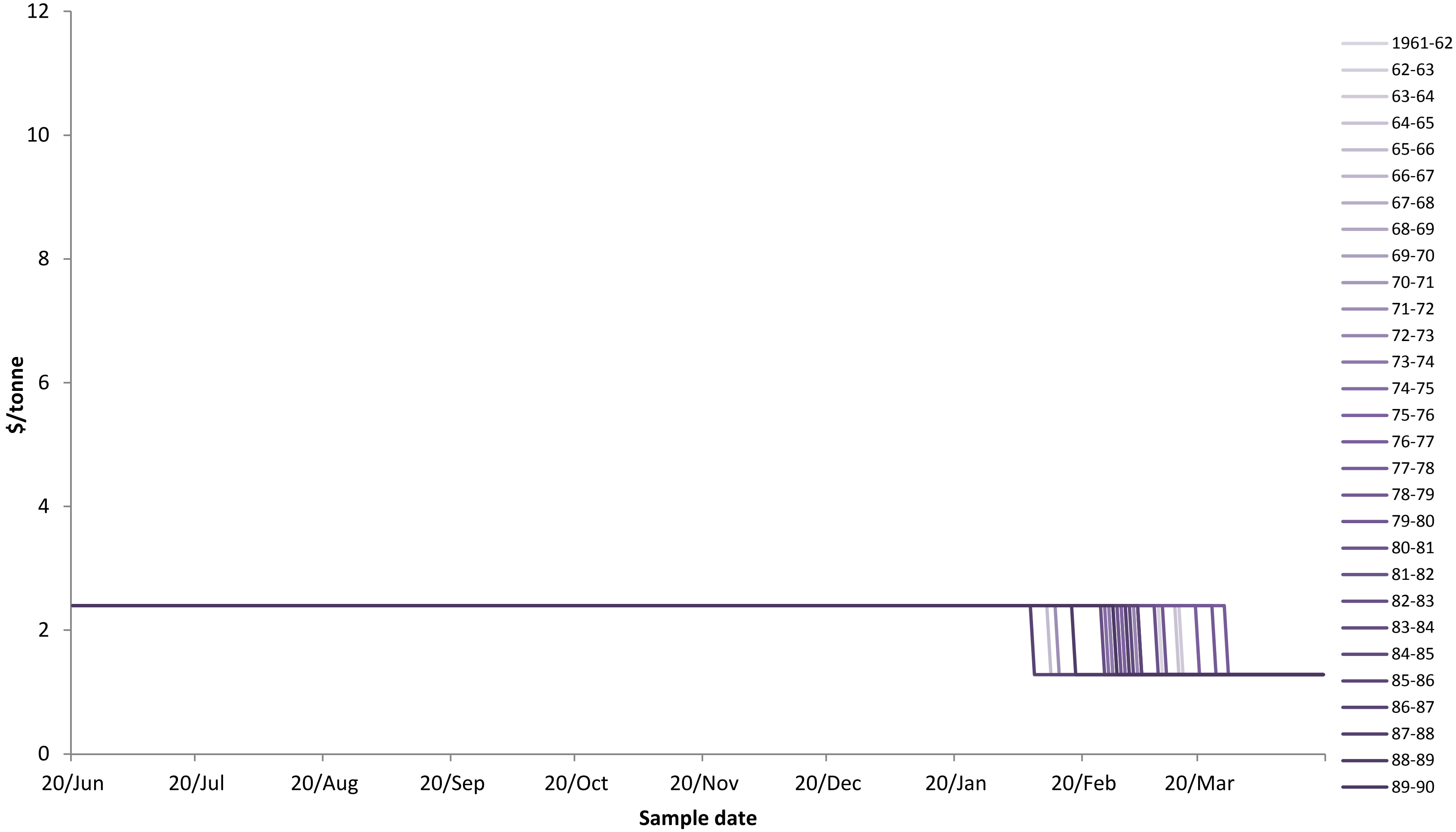

Figure 4.13 Annual Cost of Sampling-Based Fumigation: Low Immigration Rate, OKC, 1961-1990 (One Sample on the Sample Date plus Fumigation If Threshold Exceeded)

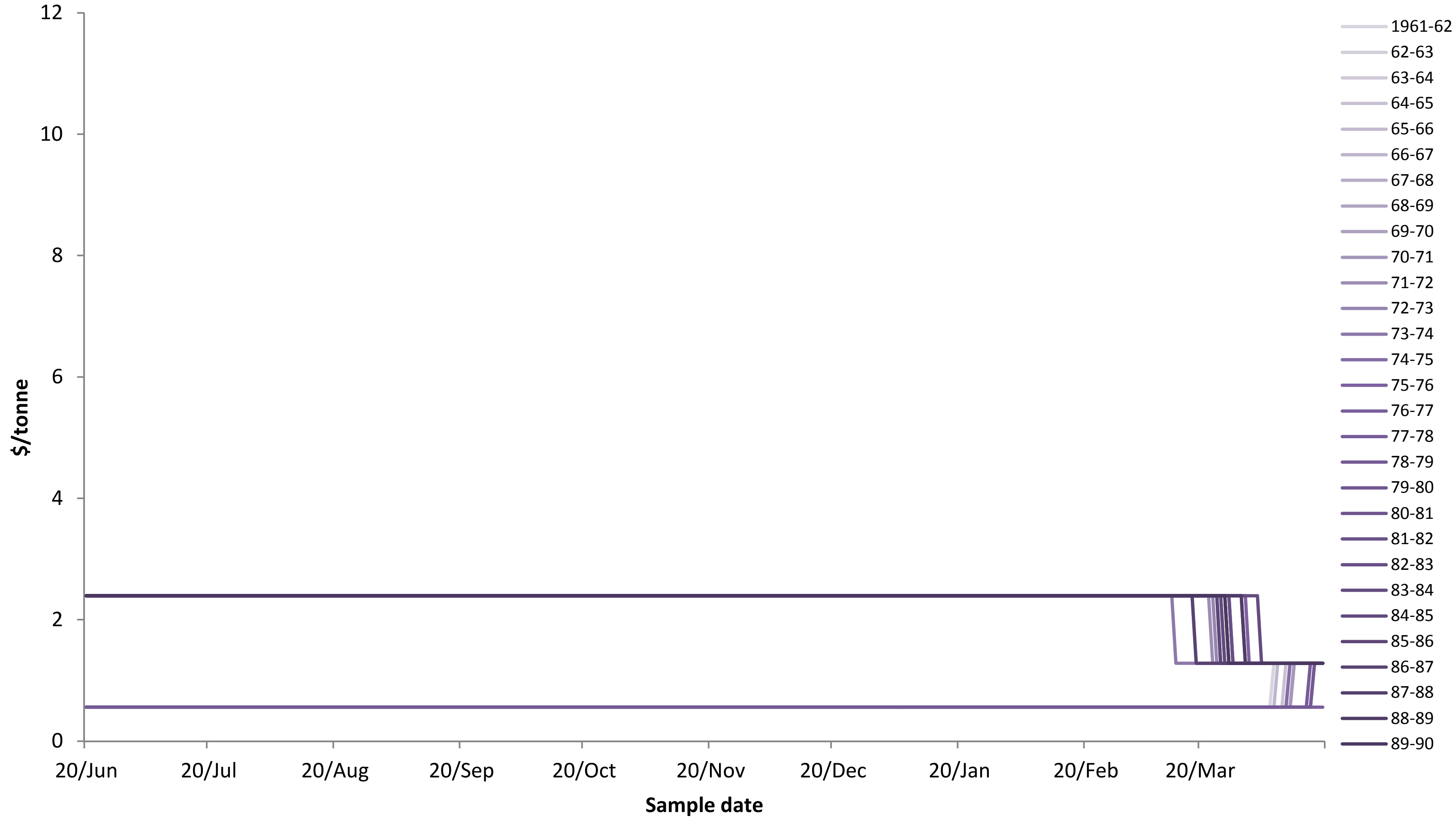

Figure 4.14 Annual Cost of Sampling-Based Fumigation: Low Immigration Rate, Wichita, 1961-1990 (One Sample on the Sample Date plus Fumigation If Threshold Exceeded)

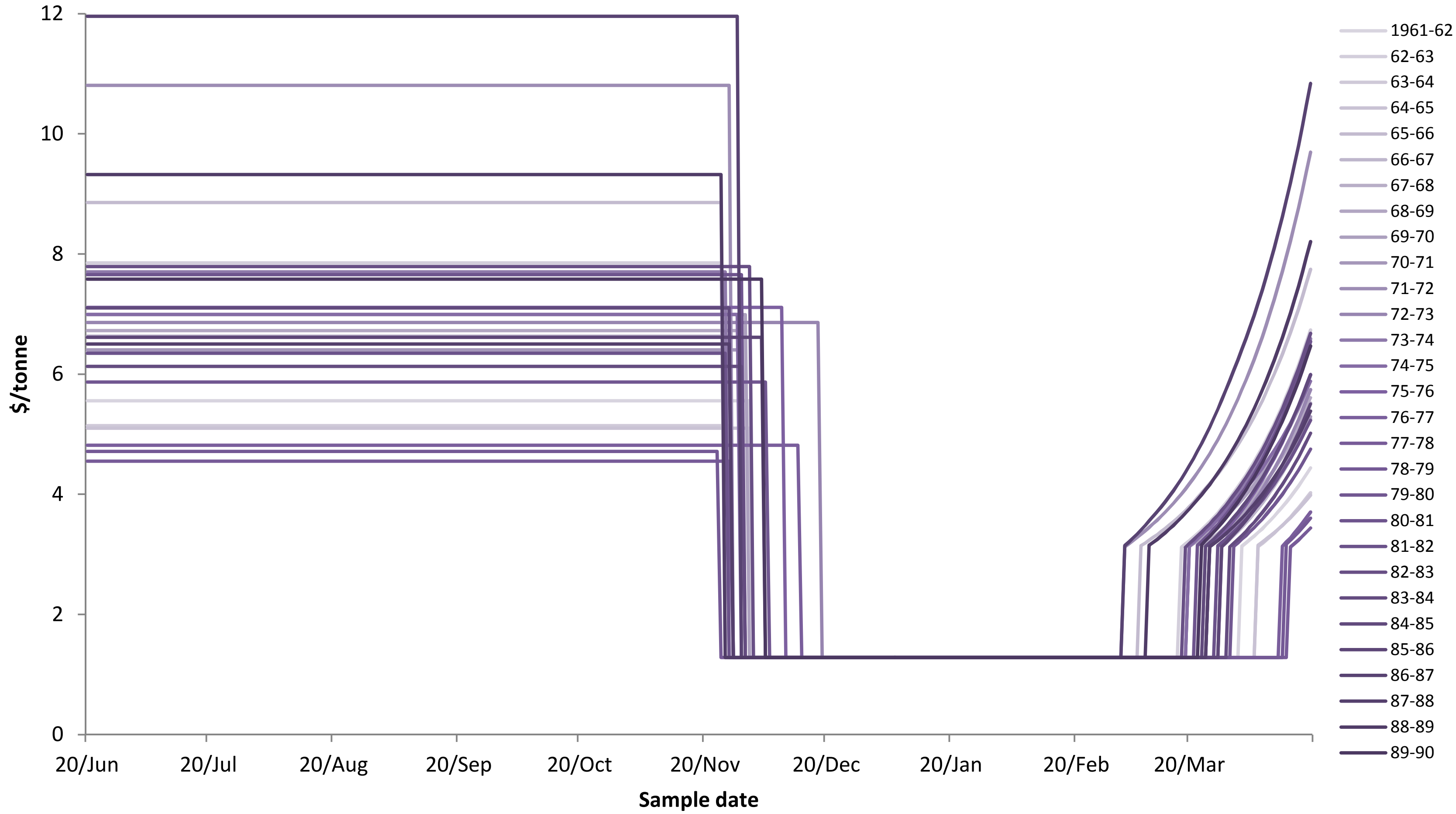

Figure 4.15 Annual Cost of Sampling-Based Fumigation: Normal Immigration Rate, OKC, 1961-1990 (One Sample on the Sample Date plus Fumigation If Threshold Exceeded)

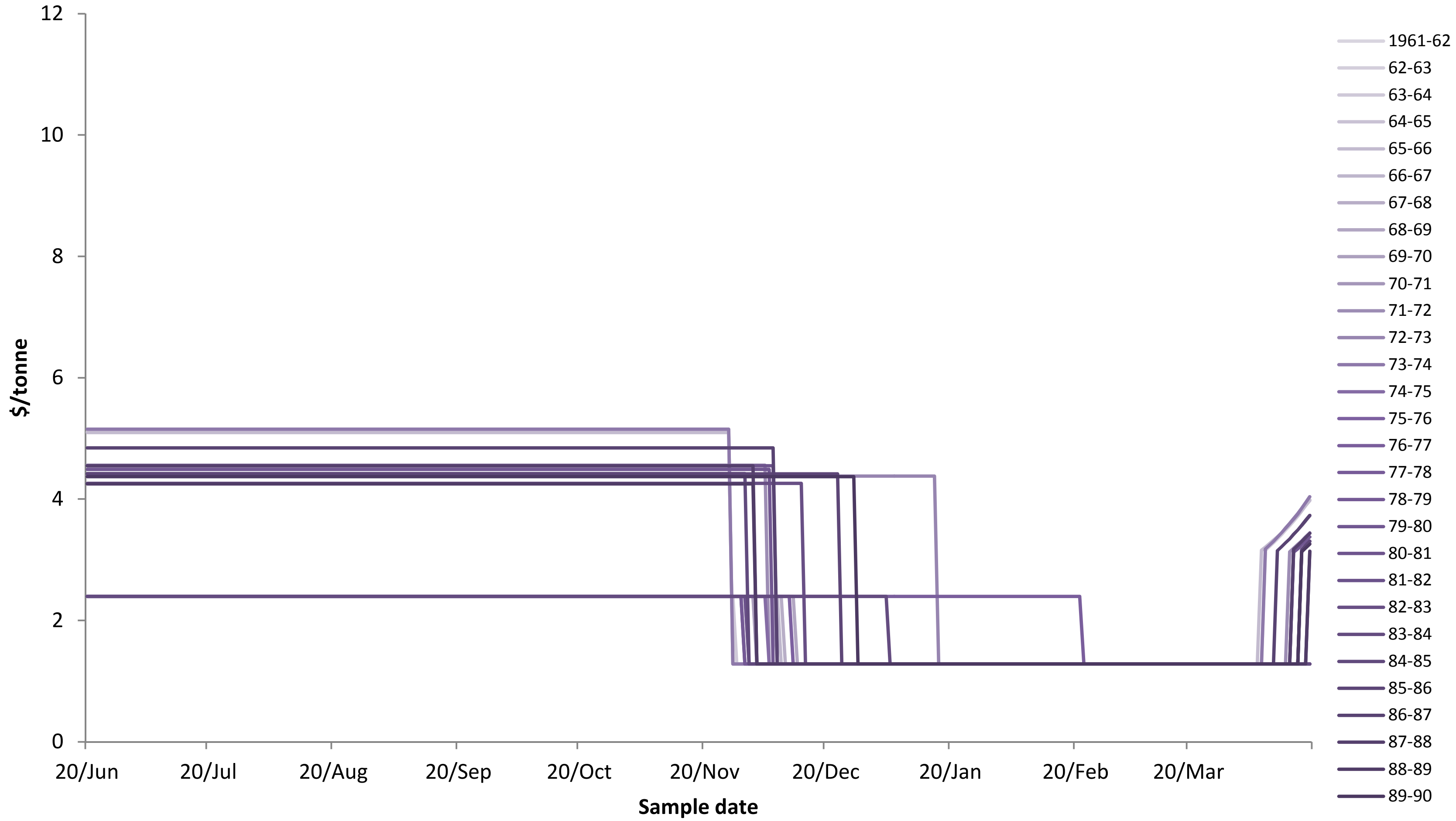

Figure 4.16 Annual Cost of Sampling-Based Fumigation: Normal Immigration Rate, Wichita, 1961-1990 (One Sample on the Sample Date plus Fumigation If Threshold Exceeded)

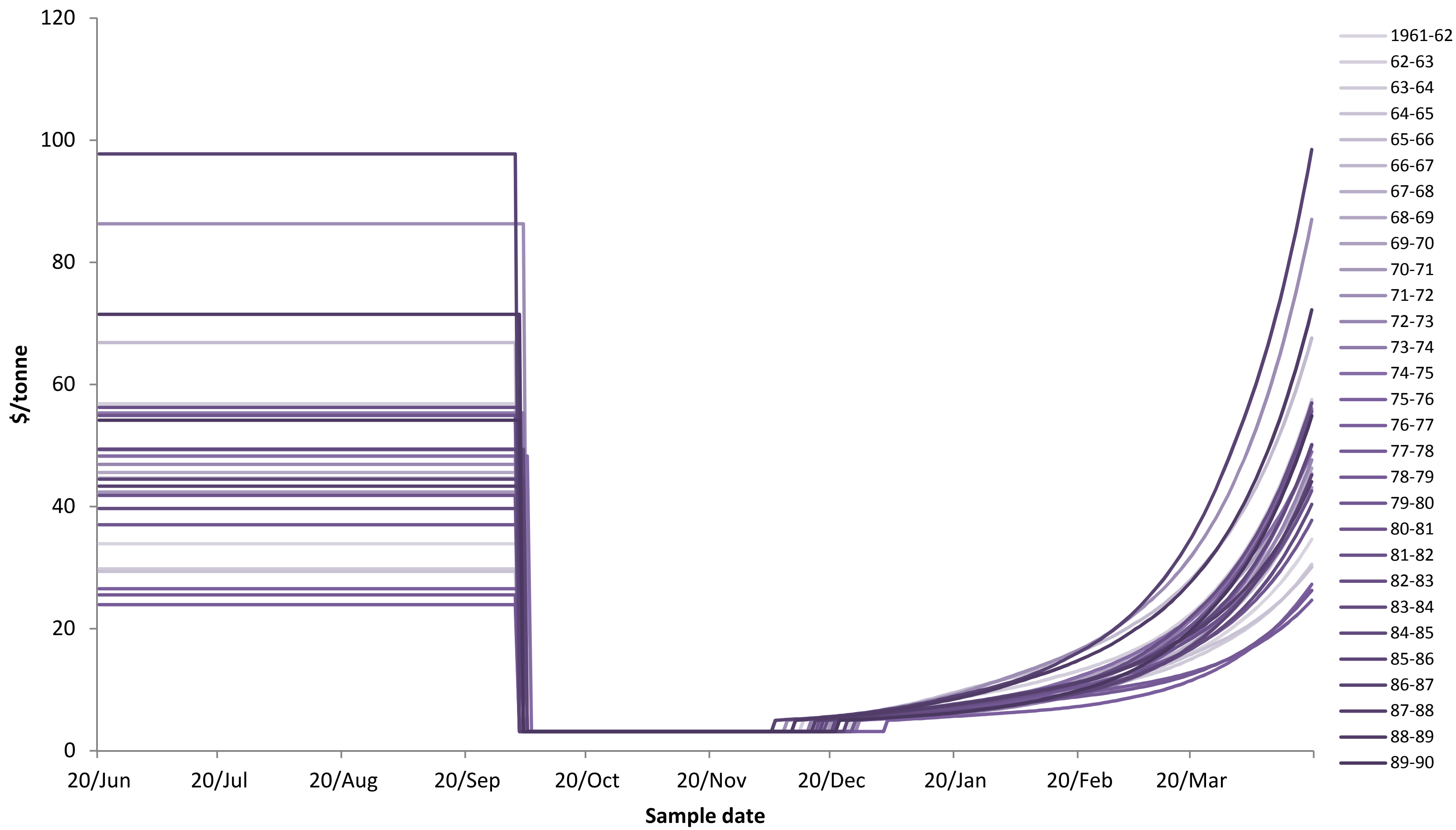

Figure 4.17 Annual Cost of Sampling-Based Fumigation: High Immigration Rate, OKC, 1961-1990 (One Sample on the Sample Date plus Fumigation If Threshold Exceeded)

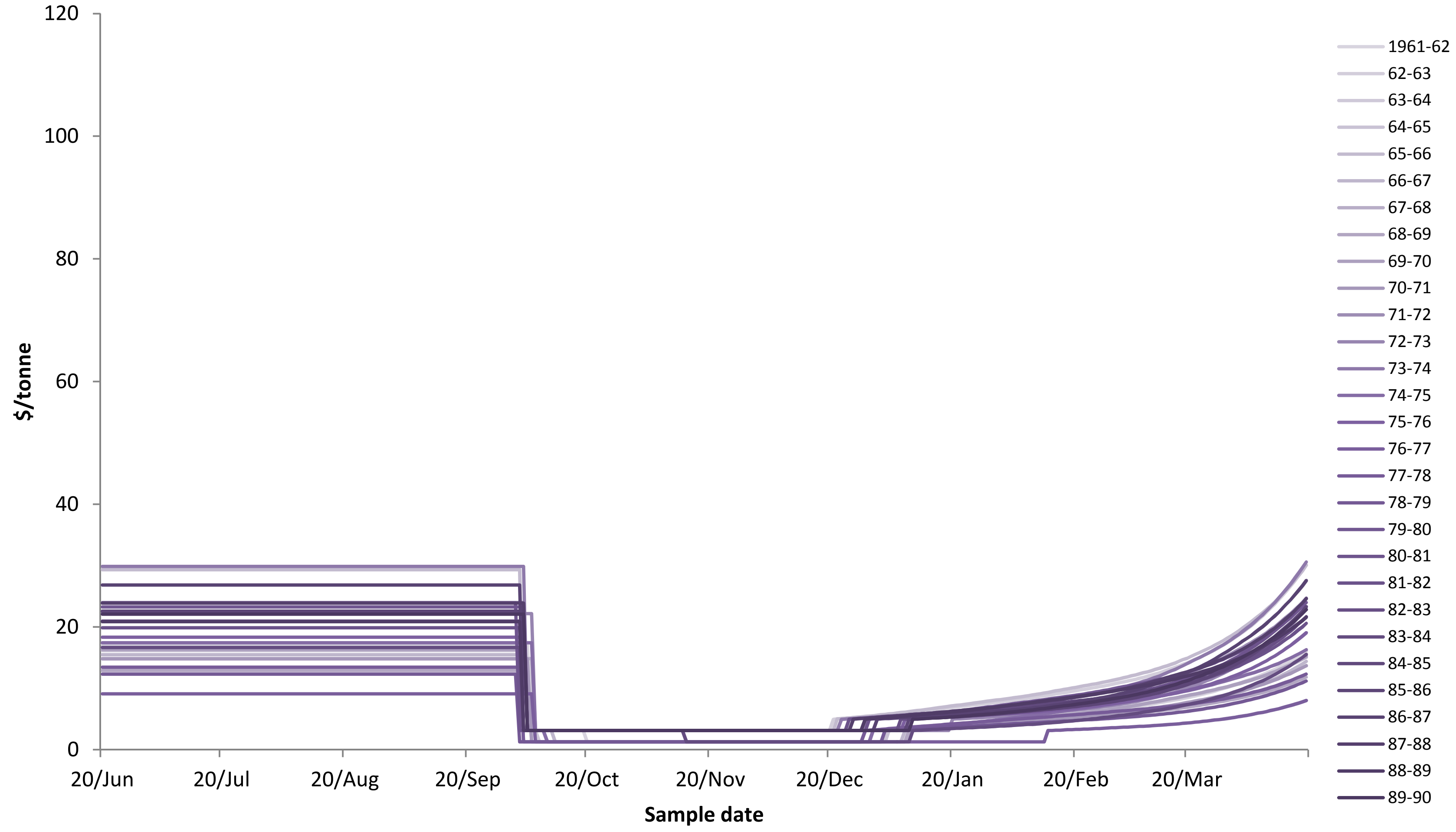

Figure 4.18 Annual Cost of Sampling-Based Fumigation: High Immigration Rate, Wichita, 1961-1990 (One Sample on the Sample Date plus Fumigation If Threshold Exceeded)

With a normal immigration rate (Figures 4.15 and 4.16), the total cost can be separated into three ranges. In OKC, from June 20 to a range (depending on the years) between November 25 and December 19, and, in Wichita to a range between November 27 and February 23, sampling did not indicate fumigation was necessary, so insect population grew unchecked, resulting in live insect and IDK discounts in most years, in addition to sampling cost. In 15 of the 29 years, no IDK discount resulted because weather conditions were less conducive for insect growth.

Sampling on any day from December through March is the second range, and has the lowest cost. Sampling once during this time period resulted in one fumigation, so the cost is one sampling cost plus one fumigation cost, but no live insect or IKD discount, for total of $1.28/tonne. The “window” of lowest cost for all years was from December 19 through March 13 of the following year in OKC. The results in Wichita are similar to these in OKC, except that the data range for the lowest cost was February 22 through April 6 for all years.

The earliest date on which sampling gave a signal to fumigate in OKC was November 24 in the 1978/79 storage period, and the latest date was December 19 in the storage period 1972/73. In Wichita, the earliest data on which sampling gave a signal to fumigate was November 27 in the 1962/63, 1965/66, and 1973/74 storage periods, and the latest date was February 22 in the storage period 1972/73.

Sampling after March in OKC or April in Wichita, the beginning of the 3rd cost range, resulted in fumigating after insects had already caused IDK, so in addition to sampling and fumigation costs, IDK discounts resulted.

Similarly, with a high immigration rate (Figures 4.17 and 4.18), the cost can be separated into three ranges. In the 1st cost range, total cost for all storage periods in OKC and Wichita contains sampling cost and both live insect and IDK discounts.

The 2nd cost range was the lowest cost, beginning October 1 in both OKC and Wichita and ending December 1 in OKC and December 20 in Wichita. In OKC, the cost was $3.12/tonne (one sampling cost + one fumigation cost + live insect discount), which implies that with a high immigration rate, fumigating once was not enough to control insect population.

In Wichita, the cost was either $3.12/tonne (one sampling cost + one fumigation cost + live insect discount) or $1.28/tonne (one sampling cost + one fumigation cost), depending on the year. There were 16 out of 29 years with a cost of $3.12/tonne: 1962/63, 1965/66, 1971/72, 1972/73, 1973/74, 1975/76, 1979/80, 1980/81, 1981/82, 1982/83, 1984/85, 1985/86, 1986/87, 1987/88, 1988/89, and 1989/90. In these years in Wichita as well as all years in OKC, the cost included live insect and IDK discounts in addition to fumigation cost. The other 13 out of 29 years in Wichita had a lower cost of $1.28/tonne, consisting of sampling cost and fumigation cost.

Monthly sampling

Monthly sampling at every end of the month. Tables 4.3 and 4.4 summarize results for monthly sampling at the end of every month from September to March with a 0.5 insect/kg threshold. Sample dates are: Sep 30, Oct 31, Nov 30, Dec 31, Jan 31, Feb 28 and Mar 31.

Table 4.3 shows that in OKC, for low and normal immigration rates, monthly sampling indicated that fumigation should occur once each year. Fumigation dates were in either November or December for a normal immigration rate and in February or March for a low immigration. The costs were $1.53/tonne (monthly sampling cost + one fumigation cost). This result is consistent with the previous result that one fumigation is necessary for storage structures with low and normal immigration rates in OKC.

Table 4.3 Summary of Results for Monthly Sampling at End of Month, September to March, 0.5 Insects/Kg Threshold, OKC

	Optimal dates and cost																							
	Low Immigration								Normal Immigration								High Immigration							
Storage Period [b]	Sep	Oct	Nov	Dec	Jan	Feb	Mar	TC ($/ton)	Sep	Oct	Nov	Dec	Jan	Feb	Mar	TC ($/ton)	Sep	Oct	Nov	Dec	Jan	Feb	Mar	TC ($/ton)
1961/62							F	1.53				F				1.53		F					F	2.25
1962/63							F	1.53			F					1.53		F				F		2.25
1963/64							F	1.53			F					1.53		F					F	2.25
1964/65							F	1.53				F				1.53		F					F	2.25
1965/66						F		1.53			F					1.53		F				F		2.25
1966/67							F	1.53			F					1.53		F					F	2.25
1967/68							F	1.53			F					1.53		F					F	2.25
1968/69						F		1.53			F					1.53		F				F		2.25
1969/70						F		1.53				F				1.53		F				F		2.25
1970/71							F	1.53			F					1.53		F					F	2.25
1971/72						F		1.53			F					1.53		F				F		2.25
1972/73							F	1.53				F				1.53		F					F	2.25
1973/74						F		1.53			F					1.53		F				F		2.25
1974/75						F		1.53			F					1.53		F				F		2.25
1975/76							F	1.53				F				1.53		F				F		2.25
1976/77							F	1.53				F				1.53		F					F	2.25
1977/78							F	1.53			F					1.53		F					F	2.25
1978/79							F	1.53			F					1.53		F					F	2.25
1979/80							F	1.53				F				1.53		F					F	2.25
1980/81							F	1.53			F					1.53		F				F		2.25
1981/82							F	1.53			F					1.53		F					F	2.25
1982/83						F		1.53				F				1.53		F				F		2.25
1983/84							F	1.53			F					1.53		F					F	2.25
1984/85							F	1.53			F					1.53		F					F	2.25
1985/86							F	1.53				F				1.53		F					F	2.25
1986/87						F		1.53			F					1.53		F				F		2.25
1987/88							F	1.53			F					1.53		F					F	2.25
1988/89						F		1.53			F					1.53		F				F		2.25
1989/90						F		1.53				F				1.53		F				F		2.25

F: means fumigation occurred in that month

Table 4.4 Summary of Results for Monthly Sampling at End of Month, September to March, 0.5 Insects/Kg Threshold, Wichita

	Optimal dates and cost																							
	Low Immigration								Normal Immigration								High Immigration							
Storage Period [b]	Sep	Oct	Nov	Dec	Jan	Feb	Mar	TC ($/ton)	Sep	Oct	Nov	Dec	Jan	Feb	Mar	TC ($/ton)	Sep	Oct	Nov	Dec	Jan	Feb	Mar	TC ($/ton)
1961/62								0.806				F				1.53		F						1.53
1962/63							F	1.53			F					1.53		F					F	2.25
1963/64								0.806			F					1.53		F						1.53
1964/65								0.806				F				1.53		F						1.53
1965/66							F	1.53			F					1.53		F					F	2.25
1966/67								0.806				F				1.53		F						1.53
1967/68								0.806				F				1.53		F						1.53
1968/69								0.806				F				1.53		F						1.53
1969/70								0.806				F				1.53		F						1.53
1970/71								0.806				F				1.53		F						1.53
1971/72							F	1.53				F				1.53		F					F	2.25
1972/73							F	1.53					F			1.53		F					F	2.25
1973/74							F	1.53			F					1.53		F					F	2.25
1974/75								0.806				F				1.53		F						1.53
1975/76								2.64 [N/O]				F				1.53		F					F	2.25
1976/77								0.806						F		1.53		F						1.53
1977/78								0.806			F					1.53		F						1.53
1978/79								0.806			F					1.53		F						1.53
1979/80							F	1.53				F				1.53		F					F	2.25
1980/81							F	1.53				F				1.53		F					F	2.25
1981/82							F	1.53				F				1.53		F					F	2.25
1982/83							F	1.53				F				1.53		F					F	2.25
1983/84								2.64 [N/O]					F			1.53		F						3.37 [N/O]
1984/85							F	1.53						F		1.53		F					F	2.25
1985/86							F	1.53						F		1.53		F					F	2.25
1986/87							F	1.53						F		1.53		F					F	2.25
1987/88							F	1.53						F		1.53		F					F	2.25
1988/89							F	1.53						F		1.53		F					F	2.25
1989/90							F	1.53						F		1.53		F					F	2.25

F: means fumigation occurred in that month
N/O: not optimal

With a high immigration rate, monthly sampling indicated that fumigation should be conducted twice, in October and then in either February or March. Costs were $2.25/tonne (monthly sampling cost + two fumigation costs).

In Wichita (Table 4.4), with a low immigration rate, monthly sampling indicated that fumigation was necessary only in 15 of 29 years. Those years were 1962/63, 1965/66, 1971/72, 1972/73, 1973/74, 1979/80, 1980/81, 1981/82, 1982/83, 1984/85, 1985/86, 1986/87, 1987/88, 1988/89 and 1989/90. The total cost for those years was $1.53/tonne (monthly sampling cost plus one fumigation cost).

For the other 14 of 29 years, total cost was $0.806/tonne (monthly sampling cost plus fixed cost of fumigation), except for 1975/1976 and 1983/1984, in which sampling incorrectly failed to indicate fumigation, when it was actually needed. In those years, either the threshold was too high, or the last sampling date (March 31) was too early to signal that fumigation was, in fact, needed to present insect population from growing to the point of triggering live insect discounts.

The "monthly sampling" approach could be modified to avoid years like that. The threshold could be lowered, but this might result in unnecessary fumigations, raising cost. Or, an additional sampling could be added (say April 30), but in most years, this would add an unnecessary sampling cost.

With a high immigration rate, sampling results for 16 out of 29 years indicated two fumigations were necessary, costing $2.25/tonne (monthly sampling cost + two fumigation costs). These years are: 1962/63, 1965/66, 1971/72, 1972/73, 1973/74, 1975/76, 1979/80, 1980/81, 1981/82, 1982/83, 1984/85, 1985/86, 1986/87, 1987/88, 1988/89 and 1989/90.

In the remaining 13 out of 29 years, monthly sampling indicated that one fumigation should be conducted, at cost of $1.53/tonne, except that in 1983/84 an additional fumigation should have been conducted but was not. As a result, the cost for that year was $3.37/tonne, including monthly sampling cost, one fumigation cost, and live insect discount.

Monthly sampling on every 19th of the month. Tables 4.5 and 4.6 summarize results for monthly sampling on every 19th from September to April with a 0.75 insect/kg threshold. Sample dates are: Sep 19, Oct 19, Nov 19, Dec 19, Jan 19, Feb 19, Mar 19, and Apr 19.

In OKC, with low and normal immigration rates, monthly sampling indicated that fumigation should be conducted one time. Fumigation dates were in either December or January for a normal immigration rate and in March or April for a low immigration rate. The costs were $1.61/tonne (monthly sampling cost + one fumigation cost). This result is consistent with previous results that one fumigation is necessary for low and normal immigration rates in OKC.

With a high immigration rate, monthly sampling indicated that two fumigations were necessary, one in October and another in either March or April. Costs were $2.34/tonne (monthly sampling cost + two fumigation costs).

In Wichita, with a low immigration rate, monthly sampling on the 19th of every month indicated that no fumigation should occur in 9 out of 29 years (1963/64, 1967/68, 1968/69, 1969/70, 1970/71, 1974/75, 1976/77, 1977/78, and 1978/79. In those years costs were $0.89/tonne (monthly sampling cost plus fumigation fixed cost).

In the other 20 out of 29 years, sampling indicated that one fumigation was necessary, with a cost of $1.61/tonne (monthly sampling cost plus one fumigation cost). Compared with the end-of-month sampling result, sampling on the 19th of every month corrected the failure to fumigate in 1975/76 and 1983/84.

Even when correcting that failure, though, another problem resulted. During the storage periods of 1961/62, 1964/65 and 1966/67, monthly sampling indicated that one fumigation was necessary when it actually was not necessary. This caused unnecessary fumigation costs of $0.723/tonne. However, this is a lower cost than the cost of failing to control insect population.

With a normal immigration rate, sampling indicated that one fumigation was necessary. Costs were $1.61/tonne and fumigation dates were mostly in January and February, though some were in December and March.

Table 4.5 Summary of results for Monthly Sampling on the 19th of Every Month, September to April, 0.75/insect/kg threshold, Oklahoma City

	Optimal dates and cost																										
	Low Immigration									Normal Immigration									High Immigration								
Storage Period [b]	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	TC ($/ton)	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	TC ($/ton)	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	TC ($/ton)
1961/62								F	1.61				F					1.61		F						F	2.34
1962/63							F		1.61				F					1.61		F					F		2.34
1963/64								F	1.61				F					1.61		F						F	2.34
1964/65								F	1.61					F				1.61		F						F	2.34
1965/66							F		1.61				F					1.61		F					F		2.34
1966/67							F		1.61				F					1.61		F					F		2.34
1967/68							F		1.61				F					1.61		F					F		2.34
1968/69							F		1.61				F					1.61		F					F		2.34
1969/70							F		1.61				F					1.61		F					F		2.34
1970/71							F		1.61				F					1.61		F					F		2.34
1971/72							F		1.61				F					1.61		F					F		2.34
1972/73							F		1.61					F				1.61		F					F		2.34
1973/74							F		1.61				F					1.61		F					F		2.34
1974/75							F		1.61				F					1.61		F					F		2.34
1975/76							F		1.61					F				1.61		F					F		2.34
1976/77								F	1.61					F				1.61		F						F	2.34
1977/78								F	1.61				F					1.61		F						F	2.34
1978/79								F	1.61				F					1.61		F						F	2.34
1979/80								F	1.61					F				1.61		F						F	2.34
1980/81							F		1.61				F					1.61		F					F		2.34
1981/82							F		1.61				F					1.61		F					F		2.34
1982/83							F		1.61				F					1.61		F					F		2.34
1983/84							F		1.61				F					1.61		F					F		2.34
1984/85							F		1.61				F					1.61		F					F		2.34
1985/86							F		1.61					F				1.61		F					F		2.34
1986/87							F		1.61				F					1.61		F				F			2.34
1987/88							F		1.61				F					1.61		F					F		2.34
1988/89							F		1.61				F					1.61		F					F		2.34
1989/90							F		1.61					F				1.61		F					F		2.34

Table 4.6 Summary of results for Monthly Sampling on the 19th of Every Moth, September to April, 0.75/insect/kg threshold, Wichita

	Optimal dates and cost																										
	Low Immigration									Normal Immigration									High Immigration								
Storage Period	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	TC ($/ton)	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	TC ($/ton)	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	TC ($/ton)
1961/62								F	1.61 [N/O]					F				1.61		F						F	2.34 [N/O]
1962/63								F	1.61				F					1.61		F						F	2.34
1963/64									0.890					F				1.61		F						F	2.34 [N/O]
1964/65								F	1.61 [N/O]					F				1.61		F						F	2.34
1965/66								F	1.61				F					1.61		F						F	2.34
1966/67								F	1.61 [N/O]						F			1.61		F						F	2.34 [N/O]
1967/68									0.890						F			1.61		F						F	2.34 [N/O]
1968/69									0.890						F			1.61		F							1.61
1969/70									0.890					F				1.61		F						F	2.34 [N/O]
1970/71									0.890					F				1.61		F							1.61
1971/72								F	1.61					F				1.61		F						F	2.34
1972/73								F	1.61						F			1.61		F						F	2.34
1973/74								F	1.61				F					1.61		F						F	2.34
1974/75									0.890					F				1.61		F						F	2.34 [N/O]
1975/76								F	1.61						F			1.61		F						F	2.34
1976/77									0.890							F		1.61		F							1.61
1977/78									0.890				F					1.61		F							1.61
1978/79									0.890							F		1.61		F							1.61
1979/80								F	1.61					F				1.61		F						F	2.34
1980/81								F	1.61					F				1.61		F						F	2.34
1981/82								F	1.61				F					1.61		F						F	2.34
1982/83								F	1.61					F				1.61		F						F	2.34
1983/84								F	1.61						F			1.61		F						F	2.34
1984/85								F	1.61					F				1.61		F						F	2.34
1985/86								F	1.61						F			1.61		F						F	2.34
1986/87								F	1.61					F				1.61		F						F	2.34
1987/88								F	1.61				F					1.61		F						F	2.34
1988/89								F	1.61					F				1.61		F						F	2.34
1989/90								F	1.61					F				1.61		F						F	2.34

N/O: not optimal-unnecessary fumigation occurs

With a high immigration rate, sampling indicated that, for some years, two fumigations were necessary, costing $2.336/tonne (monthly sampling cost + two fumigation costs). These years were: 1962/63, 1965/66, 1971/72, 1972/73, 1973/74, 1975/76, 1979/80, 1980/81, 1981/82, 1982/83, 1984/85, 1985/86, 1986/87, 1987/88, 1988/89 and 1989/90 (which are the same years indicated by end-of-month sampling), plus the years: 1961/62, 1963/64, 1966/67, 1967/68, 1969/70, 1974/75.

As with the low immigration rate, although sampling on the 19th of each month – rather than at the end of the month – solved the problem of failing to fumigate in 1983/83, it led to unnecessary fumigation costs. Cost for the remaining years in which fumigation was conducted only once was $1.61/tonne.

Overall, the cost of monthly sampling on the 19th of the month was higher than end-of-month sampling. One more sample was taken, and sampling on the 19th led to some unnecessary fumigations. Although end-of-month sampling had higher failure-to-control risk, unnecessary fumigations cost more than the live insect discounts resulting from failure to control insects. Unnecessary fumigation cost and failure to control insect damage occurred only in Wichita.

One routine fumigation with sampling-based fumigation

Tables 4.7 and 4.8 show the cost of one routine fumigation on October 31st and three scenarios of sampling-based fumigation afterwards. These three scenarios were: (I) Sample on March 31, (II) Sample on Feb 28 and March 31, and (III) Sample at end of each month from November to March.

In Oklahoma City, sampling indicated another fumigation either in February or March was necessary with a high immigration rate, but not with normal or low immigration rates.

With a high immigration rate, the costs of one routine fumigation plus one more sampling-based fumigation for three scenarios were $2.01/tonne, $2.07/tonne, and $2.08/tonne (sampling cost + two fumigation costs), respectively.

Table 4.7. Summary of Results for One Fumigation on Oct 31st and Sampling-based Fumigation afterwards, Oklahoma City

	High Immigration rate							Normal immigration rate			Low immigration rate		
	I.			II.			III.	I	II	III	I	II	III
Storage Period [b]	F in March based on sample TC ($/ton)	Feb	Mar	F in Feb or March based on sample TC ($/ton)	Feb	Mar	F in Feb or March based on sample TC ($/ton)	No F based on sample TC ($/ton)	No F based on sample TC ($/ton)	No F based on sample TC ($/ton)	No F based on sample TC ($/ton)	No F based on sample TC ($/ton)	No F based on sample TC ($/ton)
1961/62	2.01		F	2.07		F	2.08	1.28	1.35	1.36	1.28	1.35	1.36
1962/63	2.01	F		2.07	F		2.08	1.28	1.35	1.36	1.28	1.35	1.36
1963/64	2.01		F	2.07		F	2.08	1.28	1.35	1.36	1.28	1.35	1.36
1964/65	2.01		F	2.07		F	2.08	1.28	1.35	1.36	1.28	1.35	1.36
1965/66	2.01	F		2.07	F		2.08	1.28	1.35	1.36	1.28	1.35	1.36
1966/67	2.01		F	2.07		F	2.08	1.28	1.35	1.36	1.28	1.35	1.36
1967/68	2.01		F	2.07		F	2.08	1.28	1.35	1.36	1.28	1.35	1.36
1968/69	2.01	F		2.07	F		2.08	1.28	1.35	1.36	1.28	1.35	1.36
1969/70	2.01	F		2.07	F		2.08	1.28	1.35	1.36	1.28	1.35	1.36
1970/71	2.01		F	2.07		F	2.08	1.28	1.35	1.36	1.28	1.35	1.36
1971/72	2.01	F		2.07	F		2.08	1.28	1.35	1.36	1.28	1.35	1.36
1972/73	2.01		F	2.07		F	2.08	1.28	1.35	1.36	1.28	1.35	1.36
1973/74	2.01	F		2.07	F		2.08	1.28	1.35	1.36	1.28	1.35	1.36
1974/75	2.01	F		2.07	F		2.08	1.28	1.35	1.36	1.28	1.35	1.36
1975/76	2.01	F		2.07	F		2.08	1.28	1.35	1.36	1.28	1.35	1.36
1976/77	2.01		F	2.07		F	2.08	1.28	1.35	1.36	1.28	1.35	1.36
1977/78	2.01		F	2.07		F	2.08	1.28	1.35	1.36	1.28	1.35	1.36
1978/79	2.01		F	2.07		F	2.08	1.28	1.35	1.36	1.28	1.35	1.36
1979/80	2.01		F	2.07		F	2.08	1.28	1.35	1.36	1.28	1.35	1.36
1980/81	2.01	F		2.07	F		2.08	1.28	1.35	1.36	1.28	1.35	1.36
1981/82	2.01		F	2.07		F	2.08	1.28	1.35	1.36	1.28	1.35	1.36
1982/83	2.01	F		2.07	F		2.08	1.28	1.35	1.36	1.28	1.35	1.36
1983/84	2.01		F	2.07		F	2.08	1.28	1.35	1.36	1.28	1.35	1.36
1984/85	2.01		F	2.07		F	2.08	1.28	1.35	1.36	1.28	1.35	1.36
1985/86	2.01		F	2.07		F	2.08	1.28	1.35	1.36	1.28	1.35	1.36
1986/87	2.01	F		2.07	F		2.08	1.28	1.35	1.36	1.28	1.35	1.36
1987/88	2.01		F	2.07		F	2.08	1.28	1.35	1.36	1.28	1.35	1.36
1988/89	2.01	F		2.07	F		2.08	1.28	1.35	1.36	1.28	1.35	1.36
1989/90	2.01	F		2.07	F		2.08	1.28	1.35	1.36	1.28	1.35	1.36

I. Sample on March 31st
II. Sample on Feb 28th and March 31st
III. Monthly Sample at end of month from Nov to March

Table 4.8 Summary of Results for One Fumigation on Oct 31st and Sampling-based Fumigation afterwards, Wichita

	High Immigration rate						Normal immigration rate			Low immigration rate		
	I.		II.		III.		I	II	III	I	II	III
Storage Period [b]	Mar	TC ($/ton)	Mar	TC ($/ton)	Mar	TC ($/ton)	No F based on sample TC ($/ton)	No F based on sample TC ($/ton)	No F based on sample TC ($/ton)	No F based on sample TC ($/ton)	No F based on sample TC ($/ton)	No F based on sample TC ($/ton)
1961/62		1.28		1.35		1.36	1.28	1.35	1.36	1.28 [N/O]	1.35 [N/O]	1.36[N/O]
1962/63	F	2.01	F	2.07	F	2.08	1.28	1.35	1.36	1.28	1.35	1.36
1963/64		1.28		1.35		1.36	1.28	1.35	1.36	1.28 [N/O]	1.35 [N/O]	1.36[N/O]
1964/65		1.28		1.35		1.36	1.28	1.35	1.36	1.28 [N/O]	1.35 [N/O]	1.36[N/O]
1965/66	F	2.01	F	2.07	F	2.08	1.28	1.35	1.36	1.28	1.35	1.36
1966/67		1.28		1.35		1.36	1.28	1.35	1.36	1.28 [N/O]	1.35 [N/O]	1.36[N/O]
1967/68		1.28		1.35		1.36	1.28	1.35	1.36	1.28 [N/O]	1.35 [N/O]	1.36[N/O]
1968/69		1.28		1.35		1.36	1.28	1.35	1.36	1.28 [N/O]	1.35 [N/O]	1.36[N/O]
1969/70		1.28		1.35		1.36	1.28	1.35	1.36	1.28 [N/O]	1.35 [N/O]	1.36[N/O]
1970/71		1.28		1.35		1.36	1.28	1.35	1.36	1.28 [N/O]	1.35 [N/O]	1.36[N/O]
1971/72	F	2.01	F	2.07	F	2.08	1.28	1.35	1.36	1.28	1.35	1.36
1972/73	F	2.01	F	2.07	F	2.08	1.28	1.35	1.36	1.28	1.35	1.36
1973/74	F	2.01	F	2.07	F	2.08	1.28	1.35	1.36	1.28	1.35	1.36
1974/75		1.28		1.35		1.36	1.28	1.35	1.36	1.28 [N/O]	1.35 [N/O]	1.36[N/O]
1975/76	F	2.01	F	2.07	F	2.08	1.28	1.35	1.36	1.28	1.35	1.36
1976/77		1.28		1.35		1.36	1.28	1.35	1.36	1.28 [N/O]	1.35 [N/O]	1.36[N/O]
1977/78		1.28		1.35		1.36	1.28	1.35	1.36	1.28 [N/O]	1.35 [N/O]	1.36[N/O]
1978/79		1.28		1.35		1.36	1.28	1.35	1.36	1.28 [N/O]	1.35 [N/O]	1.36[N/O]
1979/80	F	2.01	F	2.07	F	2.08	1.28	1.35	1.36	1.28	1.35	1.36
1980/81	F	2.01	F	2.07	F	2.08	1.28	1.35	1.36	1.28	1.35	1.36
1981/82	F	2.01	F	2.07	F	2.08	1.28	1.35	1.36	1.28	1.35	1.36
1982/83	F	2.01	F	2.07	F	2.08	1.28	1.35	1.36	1.28	1.35	1.36
1983/84		3.12[N/O]		3.19[N/O]		3.20[N/O]	1.28	1.35	1.36	1.28	1.35	1.36
1984/85	F	2.01	F	2.07	F	2.08	1.28	1.35	1.36	1.28	1.35	1.36
1985/86	F	2.01	F	2.07	F	2.08	1.28	1.35	1.36	1.28	1.35	1.36
1986/87	F	2.01	F	2.07	F	2.08	1.28	1.35	1.36	1.28	1.35	1.36
1987/88	F	2.01	F	2.07	F	2.08	1.28	1.35	1.36	1.28	1.35	1.36
1988/89	F	2.01	F	2.07	F	2.08	1.28	1.35	1.36	1.28	1.35	1.36
1989/90	F	2.01	F	2.07	F	2.08	1.28	1.35	1.36	1.28	1.35	1.36

N/O: not optimal: damage in high immigration rate; unnecessary fumigation in low immigration rate
I. Sample on March 31st
II. Sample on Feb 28th and March 31st
III. Monthly Sample at end of month from Nov to March

With normal and low immigration rates, the costs of one routine fumigation plus sampling for three scenarios were $1.28/tonne, $1.35/tonne, and $1.36/tonne (sampling cost + one fumigation cost), respectively. Since at least one fumigation was necessary, this strategy saved some sampling cost for the first routine fumigation, so it was less costly than sampling every month.

In Wichita, with a high immigration rate, in 16 of 29 years two fumigations were needed. The years were 1962/63, 1965/66, 1971/72, 1972/73, 1973/74, 1975/76, 1979/80, 1980/81, 1981/82, 1982/83, 1984/85, 1985/86, 1986/87, 1987/88, 1988/89, and 1989/90. The costs for each of the three scenarios were $2.01/tonne, $2.07/tonne, and $2.08/tonne, respectively. In 12 of the 13 years, sampling indicated that no additional fumigations were necessary, and the costs for each of the scenarios were $1.28/tonne, $1.35/tonne, and $1.36/tonne. In one year, 1962/63, sampling indicated that an additional fumigation was not necessary even though it was, so a live insect discount resulted. In that year, cost for the three scenarios were $3.12/tonne, $3.19/tonne, and $3.20/tonne (sampling cost + one fumigation cost+ live insect discount), respectively.

With a low immigration rate, there were 12 years (1963/64, 1967/68, 1968/69, 1969/70, 1970/71, 1974/75, 1976/77, 1977/78, and 1978/79) in which fumigation was unnecessary. Thus, this strategy was not ideal for Wichita.

Optimal Strategy

Under the assumption that all of an elevator's storage bins (ten, in this simulation) have the same insect immigration rate, table 4.9 summarizes optimal strategies and corresponding costs ($/tonne) in each weather condition (year), with low, normal, and high immigration rates for Oklahoma City. It also shows the optimal strategies when weather is unknown for each immigration rate, when immigration rate is unknown, and when both immigration rate and weather are unknown. The optimal strategy in each situation is the strategy that minimizes total cost when used in each of the 29 years.

Table 4.9. Summary of Ideal Strategies and Corresponding Costs ($/tonne) for Each Storage Year under Alternative Insect Immigration Rates for Oklahoma City [a]

Storage Period [b]	Low Immigration		Normal Immigration		High Immigration		Immigration rate unknown	
1961/62	F	0.937	F	0.937	2F	1.66	1FMS ^{Mar}	+0.345[c]
1962/63	F	0.937	F	0.937	2F	1.66	1FMS ^{Mar}	+0.345
1963/64	F	0.937	F	0.937	2F	1.66	1FMS ^{Mar}	+0.345
1964/65	F	0.937	F	0.937	2F	1.66	1FMS ^{Mar}	+0.345
1965/66	F	0.937	F	0.937	2F	1.66	1FMS ^{Mar}	+0.345
1966/67	F	0.937	F	0.937	2F	1.66	1FMS ^{Mar}	+0.345
1967/68	F	0.937	F	0.937	2F	1.66	1FMS ^{Mar}	+0.345
1968/69	F	0.937	F	0.937	2F	1.66	1FMS ^{Mar}	+0.345
1969/70	F	0.937	F	0.937	2F	1.66	1FMS ^{Mar}	+0.345
1970/71	F	0.937	F	0.937	2F	1.66	1FMS ^{Mar}	+0.345
1971/72	F	0.937	F	0.937	2F	1.66	1FMS ^{Mar}	+0.345
1972/73	F	0.937	F	0.937	2F	1.66	1FMS ^{Mar}	+0.345
1973/74	F	0.937	F	0.937	2F	1.66	1FMS ^{Mar}	+0.345
1974/75	F	0.937	F	0.937	2F	1.66	1FMS ^{Mar}	+0.345
1975/76	F	0.937	F	0.937	2F	1.66	1FMS ^{Mar}	+0.345
1976/77	F	0.937	F	0.937	2F	1.66	1FMS ^{Mar}	+0.345
1977/78	F	0.937	F	0.937	2F	1.66	1FMS ^{Mar}	+0.345
1978/79	F	0.937	F	0.937	2F	1.66	1FMS ^{Mar}	+0.345
1979/80	F	0.937	F	0.937	2F	1.66	1FMS ^{Mar}	+0.345
1980/81	F	0.937	F	0.937	2F	1.66	1FMS ^{Mar}	+0.345
1981/82	F	0.937	F	0.937	2F	1.66	1FMS ^{Mar}	+0.345
1982/83	F	0.937	F	0.937	2F	1.66	1FMS ^{Mar}	+0.345
1983/84	F	0.937	F	0.937	2F	1.66	1FMS ^{Mar}	+0.345
1984/85	F	0.937	F	0.937	2F	1.66	1FMS ^{Mar}	+0.345
1985/86	F	0.937	F	0.937	2F	1.66	1FMS ^{Mar}	+0.345
1986/87	F	0.937	F	0.937	2F	1.66	1FMS ^{Mar}	+0.345
1987/88	F	0.937	F	0.937	2F	1.66	1FMS ^{Mar}	+0.345
1988/89	F	0.937	F	0.937	2F	1.66	1FMS ^{Mar}	+0.345
1989/90	F	0.937	F	0.937	2F	1.66	1FMS ^{Mar}	+0.345
Weather unknown	F	0.937	F	0.937	2F	1.66	1FMS ^{Mar}	+0.345

a. F: one fumigation, 2F: two fumigations, 1FMS ^{Mar}: one fumigation and one sampling in March
b. Storage period begins on 6/20 and ends on 4/18 or 4/19 for the following year
c. Corresponding cost plus sampling cost

The table shows that in OKC fumigation is always lowest cost if the manager can get accurate information about weather and immigration rate because the cost of fumigating is less than the cost of sampling-based fumigation.

Objective 3: Determine optimal insect control strategies that are robust to varying weather conditions and insect immigration rates.

The assumption above that the storage manager knows the weather and immigration rate is unrealistic. A manager must make the best possible decision without having perfect knowledge about those factors. Assuming a normal or low rate of insect immigration when the rate is actually high, for example, would likely lead to too little insect control, and live insect or IDK discounts. Temperatures or humidity higher than expected would lead to the same result. Conversely, assuming an immigration rate, temperatures, or humidity that is too high would lead to excessive fumigation. Both errors would make insect control more expensive than it needs to be. This section of the analysis attempts to identify the best insect control strategies under a range of weather conditions or insect immigration rates.

The bottom row of Table 4.9 shows the optimal strategy if insect immigration rate is known but weather is unknown. It shows that weather variation in OKC did not affect fumigation strategies, since in each column the same strategy was optimal in all years (at least one fumigation was needed in all years for low and normal immigration rates, and two fumigations were needed under a high immigration rate); sampling-based strategies only increased costs, since sampling gave a correct indication that fumigation was always necessary. Sampling was an added expense that had no effect on which treatment would be chosen.

The right-most column of Table 4.9 shows the optimal strategy in each year when immigration rate is unknown, and the lower right cell of the table shows the optimal strategy when both weather and immigration rate are unknown. After an initial fumigation, conducting a sampling in March detected those situations in which an additional fumigation was needed (i.e., if immigration rate is high). Using this strategy of an initial fumigation followed by a sampling in March resulted in no unnecessary fumigations, and also no live insect or IDK discounts. Sampling detected when no further fumigations were necessary (all years under low and normal immigration rates), and when an additional fumigation was necessary (all years with a high immigration rate.)

For example, suppose that all ten bins had the same immigration rate under weather conditions of 1961/62 and the insect immigration rate was unknown. After an initial fumigation on October 31, if sampling indicated that no more fumigations were necessary (which would be the case under low or normal immigration rates), the total cost would be 1.2823 (0.937+0.3454), which is monthly sampling cost plus one fumigation cost. If, instead, sampling indicated that an additional fumigation was necessary (which it would under a high immigration rate), then the cost would be monthly sampling cost plus two fumigations, or $2.01/tonne (1.66 + 0.345).

If the strategy would have been to conduct two fumigations without sampling, the cost would have been $1.66/tonne. This is $0.723/tonne higher than would have been necessary if, in fact, the immigration rate was low or normal. Monthly sampling added $0.345/tonne, rather than $0.723 for an additional fumigation, for low or normal immigration rates.

Table 4.10 summarizes results of the same exercise for Wichita. Unlike the results for OKC, weather variation affects optimal strategies in Wichita. As shown in the bottom row, one sampling is optimal for a low immigration rate, and one routine fumigation is optimal for normal immigration rate. However, there was no identifiable optimal strategy for a high immigration rate across all years. One routine fumigation plus sampling-based and end-of-month sampling result in one year with failure to control, and thus a live insect discount. Monthly sampling on the 19th avoided insect discounts, but there were unnecessary fumigations.

Table 4.10. Summary of Ideal Strategies and Corresponding Costs ($/tonne) for Each Storage Year under Alternative Insect Immigration Rates for Wichita [a]

Storage Period b	Low Immigration		Normal Immigration		High Immigration		Immigration rate unknown	
1961/62	NF	0	F	0.937	F	0.937	S	+0.345
1962/63	F	0.937	F	0.937	2F	1.66	1FMS Mar	+0.345
1963/64	NF	0	F	0.937	F	0.937	S	+0.345
1964/65	NF	0	F	0.937	F	0.937	S	+0.345
1965/66	F	0.937	F	0.937	2F	1.66	1FMS Mar	+0.345
1966/67	NF	0	F	0.937	F	0.937	S	+0.345
1967/68	NF	0	F	0.937	F	0.937	S	+0.345
1968/69	NF	0	F	0.937	F	0.937	S	+0.345
1969/70	NF	0	F	0.937	F	0.937	S	+0.345
1970/71	NF	0	F	0.937	F	0.937	S	+0.345
1971/72	F	0.937	F	0.937	2F	1.66	1FMS Mar	+0.345
1972/73	F	0.937	F	0.937	2F	1.66	1FMS Mar	+0.345
1973/74	F	0.937	F	0.937	2F	1.66	1FMS Mar	+0.345
1974/75	NF	0	F	0.937	F	0.937	S	+0.345
1975/76	F	0.937	F	0.937	2F	1.66	1FMS Mar	+0.345
1976/77	NF	0	F	0.937	F	0.937	S	+0.345
1977/78	NF	0	F	0.937	F	0.937	S	+0.345
1978/79	NF	0	F	0.937	F	0.937	S	+0.345
1979/80	F	0.937	F	0.937	2F	1.66	1FMS Mar	+0.345
1980/81	F	0.937	F	0.937	2F	1.66	1FMS Mar	+0.345
1981/82	F	0.937	F	0.937	2F	1.66	1FMS Mar	+0.345
1982/83	F	0.937	F	0.937	2F	1.66	1FMS Mar	+0.345
1983/84	F	0.937	F	0.937	F	0.937	F	0.937
1984/85	F	0.937	F	0.937	2F	1.66	1FMS Mar	+0.345
1985/86	F	0.937	F	0.937	2F	1.66	1FMS Mar	+0.345
1986/87	F	0.937	F	0.937	2F	1.66	1FMS Mar	+0.345
1987/88	F	0.937	F	0.937	2F	1.66	1FMS Mar	+0.345
1988/89	F	0.937	F	0.937	2F	1.66	1FMS Mar	+0.345
1989/90	F	0.937	F	0.937	2F	1.66	1FMS Mar	+0.345
Weather unknown	S	+0.3454	F	0.937	N/A		N/A	

a. NF : doing nothing F: one fumigating, 2F: two fumigating, S: one sampling-based fumigation, 1FMS Mar: one fumigation and one sampling on march afterwards

b. Storage period begins on 6/20 and ends on 4/18 or 4/19 for the following year

Since none of these strategies provided an optimal solution, the choice of strategy depended on relative costs of insect discounts and treatments. When immigration rate was unknown, sampling was the best strategy in 12 out of 29 years, and in another 16 years one routine fumigation plus sampling-based fumigation was best. In 1983/84, one fumigation was optimal.

The following results assume that weather is uncertain and that insect immigration rate is not known but that the manager has some information about it. For example, the manager may know that out of 10 storage bins, one third have a low immigration rate, 1/3 have a normal immigration rate, and 1/3 have a high immigration rate. Results for the previous assumption that all bins were either low, or normal, or high are presented for comparison.

Tables 4.11 and 4.12 summarize the optimal fumigation date for routine fumigation in OKC and Wichita and tables 4.13 and 4.14 summarize the optimal sampling date for sampling-based fumigation in OKC and Wichita.

The "overlaps" row at the bottom shows the optimal dates when weather conditions are unknown. In OKC (table 4.11), for one fumigation, the optimal window range was 3/Aug-19/Apr for low immigration rate, 7/Oct-3/Mar for normal immigration rate, and 25/Sep-5/Dec for a high immigration rate. In the lower right cell, the date range 7/Oct-5/Dec included all of these ranges, so that the range 7/Oct-5/Dec was robust across the three insect immigration rates and across years.

Similar results for Wichita are shown in Table 4.12. The optimal dates were 4/Jul-19/Apr for a low immigration rate, 27/Aug-7/Apr for a normal immigration rate, and 25/Sep-5/Dec for a high immigration rate. The lower right cell gives the best dates for one fumigation that applied across years and immigration rates, 14/Nov-20/Dec.

Table 4.11 Dates and Cost ($/tonne) Summary of Least Cost Window Range for One Fumigation over the Storage Period in Oklahoma City

Storage Period [b]	Optimal dates and cost						
	Low Immigration		Normal Immigration		High Immigration		Overlaps
1961/62	8/Jul-19/Apr	0.937	29/Aug-1/Apr	0.937	24/Aug-24/Dec [N/O]	2.77	29/Aug-24/Dec [N/O]
1962/63	22/Jul-19/Apr	0.937	16/Sep-17/Mar	0.937	7/Sep-12/Dec [N/O]	2.77	16/Sep-12/Dec [N/O]
1963/64	3/Jul-19/Apr	0.937	25/Aug-5/Apr	0.937	21/Aug-21/Dec [N/O]	2.77	25/Aug-21/Dec [N/O]
1964/65	1/Jul-19/Apr	0.937	23/Aug-5/Apr	0.937	20/Aug-26/Dec [N/O]	2.77	23/Aug-26/Dec [N/O]
1965/66	24/Jul-19/Apr	0.937	18/Sep-7/Mar	0.937	11/Sep-10/Dec [N/O]	2.77	18/Sep-10/Dec [N/O]
1966/67	15/Jul-19/Apr	0.937	4/Sep-27/Mar	0.937	28/Aug-20/Dec [N/O]	2.77	4/Sep-20/Dec [N/O]
1967/68	13/Jul-19/Apr	0.937	6/Sep-22/Mar	0.937	30/Aug-17/Dec [N/O]	2.77	6/Sep-17/Dec [N/O]
1968/69	17/Jul-19/Apr	0.937	7/Sep-24/Mar	0.937	30/Aug-21/Dec [N/O]	2.77	7/Sep-21/Dec [N/O]
1969/70	15/Jul-19/Apr	0.937	7/Sep-19/Mar	0.937	31/Aug-17/Dec [N/O]	2.77	7/Sep-17/Dec [N/O]
1970/71	13/Jul-19/Apr	0.937	4/Sep-24/Mar	0.937	30/Aug-19/Dec [N/O]	2.77	4/Sep-19/Dec [N/O]
1971/72	1/Aug-19/Apr	0.937	3/Oct-3/Mar	0.937	19/Sep-8/Dec [N/O]	2.77	3/Oct-8/Dec [N/O]
1972/73	19/Jul-19/Apr	0.937	12/Sep-27/Mar	0.937	3/Sep-26/Dec [N/O]	2.77	12/Sep-26/Dec [N/O]
1973/74	22/Jul-19/Apr	0.937	16/Sep-19/Mar	0.937	6/Sep-14/Dec [N/O]	2.77	16/Sep-14/Dec [N/O]
1974/75	16/Jul-19/Apr	0.937	7/Sep-19/Mar	0.937	31/Aug-20/Dec [N/O]	2.77	7/Sep-20/Dec [N/O]
1975/76	20/Jul-19/Apr	0.937	10/Sep-24/Mar	0.937	1/Sep-25/Dec [N/O]	2.77	10/Sep-25/Dec [N/O]
1976/77	4/Jul-19/Apr	0.937	25/Aug-11/Apr	0.937	17/Aug-2/Jan [N/O]	2.77	25/Aug-2/Jan [N/O]
1977/78	27/Jun-19/Apr	0.937	19/Aug-13/Apr	0.937	15/Aug-21/Dec [N/O]	2.77	19/Aug-21/Dec [N/O]
1978/79	1/Jul-19/Apr	0.937	23/Aug-12/Apr	0.937	17/Aug-20/Dec [N/O]	2.77	23/Aug-20/Dec [N/O]
1979/80	10/Jul-19/Apr	0.937	31/Aug-30/Mar	0.937	25/Aug-25/Dec [N/O]	2.77	31/Aug-25/Dec [N/O]
1980/81	21/Jul-19/Apr	0.937	14/Sep-21/Mar	0.937	5/Sep-16/Dec [N/O]	2.77	14/Sep-16/Dec [N/O]
1981/82	13/Jul-19/Apr	0.937	4/Sep-26/Mar	0.937	28/Aug-15/Dec [N/O]	2.77	4/Sep-15/Dec [N/O]
1982/83	23/Jul-19/Apr	0.937	14/Sep-18/Mar	0.937	6/Sep-18/Dec [N/O]	2.77	14/Sep-18/Dec [N/O]
1983/84	14/Jul-19/Apr	0.937	5/Sep-29/Mar	0.937	28/Aug-20/Dec [N/O]	2.77	5/Sep-20/Dec [N/O]
1984/85	18/Jul-19/Apr	0.937	10/Sep-23/Mar	0.937	1/Sep-17/Dec [N/O]	2.77	10/Sep-17/Dec [N/O]
1985/86	18/Jul-19/Apr	0.937	9/Sep-27/Mar	0.937	1/Sep-23/Dec [N/O]	2.77	9/Sep-23/Dec [N/O]
1986/87	3/Aug-19/Apr	0.937	7/Oct-3/Mar	0.937	25/Sep-5/Dec [N/O]	2.77	7/Oct-5/Dec [N/O]
1987/88	15/Jul-19/Apr	0.937	5/Sep-24/Mar	0.937	29/Aug-15/Dec [N/O]	2.77	5/Sep-15/Dec [N/O]
1988/89	28/Jul-19/Apr	0.937	22/Sep-9/Mar	0.937	13/Sep-10/Dec [N/O]	2.77	22/Sep-10/Dec [N/O]
1989/90	21/Jul-19/Apr	0.937	12/Sep-22/Mar	0.937	3/Sep-21/Dec [N/O]	2.77	12/Sep-21/Dec [N/O]
Overlaps	3/Aug-19/Apr		7/Oct-3/Mar		25/Sep-5/Dec [N/O]		7/Oct-5/Dec [N/O]

N/O: Not optimal (one fumigation is not sufficient for high immigration rate, so is not minimum cost)

Table 4.12 Dates and Cost ($/tonne) Summary of Least Cost Window Range for One Fumigation over the Storage Period in Wichita

Storage Period [b]	Optimal dates and cost						Overlaps
	Low Immigration		Normal Immigration		High Immigration		
1961/62	20/Jun-19/Apr [N/O]	0.937	8/Aug-19/Apr	0.937	20/Oct-3/Jan	0.937	20/Oct -3/Jan [N/O]
1962/63	4/Jul-19/Apr	0.937	25/Aug-7/Apr	0.937	19/Aug-20/Dec [N/O]	2.77	25/Aug-20/Dec [N/O]
1963/64	20/Jun-19/Apr [N/O]	0.937	3/Aug-19/Apr	0.937	8/Oct-28/Dec	0.937	8/Oct-28/Dec [N/O]
1964/65	20/Jun-19/Apr [N/O]	0.937	4/Aug-19/Apr	0.937	10/Oct-3/Jan	0.937	10/Oct-3/Jan [N/O]
1965/66	2/Jul-19/Apr	0.937	23/Aug-6/Apr	0.937	19/Aug-21/Dec [N/O]	2.77	23/Aug-21/Dec [N/O]
1966/67	20/Jun-19/Apr [N/O]	0.937	5/Aug-19/Apr	0.937	12/Oct-7/Jan	0.937	12/Oct-7/Jan [N/O]
1967/68	20/Jun-19/Apr [N/O]	0.937	1/Aug-19/Apr	0.937	3/Oct-8/Jan	0.937	3/Oct-8/Jan [N/O]
1968/69	20/Jun-19/Apr [N/O]	0.937	29/Jul-19/Apr	0.937	24/Sep-8/Jan	0.937	24/Sep-8/Jan [N/O]
1969/70	20/Jun-19/Apr [N/O]	0.937	3/Aug-19/Apr	0.937	2/Oct-30/Dec	0.937	2/Oct-30/Dec [N/O]
1970/71	20/Jun-19/Apr [N/O]	0.937	3/Aug-19/Apr	0.937	30/Sep-2/Jan	0.937	30/Sep-2/Jan [N/O]
1971/72	27/Jun-19/Apr	0.937	18/Aug-13/Apr	0.937	15/Aug-28/Dec [N/O]	2.77	18/Aug-28/Dec [N/O]
1972/73	29/Jun-19/Apr	0.937	20/Aug-16/Apr	0.937	14/Aug-19/Jan [N/O]	2.77	20/Aug-19/Jan [N/O]
1973/74	5/Jul-19/Apr	0.937	27/Aug-7/Apr	0.937	21/Aug-22/Dec [N/O]	2.77	27/Aug-22/Dec [N/O]
1974/75	20/Jun-19/Apr [N/O]	0.937	4/Aug-19/Apr	0.937	10/Oct-30/Dec	0.937	10/Oct-30/Dec [N/O]
1975/76	22/Jun-19/Apr	0.937	14/Aug-19/Apr	0.937	8/Aug-7/Jan [N/O]	2.77	14/Aug-7/Jan [N/O]
1976/77	20/Jun-19/Apr [N/O]	0.937	24/Jul-19/Apr	0.937	15/Sep-12/Feb	0.937	15/Sep-12/Feb [N/O]
1977/78	20/Jun-19/Apr [N/O]	0.937	30/Jul-19/Apr	0.937	26/Sep-28/Dec	0.937	26/Sep-28/Dec [N/O]
1978/79	20/Jun-19/Apr [N/O]	0.937	28/Jul-19/Apr	0.937	23/Sep-2/Jan	0.937	23/Sep-2/Jan [N/O]
1979/80	27/Jun-19/Apr	0.937	17/Aug-14/Apr	0.937	13/Aug-29/Dec [N/O]	2.77	17/Aug-29/Dec [N/O]
1980/81	30/Jun-19/Apr	0.937	20/Aug-14/Apr	0.937	14/Aug-29/Dec [N/O]	2.77	20/Aug-29/Dec [N/O]
1981/82	22/Jun-19/Apr	0.937	12/Aug-19/Apr	0.937	8/Aug-24/Dec [N/O]	2.77	12/Aug-24/Dec [N/O]
1982/83	25/Jun-19/Apr	0.937	17/Aug-18/Apr	0.937	12/Aug-6/Jan [N/O]	2.77	17/Aug-6/Jan [N/O]
1983/84	20/Jun-19/Apr	0.937	12/Aug-19/Apr	0.937	14/Nov-9/Jan	0.937	14/Nov-9/Jan
1984/85	28/Jun-19/Apr	0.937	19/Aug-16/Apr	0.937	14/Aug-28/Dec [N/O]	2.77	19/Aug-28/Dec [N/O]
1985/86	29/Jun-19/Apr	0.937	20/Aug-16/Apr	0.937	13/Aug-31/Dec [N/O]	2.77	20/Aug-31/Dec [N/O]
1986/87	1/Jul-19/Apr	0.937	22/Aug-10/Apr	0.937	17/Aug-31/Dec [N/O]	2.77	22/Aug-31/Dec [N/O]
1987/88	28/Jun-19/Apr	0.937	17/Aug-14/Apr	0.937	14/Aug-25/Dec [N/O]	2.77	17/Aug-25/Dec [N/O]
1988/89	21/Jun-19/Apr	0.937	12/Aug-18/Apr	0.937	11/Aug-28/Dec [N/O]	2.77	12/Aug-28/Dec [N/O]
1989/90	26/Jun-19/Apr	0.937	17/Aug-16/Apr	0.937	12/Aug-9/Jan [N/O]	2.77	17/Aug-9/Jan [N/O]
Overlaps	4/Jul-19/Apr [N/O]		27/Aug-7/Apr		14/Nov-20/Dec [N/O]		14/Nov-20/Dec [N/O]

N/O: Not optimal (one fumigation is not needed in all years for low immigration rate, and is not sufficient in all years for high immigration rate)

Table 4.13. Dates and Cost ($/tonne) Summary of Least Cost Window Range for Sampling-Based Fumigation over the Storage Period in Oklahoma City

Storage Period [b]	Optimal dates and cost						Overlaps
	Low Immigration		Normal Immigration		High Immigration		
1961/62	11/Mar-19/Apr	1.28	2/Dec-1/Apr	1.28	13/Oct-24/Dec [N/O]	3.12	N/O
1962/63	1/Mar-19/Apr	1.28	25/Nov-17/Mar	1.28	11/Oct-12/Dec [N/O]	3.12	N/O
1963/64	16/Mar-19/Apr	1.28	27/Nov-5/Apr	1.28	11/Oct-21/Dec [N/O]	3.12	N/O
1964/65	15/Mar-19/Apr	1.28	2/Dec-5/Apr	1.28	12/Oct-26/Dec [N/O]	3.12	N/O
1965/66	12/Feb-19/Apr	1.28	25/Nov-7/Mar	1.28	11/Oct-10/Dec [N/O]	3.12	N/O
1966/67	6/Mar-19/Apr	1.28	27/Nov-27/Mar	1.28	11/Oct-20/Dec [N/O]	3.12	N/O
1967/68	3/Mar-19/Apr	1.28	27/Nov-22/Mar	1.28	13/Oct-17/Dec [N/O]	3.12	N/O
1968/69	28/Feb-19/Apr	1.28	30/Nov-24/Mar	1.28	13/Oct-21/Dec [N/O]	3.12	N/O
1969/70	27/Feb-19/Apr	1.28	1/Dec-19/Mar	1.28	10/Oct-17/Dec [N/O]	3.12	N/O
1970/71	2/Mar-19/Apr	1.28	30/Nov-24/Mar	1.28	12/Oct-19/Dec [N/O]	3.12	N/O
1971/72	14/Feb-19/Apr	1.28	27/Nov-3/Mar	1.28	12/Oct-8/Dec [N/O]	3.12	N/O
1972/73	5/Mar-19/Apr	1.28	19/Dec-27/Mar	1.28	13/Oct-26/Dec [N/O]	3.12	N/O
1973/74	27/Feb-19/Apr	1.28	26/Nov-19/Mar	1.28	12/Oct-14/Dec [N/O]	3.12	N/O
1974/75	26/Feb-19/Apr	1.28	29/Nov-19/Mar	1.28	14/Oct-20/Dec [N/O]	3.12	N/O
1975/76	2/Mar-19/Apr	1.28	10/Dec-24/Mar	1.28	12/Oct-25/Dec [N/O]	3.12	N/O
1976/77	20/Mar-19/Apr	1.28	14/Dec-11/Apr	1.28	13/Oct-2/Jan [N/O]	3.12	N/O
1977/78	27/Mar-19/Apr	1.28	27/Nov-13/Apr	1.28	11/Oct-21/Dec [N/O]	3.12	N/O
1978/79	24/Mar-19/Apr	1.28	24/Nov-12/Apr	1.28	10/Oct-20/Dec [N/O]	3.12	N/O
1979/80	12/Mar-19/Apr	1.28	6/Dec-30/Mar	1.28	12/Oct-25/Dec [N/O]	3.12	N/O
1980/81	1/Mar-19/Apr	1.28	30/Nov-21/Mar	1.28	11/Oct-16/Dec [N/O]	3.12	N/O
1981/82	10/Mar-19/Apr	1.28	26/Nov-26/Mar	1.28	11/Oct-15/Dec [N/O]	3.12	N/O
1982/83	25/Feb-19/Apr	1.28	2/Dec-18/Mar	1.28	12/Oct-18/Dec [N/O]	3.12	N/O
1983/84	6/Mar-19/Apr	1.28	30/Nov-29/Mar	1.28	12/Oct-20/Dec [N/O]	3.12	N/O
1984/85	4/Mar-19/Apr	1.28	27/Nov-23/Mar	1.28	13/Oct-17/Dec [N/O]	3.12	N/O
1985/86	6/Mar-19/Apr	1.28	5/Dec-27/Mar	1.28	13/Oct-23/Dec [N/O]	3.12	N/O
1986/87	8/Feb-19/Apr	1.28	29/Nov-3/Mar	1.28	11/Oct-5/Dec [N/O]	3.12	N/O
1987/88	3/Mar-19/Apr	1.28	27/Nov-24/Mar	1.28	12/Oct-15/Dec [N/O]	3.12	N/O
1988/89	18/Feb-19/Apr	1.28	25/Nov-9/Mar	1.28	11/Oct-10/Dec [N/O]	3.12	N/O
1989/90	28/Feb-19/Apr	1.28	5/Dec-22/Mar	1.28	12/Oct-21/Dec [N/O]	3.12	N/O
Overlaps	27/Mar-19/Apr		19/Dec-3/Mar		13/Oct-5/Dec [N/O]		N/O

N/O: Not Optimal

Table 4.14 Dates and Cost ($/tonne) Summary of Least Cost Window Range for Sampling-Based Fumigation over the Storage Period in Wichita

Storage Period [b]	Optimal dates and cost						
	Low Immigration		Normal Immigration		High Immigration		Overlaps
1961/62	20/Jun-6/Apr [NF]	0.559	3/Dec-19/Apr	1.28	20/Oct-3/Jan	1.28	3/Dec-3/Jan
1962/63	19/Mar-19/Apr	1.28	27/Nov-7/Apr	1.28	4/Oct-20/Dec [N/O]	3.12	Not optimal
1963/64	20/Jun-11/Apr [NF]	0.559	28/Nov-19/Apr	1.28	8/Oct-28/Dec	1.28	28/Nov-28/Dec
1964/65	20/Jun-9/Apr [NF]	0.559	12/Dec-19/Apr	1.28	10/Oct-3/Jan	1.28	12/Dec-3/Jan
1965/66	19/Mar-19/Apr	1.28	27/Nov-6/Apr	1.28	4/Oct-21/Dec [N/O]	3.12	Not optimal
1966/67	20/Jun-7/Apr [NF]	0.559	9/Dec-19/Apr	1.28	12/Oct-7/Jan	1.28	9/Dec-7/Jan
1967/68	20/Jun-11/Apr [NF]	0.559	10/Dec-19/Apr	1.28	7/Oct-8/Jan	1.28	10/Dec-8/Jan
1968/69	20/Jun-16/Apr [NF]	0.559	13/Dec-19/Apr	1.28	6/Oct-8/Jan	1.28	13/Dec-8/Jan
1969/70	20/Jun-11/Apr [NF]	0.559	3/Dec-19/Apr	1.28	4/Oct-30/Dec	1.28	3/Dec-30/Dec
1970/71	20/Jun-12/Apr [NF]	0.559	8/Dec-19/Apr	1.28	6/Oct-2/Jan	1.28	8/Dec-2/Jan
1971/72	23/Mar-19/Apr	1.28	6/Dec-13/Apr	1.28	5/Oct-28/Dec [N/O]	3.12	Not optimal
1972/73	24/Mar-19/Apr	1.28	17/Jan-16/Apr	1.28	7/Oct-30/Dec [N/O]	3.12	Not optimal
1973/74	14/Mar-19/Apr	1.28	27/Nov-7/Apr	1.28	5/Oct-22/Dec [N/O]	3.12	Not optimal
1974/75	20/Jun-10/Apr [NF]	0.559	6/Dec-19/Apr	1.28	10/Oct-30/Dec	1.28	6/Dec-30/Dec
1975/76	1/Apr-19/Apr	1.28	12/Dec-19/Apr	1.28	5/Oct-7/Jan [N/O]	3.12	Not optimal
1976/77	20/Jun-19/Apr [NF]	0.559	22/Feb-19/Apr	1.28	7/Oct-12/Feb	1.28	Not optimal
1977/78	20/Jun-15/Apr [NF]	0.559	30/Nov-19/Apr	1.28	4/Oct-28/Dec	1.28	30/Nov-28/Dec
1978/79	20/Jun-16/Apr [NF]	0.559	30/Nov-19/Apr	1.28	3/Oct-2/Jan	1.28	30/Nov-2/Jan
1979/80	28/Mar-19/Apr	1.28	7/Dec-14/Apr	1.28	5/Oct-29/Dec [N/O]	3.12	Not optimal
1980/81	25/Mar-19/Apr	1.28	8/Dec-19/Apr	1.28	3/Oct-29/Dec [N/O]	3.12	Not optimal
1981/82	31/Mar-19/Apr	1.28	1/Dec-14/Apr	1.28	4/Oct-24/Dec [N/O]	3.12	Not optimal
1982/83	28/Mar-19/Apr	1.28	15/Dec-18/Apr	1.28	5/Oct-6/Jan [N/O]	3.12	Not optimal
1983/84	4/Apr-19/Apr	1.28	5/Jan-19/Apr	1.28	14/Nov-9/Jan	1.28	5/Jan-9/Jan
1984/85	26/Mar-19/Apr	1.28	1/Dec-16/Apr	1.28	5/Oct-28/Dec [N/O]	3.12	Not optimal
1985/86	25/Mar-19/Apr	1.28	24/Dec-16/Apr	1.28	5/Oct-8/Jan [N/O]	3.12	Not optimal
1986/87	19/Mar-19/Apr	1.28	8/Dec-10/Apr	1.28	4/Oct-31/Dec [N/O]	3.12	Not optimal
1987/88	27/Mar-19/Apr	1.28	3/Dec-14/Apr	1.28	5/Oct-25/Dec [N/O]	3.12	Not optimal
1988/89	31/Mar-19/Apr	1.28	3/Dec-18/Apr	1.28	4/Oct-28/Dec [N/O]	3.12	Not optimal
1989/90	27/Mar-19/Apr	1.28	28/Dec-16/Apr	1.28	5/Oct-9/Jan [N/O]	3.12	Not optimal
Overlaps	4/Apr-6/Apr		22/Feb-6/Apr		14/Nov-20/Dec [N/O]		Not optimal

N/O: Not Optimal. NF: No fumigation

For sampling-based fumigation in OKC (Table 4.13), the optimal window range was 27/Mar-19/Apr for a low immigration rate, 19/Dec-3/Mar for a normal immigration rate, and 13/Oct-5/Dec for a high immigration rate. There were no common dates across years and immigration rates.

For sampling-based fumigation in Wichita (Table 4.14), the optimal window range was 4/Apr-6/Apr for a low immigration rate, 22/Feb-6/Apr for a normal immigration rate, and 14/Nov-20/Dec for a high immigration rate. There were no common dates across years and immigration rates.

The following results apply for when the storage manager has better, though not perfect, information about insect immigration rates in the facility's ten storage bins. The manager is assumed to know the proportion of bins that have low, normal, and high immigration rates. Table 4.15 shows the average cost as well as measures of risk (minimum, maximum, and standard deviation of cost) when a manager assumes all bins have a normal immigration rate and applies the optimal strategy for that assumption, routine fumigation on Dec. 4, when the bins actually have three different immigration rates in varied proportions, either one third each of low, normal, and high, 40% low, 40% normal, and 20% high, or 50% low and 50% normal immigration rates.

Values in parentheses are the costs of choosing the optimal strategy for the given mix of immigration rates. Those values minus the table's values gives the unnecessary cost paid. As the proportion of high immigration rate bins decreased, the cost and risk decreased and the unnecessary fumigation cost increased. In OKC, a high immigration rate raised the likelihood of damage due to failure to control insects. As the proportions of bins with a high immigration rate decreased, the cost of using one fumigation decreased. In Wichita, a high immigration rate in some years led to insect discounts, while a low immigration rate in other years resulted in unnecessary fumigation costs.

Table 4.15 Cost ($/tonne) Summary for One Routine Fumigation on Dec. 4th with Alternative Proportions of Immigration Rates

	Oklahoma City			Wichita		
Storage Period	1/3Low, 1/3Normal, 1/3High	0.4Low, 0.4Normal, 0.2High	0.5Low, 0.5Normal (0.937)	1/3Low, 1/3Normal, 1/3High (0.625)[a]	0.4Low, 0.4Normal, 0.2High (0.562)[a]	0.5Low, 0.5Normal (0.469)[a]
1961/62	1.55 [LD]	1.30 [LD]	0.937	0.937 [a]	0.937 [a]	0.937 [a]
1962/63	1.55 [LD]	1.30 [LD]	0.937	1.55 [LD]	1.30 [LD]	0.937
1963/64	1.55 [LD]	1.30 [LD]	0.937	0.937 [a]	0.937 [a]	0.937 [a]
1964/65	1.55 [LD]	1.30 [LD]	0.937	0.937 [a]	0.937 [a]	0.937 [a]
1965/66	1.55 [LD]	1.30 [LD]	0.937	1.55 [LD]	1.30 [LD]	0.937
1966/67	1.55 [LD]	1.30 [LD]	0.937	0.937 [a]	0.937 [a]	0.937 [a]
1967/68	1.55 [LD]	1.30 [LD]	0.937	0.937 [a]	0.937 [a]	0.937 [a]
1968/69	1.55 [LD]	1.30 [LD]	0.937	0.937 [a]	0.937 [a]	0.937 [a]
1969/70	1.55 [LD]	1.30 [LD]	0.937	0.937 [a]	0.937 [a]	0.937 [a]
1970/71	1.55 [LD]	1.30 [LD]	0.937	0.937 [a]	0.937 [a]	0.937 [a]
1971/72	1.55 [LD]	1.30 [LD]	0.937	1.55 [LD]	1.30 [LD]	0.937
1972/73	1.55 [LD]	1.30 [LD]	0.937	1.55 [LD]	1.30 [LD]	0.937
1973/74	1.55 [LD]	1.30 [LD]	0.937	1.55 [LD]	1.30 [LD]	0.937
1974/75	1.55 [LD]	1.30 [LD]	0.937	0.937 [a]	0.937 [a]	0.937 [a]
1975/76	1.55 [LD]	1.30 [LD]	0.937	1.55 [LD]	1.30 [LD]	0.937
1976/77	1.55 [LD]	1.30 [LD]	0.937	0.937 [a]	0.937 [a]	0.937 [a]
1977/78	1.55 [LD]	1.30 [LD]	0.937	0.937 [a]	0.937 [a]	0.937 [a]
1978/79	1.55 [LD]	1.30 [LD]	0.937	0.937 [a]	0.937 [a]	0.937 [a]
1979/80	1.55 [LD]	1.30 [LD]	0.937	1.55 [LD]	1.30 [LD]	0.937
1980/81	1.55 [LD]	1.30 [LD]	0.937	1.55 [LD]	1.30 [LD]	0.937
1981/82	1.55 [LD]	1.30 [LD]	0.937	1.55 [LD]	1.30 [LD]	0.937
1982/83	1.55 [LD]	1.30 [LD]	0.937	1.55 [LD]	1.30 [LD]	0.937
1983/84	1.55 [LD]	1.30 [LD]	0.937	0.937	0.937	0.937
1984/85	1.55 [LD]	1.30 [LD]	0.937	1.55 [LD]	1.30 [LD]	0.937
1985/86	1.55 [LD]	1.30 [LD]	0.937	1.55 [LD]	1.30 [LD]	0.937
1986/87	1.55 [LD]	1.30 [LD]	0.937	1.55 [LD]	1.30 [LD]	0.937
1987/88	1.55 [LD]	1.30 [LD]	0.937	1.55 [LD]	1.30 [LD]	0.937
1988/89	1.55 [LD]	1.30 [LD]	0.937	1.55 [LD]	1.30 [LD]	0.937
1989/90	1.55 [LD]	1.30 [LD]	0.937	1.55 [LD]	1.30 [LD]	0.937
Average	1.55	1.30	0.937	1.27	1.14	0.937
Minimum	1.55	1.30	0.937	0.937	0.937	0.937
Maximum	1.55	1.30	0.937	1.55	1.30	0.937
Standard deviation	1.11E-15	6.66E-16	2.22E-16	0.305	0.183	2.22E-16

a. The optimal cost for each proportion is in parentheses; 0.937 minus that value is the unnecessary cost paid

b. LD = live insect discount

Table 4.16 show the cost as well as risk when a firm assumes all bins have a high immigration rate and applies two calendar-based fumigations, one on Oct 31 and one on March 31, when the bins actually have three different immigration rates in varied proportions, as described above. There were no live insect or IDK discounts because two fumigations killed all the insects, but there were unnecessary fumigation costs because only one fumigation was needed for low and normal immigration rates. Generally, as the proportion of bins with a high immigration rate decreased, the unnecessary fumigation cost increased.

Tables 4.17 and 4.18 show the average cost as well as measures of risk (minimum, maximum, and standard deviation of cost) when a manager does not know the immigration rate for the bins but conducts monthly samples (at the end of every month, September through March) and fumigates if any month's sample exceeds the threshold, when the bins actually have three different immigration rates in varied proportions, either one third each of low, normal, and high, 40% low, 40% normal, and 20% high, or 50% low and 50% normal immigration rates.

In OKC, only when the proportion of bins with a high immigration rate was less than 20% was end-of-month sampling a lower cost strategy than fumigating twice. In Wichita, if possible live insect appearance is acceptable in the marketing, end-of-month sampling would have resulted in a lower cost than fumigating twice. But if live insects could be a serious problem, monthly sampling on the 19th of each month was preferred when the proportion of bins with a high immigration rate was less than 0.3.

Table 4.16 Cost ($/tonne) Summary for Two Routine Fumigations on Oct. 31 and Mar. 31 with Alternative Proportion of Immigration Rates

	Oklahoma City			Wichita		
Storage Period [b]	1/3Low, 1/3Normal, 1/3High (1.18)[a]	0.4Low, 0.4Normal, 0.2High (1.0816)[a]	0.5Low, 0.5Normal (0.937)[a]	1/3Low, 1/3Normal, 1/3High (0.6247)[b] (1.178)[c] (0.937)[d]	0.4Low, 0.4Normal, 0.2High (0.5622)[b] (1.0816)[c] (0.937)[d]	0.5Low, 0.5Normal (0.4685)[b] (0.937)[c] (0.937)[d]
1961/62	1.66	1.66	1.66	1.66 [b]	1.66 [b]	1.66 [b]
1962/63	1.66	1.66	1.66	1.66	1.66	1.66
1963/64	1.66	1.66	1.66	1.66 [b]	1.66 [b]	1.66 [b]
1964/65	1.66	1.66	1.66	1.66 [b]	1.66 [b]	1.66 [b]
1965/66	1.66	1.66	1.66	1.66	1.66	1.66
1966/67	1.66	1.66	1.66	1.66 [b]	1.66 [b]	1.66 [b]
1967/68	1.66	1.66	1.66	1.66 [b]	1.66 [b]	1.66 [b]
1968/69	1.66	1.66	1.66	1.66 [b]	1.66 [b]	1.66 [b]
1969/70	1.66	1.66	1.66	1.66 [b]	1.66 [b]	1.66 [b]
1970/71	1.66	1.66	1.66	1.66 [b]	1.66 [b]	1.66 [b]
1971/72	1.66	1.66	1.66	1.66	1.66	1.66
1972/73	1.66	1.66	1.66	1.66	1.66	1.66
1973/74	1.66	1.66	1.66	1.66	1.66	1.66
1974/75	1.66	1.66	1.66	1.66 [b]	1.66 [b]	1.66 [b]
1975/76	1.66	1.66	1.66	1.66	1.66	1.66
1976/77	1.66	1.66	1.66	1.66 [b]	1.66 [b]	1.66 [b]
1977/78	1.66	1.66	1.66	1.66 [b]	1.66 [b]	1.66 [b]
1978/79	1.66	1.66	1.66	1.66 [b]	1.66 [b]	1.66 [b]
1979/80	1.66	1.66	1.66	1.66	1.66	1.66
1980/81	1.66	1.66	1.66	1.66	1.66	1.66
1981/82	1.66	1.66	1.66	1.66	1.66	1.66
1982/83	1.66	1.66	1.66	1.66	1.66	1.66
1983/84	1.66	1.66	1.66	1.66 [d]	1.66 [d]	1.66 [d]
1984/85	1.66	1.66	1.66	1.66	1.66	1.66
1985/86	1.66	1.66	1.66	1.66	1.66	1.66
1986/87	1.66	1.66	1.66	1.66	1.66	1.66
1987/88	1.66	1.66	1.66	1.66	1.66	1.66
1988/89	1.66	1.66	1.66	1.66	1.66	1.66
1989/90	1.66	1.66	1.66	1.66	1.66	1.66
Average	1.66	1.66	1.66	1.66	1.66	1.66
Minimum	1.66	1.66	1.66	1.66	1.66	1.66
Maximum	1.66	1.66	1.66	1.66	1.66	1.66
Standard deviation	8.89E-16	1.11E-15	1.11E-15	8.89E-16	1.11E-15	1.11E-15

a. The optimal cost for each proportion is in parentheses; 1.66 minus that value is the unnecessary cost paid
c. d. in Wichita, there are three optimal strategies, depending on the year

Table 4.17 Cost ($/Tonne) Summary for Sampling-Based Fumigation at End of Months from September to March with Alternative Proportions of Immigration Rates

	Oklahoma City			Wichita		
Storage Period [b]	1/3Low, 1/3Normal, 1/3High (1.77)	0.4Low, 0.4Normal, 0.2High (1.67)	0.5Low, 0.5Normal (1.53)	1/3Low, 1/3Normal, 1/3High (1.29) (1.77)	0.4Low, 0.4Normal, 0.2High (1.24) (1.67)	0.5Low, 0.5Normal (1.17) (1.53)
1961/62	1.77	1.67	1.53	1.29	1.24	1.17
1962/63	1.77	1.67	1.53	1.77	1.67	1.53
1963/64	1.77	1.67	1.53	1.29	1.24	1.17
1964/65	1.77	1.67	1.53	1.29	1.24	1.17
1965/66	1.77	1.67	1.53	1.77	1.67	1.53
1966/67	1.77	1.67	1.53	1.29	1.24	1.17
1967/68	1.77	1.67	1.53	1.29	1.24	1.17
1968/69	1.77	1.67	1.53	1.29	1.24	1.17
1969/70	1.77	1.67	1.53	1.29	1.24	1.17
1970/71	1.77	1.67	1.53	1.29	1.24	1.17
1971/72	1.77	1.67	1.53	1.77	1.67	1.53
1972/73	1.77	1.67	1.53	1.77	1.67	1.53
1973/74	1.77	1.67	1.53	1.77	1.67	1.53
1974/75	1.77	1.67	1.53	1.29	1.24	1.17
1975/76	1.77	1.67	1.53	2.14 [LD]	2.29 [LD]	2.09 [LD]
1976/77	1.77	1.67	1.53	1.29	1.24	1.17
1977/78	1.77	1.67	1.53	1.29	1.24	1.17
1978/79	1.77	1.67	1.53	1.29	1.24	1.17
1979/80	1.77	1.67	1.53	1.77	1.67	1.53
1980/81	1.77	1.67	1.53	1.77	1.67	1.53
1981/82	1.77	1.67	1.53	1.77	1.67	1.53
1982/83	1.77	1.67	1.53	1.77	1.67	1.53
1983/84	1.77	1.67	1.53	2.51 [LD]	2.34 [LD]	2.09 [LD]
1984/85	1.77	1.67	1.53	1.77	1.67	1.53
1985/86	1.77	1.67	1.53	1.77	1.67	1.53
1986/87	1.77	1.67	1.53	1.77	1.67	1.53
1987/88	1.77	1.67	1.53	1.77	1.67	1.53
1988/89	1.77	1.67	1.53	1.77	1.67	1.53
1989/90	1.77	1.67	1.53	1.77	1.67	1.53
Average	1.77	1.67	1.53	1.61	1.54	1.42
Minimum	1.77	1.67	1.53	1.29	1.24	1.17
Maximum	1.77	1.67	1.53	2.51	2.34	2.09
Standard deviation	6.66E-16	2.22E-16	6.66E-16	0.307	0.297	0.251

LD: Live insect discount included

Table 4.18 Cost ($/Tonne) Summary for Sampling-Based Fumigations on 19th of Each Month from September to April with Alternative Proportions of Immigration Rates

	Oklahoma City			Wichita		
Storage Period [b]	1/3Low, 1/3Normal, 1/3High (1.85)	0.4Low, 0.4Normal, 0.2High (1.76)	0.5Low, 0.5Normal (1.61)	1/3Low, 1/3Normal, 1/3High (1.30)[b]	0.4Low, 0.4Normal, 0.2High (1.24)[b]	0.5Low, 0.5Normal (1.14)[b]
1961/62	1.85	1.76	1.61	1.85 [b]	1.76 [b]	1.61 [b]
1962/63	1.85	1.76	1.61	1.85	1.76	1.61
1963/64	1.85	1.76	1.61	1.61 [b]	1.47 [b]	1.25 [b]
1964/65	1.85	1.76	1.61	1.85 [b]	1.76 [b]	1.61 [b]
1965/66	1.85	1.76	1.61	1.85	1.76	1.61
1966/67	1.85	1.76	1.61	1.85 [b]	1.76 [b]	1.61 [b]
1967/68	1.85	1.76	1.61	1.61	1.47	1.25
1968/69	1.85	1.76	1.61	1.37	1.12	1.25
1969/70	1.85	1.76	1.61	1.61	1.47	1.25
1970/71	1.85	1.76	1.61	1.37	1.12	1.25
1971/72	1.85	1.76	1.61	1.85	1.76	1.61
1972/73	1.85	1.76	1.61	1.85	1.76	1.61
1973/74	1.85	1.76	1.61	1.85	1.76	1.61
1974/75	1.85	1.76	1.61	1.61 [b]	1.47 [b]	1.25 [b]
1975/76	1.85	1.76	1.61	1.85	1.76	1.61
1976/77	1.85	1.76	1.61	1.37	1.12	1.25
1977/78	1.85	1.76	1.61	1.37	1.12	1.25
1978/79	1.85	1.76	1.61	1.37	1.12	1.25
1979/80	1.85	1.76	1.61	1.85	1.76	1.61
1980/81	1.85	1.76	1.61	1.85	1.76	1.61
1981/82	1.85	1.76	1.61	1.85	1.76	1.61
1982/83	1.85	1.76	1.61	1.85	1.76	1.61
1983/84	1.85	1.76	1.61	1.85	1.76	1.61
1984/85	1.85	1.76	1.61	1.85	1.76	1.61
1985/86	1.85	1.76	1.61	1.85	1.76	1.61
1986/87	1.85	1.76	1.61	1.85	1.76	1.61
1987/88	1.85	1.76	1.61	1.85	1.76	1.61
1988/89	1.85	1.76	1.61	1.85	1.76	1.61
1989/90	1.85	1.76	1.61	1.85	1.76	1.61
Average	1.85	1.76	1.61	1.74	1.61	1.50
Minimum	1.85	1.76	1.61	1.37	1.12	1.25
Maximum	1.85	1.76	1.61	1.85	1.76	1.61
Standard deviation	4.44E-16	1.11E-15	2.22E-16	0.186	0.242	0.167

Tables 4.19 and 4.20 show the average cost as well as measures of risk (minimum, maximum, and standard deviation of cost) of the insect control strategies considered for each location assuming weather is unknown and under alternative immigration rates. In OKC, at least one fumigation was required regardless of immigration rate. Under low and normal immigration rates, one fumigation (Strategy II) was optimal, and under a high immigration rate two fumigations (Strategy III) were optimal. Under an assumption of 30% of the bins with low, 30% with normal, and 40% with high immigration rate, or an assumption of 1/3 of the bins with each immigration rate, the best strategy was Strategy VI, fumigation Oct 31, followed by one sample on Mar 31.

Under an assumption of 40% low, 40% high, and 20% high immigration rate, or an assumption of 50% low and 50% normal immigration rate the best strategy was Strategy II, one routine fumigation. At least one fumigation was required in OKC regardless of the immigration rate, and if the storage manager was confident that few bins have a high immigration rate, sampling beyond the initial fumigation simply added costs; it did not change treatments. However, if it is likely that more than 20% of the bins have a high immigration rate, sampling beyond the initial fumigation would protect from uncontrolled insect populations without a large additional cost.

In Wichita, as in OKC, under low and normal immigration rates, one fumigation (Strategy II) was optimal, and under a high immigration rate two fumigations (Strategy III) were optimal. Under an assumption that 30% of the bins have low, 30% normal, and 40% high immigration rate, one fumigations was optimal. Under the other assumptions (which have lower percentages of high-immigration-rate bins), one fumigation was lowest cost. However, Strategy VX (fumigation Oct 31 followed by samples at the end of February and March) was nearly as good.

Table 4.19 Average, Minimum and Maximum Cost ($/tonne) of Alternate Strategies across 29 Storage Periods under Unknown Weather Conditions and Alternative Immigration Rates, OKC

Strategies	Description	Low			Normal			High			0.3 Low, 0.3Normal, 0.4 High			1/3 Low, 1/3Normal, 1/3 High			0.4 Low, 0.4Normal, 0.2 High			0.5 Low, 0.5 Normal		
		Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max
I	Doing Nothing	1.84	1.84	1.84	6.41	3.99	11.4	47.4	23.4	97.2	21.4	11.1	42.8	18.6	9.73	36.8	12.8	7.00	24.7	4.12	2.92	6.62
Calendar-based Strategies																						
II	One Fumigation (Dec 4th)	**0.937**	**0.937**	**0.937**	**0.937**	**0.937**	**0.937**	2.77	2.77	2.77	1.67	1.67	1.67	1.55	1.55	1.55	**1.30**	**1.30**	**1.30**	**0.937**	**0.937**	**0.937**
III	Two Fumigations (Oct & Mar 31st)	1.66	1.66	1.66	1.66	1.66	1.66	**1.66**	**1.66**	**1.66**	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66
Sampling-based Strategies																						
IV	One sampling-based fumigation (no optimal dates)	1.28	1.28	1.28	1.28	1.28	1.28	3.12	3.12	3.12	2.02	2.02	2.02	1.89	1.89	1.89	1.65	1.65	1.65	1.28	1.28	1.28
V	Monthly Sampling with 0.5/kg threshold (Sep-Mar 31st)	1.53	1.53	1.53	1.53	1.53	1.53	2.25	2.25	2.25	1.82	1.82	1.82	1.77	1.77	1.77	1.67	1.67	1.67	1.53	1.53	1.53
VI	Monthly Sampling with a 0.75/kg threshold (Sep-April 19th)	1.61	1.61	1.61	1.61	1.61	1.61	2.34	2.34	2.34	1.90	1.90	1.90	1.85	1.85	1.85	1.76	1.76	1.76	1.61	1.61	1.61
Combination Strategies																						
VII	Fumigation Oct 31st , One Sample (Mar 31st)	1.28	1.28	1.28	1.28	1.28	1.28	2.01	2.01	2.01	**1.57**	**1.57**	**1.57**	**1.52**	**1.52**	**1.52**	1.43	1.43	1.43	1.28	1.28	1.28
VIII	Fumigation Oct 31st , Monthly Sample (Nov-Mar 31st)	1.36	1.36	1.36	1.36	1.36	1.36	2.08	2.08	2.08	1.65	1.65	1.65	1.60	1.60	1.60	1.504	1.504	1.504	1.36	1.36	1.36
VX	Fumigation Oct 31st , Two Samples (Feb 28, Mar 31)	1.35	1.35	1.35	1.35	1.35	1.35	2.07	2.07	2.07	1.64	1.64	1.64	1.59	1.59	1.59	1.49	1.49	1.49	1.35	1.35	1.35

Table 4.20 Average, Minimum and Maximum Cost ($/tonne) of Alternate Strategies across 29 Storage Periods under Unknown Weather Conditions and Alternative Immigration Rates, Wichita

Strategies	Description	Low		Normal		High		0.3Low, 0.3Normal, 0.4High		1/3Low, 1/3Normal, 1/3High		0.4Low, 0.4Normal, 0.2High		0.5Low, 0.5Normal	
I	Doing Nothing	1.08		2.90		19.2		8.87		7.72		5.43		1.99	
		0	1.84	1.84	4.59	8.55	29.3	3.97	13.7	3.46	11.9	2.45	8.43	0.919	3.21
Calendar-based Strategies															
II	One Fumigation (Dec 4th)	**0.937**		**0.937**		1.95		**1.34**		**1.28**		**1.14**		**0.937**	
		0.937	**0.937**	**0.937**	**0.937**	0.937	2.77	**0.937**	**1.67**	**0.937**	**1.55**	**0.937**	**1.30**	**0.937**	**0.937**
III	Two Fumigations (Oct & Mar 31st)	1.66		1.66		**1.66**		1.66		1.66		1.66		1.66	
		1.66	1.66	1.66	1.66	**1.66**	**1.66**	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66
Sampling-based Strategies															
IV	One sampling-based fumigation	0.982		1.28		2.30		1.60		1.52		1.36		1.13	
		0.56	1.28	1.28	1.28	1.28	3.12	1.06	2.02	1.04	1.89	0.992	1.65	0.920	1.28
V	Monthly Sampling with 0.5/kg threshold (Sep-Mar 31st)	1.31		1.53		1.99		1.65		1.61		1.53		1.42	
		0.806	2.64	1.53	1.53	1.53	3.37	1.31	2.60	1.29	2.51	1.24	2.34	1.17	2.09
VI	Monthly Sampling with a 0.75/kg threshold (Sep-April 19th)	1.39		1.61		2.21		1.79		1.74		1.64		1.501	
		0.89	1.61	1.61	1.61	1.61	2.34	1.40	1.90	1.37	1.85	1.32	1.76	1.25	1.61
Combination Strategies															
VII	Fumigation Oct 31st , One Sample (Mar 31st)	1.28		1.28		1.74		1.47		1.44		1.37		1.28	
		1.28	1.28	1.28	1.28	1.28	3.12	1.28	2.02	1.28	1.89	1.28	1.65	1.28	1.28
VIII	Fumigation Oct 31st , Monthly Sample (Nov-Mar 31st)	1.36		1.36		1.82		1.54		1.51		1.45		1.36	
		1.36	1.36	1.36	1.36	1.36	3.92	1.36	2.38	1.36	2.21	1.36	1.87	1.36	1.36
VX	Fumigation Oct 31st , Two Samples (Feb 28, Mar 31)	1.35		1.35		1.81		1.54		1.51		1.44		1.35	
		1.35	1.35	1.35	1.35	1.35	3.19	1.35	2.09	1.35	1.96	1.35	1.72	1.35	1.35

Doubling Live Insect Discount/Halving Sampling Cost

Tables 4.21 and 4.22 show that when live insect discount was doubled, optimal strategies were more likely to include sampling. For Oklahoma City, the only change from Table 4.19 to Table 4.21 is that when the bins were 40% low, 40% normal, and 20% high immigration rates, the optimal strategy shifted from one fumigation to a strategy with one fumigation followed by a sample on March 31. For Wichita, though, optimal strategies under the three cases where some bins have a high immigration rate shifted from one fumigation to a strategy of monthly sampling.

Tables 4.23 and 4.24 show the effect of halving sampling cost. For Oklahoma City, the lone strategy shift was the same as that for doubling the live insect discount – from one fumigation to one fumigation plus one sample. For Wichita, when at least 1/3 of bins have a high immigration rate, the optimal strategy shifted from one fumigation to a strategy of one fumigation followed by a sample. This is in contrast to the result from doubling the live insect discount, where the optimal strategy for all cases that included bins with a high immigration rate shifted to monthly sampling.

To summarize, when the live insect discount is doubled or sampling cost halved, in both OKC and Wichita sampling–based fumigation become more attractive than one fumigation if there were some proportions of bins with high immigration rates. Doubling the live insect discount increased the costs of failing to control insects; sampling helped avoid this cost

Table 4.21 Average, Minimum and Maximum Cost ($/tonne) of Alternate Strategies across 29 Storage Periods under Unknown Weather Conditions and Alternative Immigration Rates, OKC, Doubled Live Insect Discount

Strategies	Description	Low		Normal		High		0.3 Low, 0.3Normal, 0.4 High		1/3 Low, 1/3Normal, 1/3 High		0.4 Low, 0.4Normal, 0.2 High		0.5 Low, 0.5 Normal	
I	Doing Nothing	3.67		8.24		49.3		23.3		20.4		14.6		5.96	
		3.67	3.67	5.83	13.2	25.2	99.02	12.9	44.7	11.6	38.6	8.84	26.6	4.75	8.45
Calendar-based Strategies															
II	One Fumigation (Dec 4th)	**0.937**		**0.937**		4.61		2.41		2.16		1.67		**0.937**	
		0.937	**0.937**	**0.937**	**0.937**	4.61	4.61	2.41	2.41	2.16	2.16	1.67	1.67	**0.937**	**0.937**
III	Two Fumigations (Oct & Mar 31st)	1.66		1.66		**1.66**		1.66		1.66		1.66		1.66	
		1.66	1.66	1.66	1.66	**1.66**	**1.66**	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66
Sampling-based Strategies															
IV	One sampling-based fumigation (no optimal dates)	1.28		1.28		4.96		2.75		2.51		2.02		1.28	
		1.28	1.28	1.28	1.28	4.96	4.96	2.75	2.75	2.51	2.51	2.02	2.02	1.28	1.28
V	Monthly Sampling with 0.5/kg threshold (Sep-Mar 31st)	1.53		1.53		2.25		1.82		1.77		1.67		1.53	
		1.53	1.53	1.53	1.53	2.25	2.25	1.82	1.82	1.77	1.77	1.67	1.67	1.53	1.53
VI	Monthly Sampling with a 0.75/kg threshold (Sep-April 19th)	1.61		1.61		2.34		1.90		1.85		1.76		1.61	
		1.61	1.61	1.61	1.61	2.34	2.34	1.90	1.90	1.85	1.85	1.76	1.76	1.61	1.61
Combination Strategies															
VII	Fumigation Oct 31st , One Sample (Mar 31st)	1.28		1.28		2.01		**1.57**		**1.52**		**1.43**		1.28	
		1.28	1.28	1.28	1.28	2.01	2.01	**1.57**	**1.57**	**1.52**	**1.52**	**1.43**	**1.43**	1.28	1.28
VIII	Fumigation Oct 31st , Monthly Sample (Nov-Mar 31st)	1.36		1.36		2.08		1.65		1.60		1.504		1.36	
		1.36	1.36	1.36	1.36	2.08	2.08	1.65	1.65	1.60	1.60	1.504	1.504	1.36	1.36
VX	Fumigation Oct 31st , Two Samples (Feb 28, Mar 31)	1.35		1.35		2.07		1.64		1.59		1.49		1.35	
		1.35	1.35	1.35	1.35	2.07	2.07	1.64	1.64	1.59	1.59	1.49	1.49	1.35	1.35

Table 4.22 Average, Minimum and Maximum Cost ($/tonne) of Alternate Strategies across 29 Storage Periods under Unknown Weather Conditions and Alternative Immigration Rates, Wichita, Doubled Live Insect Discount

Strategies	Description	Low		Normal		High		0.3Low, 0.3Normal, 0.4High		1/3Low, 1/3Normal, 1/3High		0.4Low, 0.4Normal, 0.2High		0.5Low, 0.5Normal	
I	Doing Nothing	2.15		4.74		21.0		10.5		9.31		6.96		3.45	
		0	3.67	3.67	6.43	10.4	31.1	5.26	15.5	4.69	13.7	3.55	10.3	1.84	5.05
Calendar-based Strategies															
II	One Fumigation (Dec 4th)	**0.937**		**0.937**		1.95		1.75		1.61		1.33		**0.937**	
		0.937	**0.937**	**0.937**	**0.937**	0.937	2.77	0.937	2.41	0.937	2.16	0.937	1.67	**0.937**	**0.937**
III	Two Fumigations (Oct & Mar 31st)	1.66		1.66		**1.66**		1.66		1.66		1.66		1.66	
		1.66	1.66	1.66	1.66	**1.66**	**1.66**	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66
Sampling-based Strategies															
IV	One sampling-based fumigation	0.983		1.28		3.31		2.00		1.85		1.56		1.13	
		0.56	1.28	1.28	1.28	1.28	4.96	1.06	2.75	1.04	2.51	0.993	2.02	0.921	1.28
V	Monthly Sampling with 0.5/kg threshold (Sep-Mar 31st)	0.43		1.53		2.05		**1.41**		**1.34**		**1.19**		0.98	
		0.806	4.48	1.53	1.53	1.53	5.20	**1.31**	**3.88**	**1.29**	**3.74**	**1.24**	**3.44**	1.17	3.01
VI	Monthly Sampling with a 0.75/kg threshold (Sep-April 19th)	1.39		1.61		2.21		1.79		1.74		1.64		1.501	
		0.89	1.61	1.61	1.61	1.61	2.34	1.40	1.90	1.37	1.85	1.32	1.76	1.25	1.61
Combination Strategies															
VII	Fumigation Oct 31st, One Sample (Mar 31st)	1.28		1.28		1.81		1.49		1.46		1.39		1.28	
		1.28	1.28	1.28	1.28	1.28	4.96	1.28	2.75	1.28	2.51	1.28	2.02	1.28	1.28
VIII	Fumigation Oct 31st, Monthly Sample (Nov-Mar 31st)	1.36		1.36		1.88		1.56		1.53		1.46		1.36	
		1.36	1.36	1.36	1.36	1.36	5.03	1.36	2.83	1.36	2.58	1.36	2.09	1.36	1.36
VX	Fumigation Oct 31st, Two Samples (Feb 28, Mar 31)	1.35		1.35		1.88		1.56		1.53		1.46		1.35	
		1.35	1.35	1.35	1.35	1.35	5.03	1.35	2.82	1.35	2.58	1.35	2.09	1.35	1.35

Table 4.23 Average, Minimum and Maximum Cost ($/tonne) of Alternate Strategies across 29 Storage Periods under Unknown Weather Conditions and Alternative Immigration Rates, OKC, Sampling Cost Halved

Strategies	Description	Low		Normal		High		0.3 Low, 0.3Normal, 0.4 High		1/3 Low, 1/3Normal, 1/3 High		0.4 Low, 0.4Normal, 0.2 High		0.5 Low, 0.5 Normal	
I	Doing Nothing	1.84		6.41		47.4		21.4		18.6		12.8		4.12	
		1.84	1.84	3.99	11.4	23.4	97.2	11.1	42.8	9.73	36.8	7.00	24.7	2.92	6.62
Calendar-based Strategies															
II	One Fumigation (Dec 4th)	**0.937**		**0.937**		2.77		1.67		1.55		1.30		**0.937**	
		0.937	**0.937**	**0.937**	**0.937**	2.77	2.77	1.67	1.67	1.55	1.55	1.30	1.30	**0.937**	**0.937**
III	Two Fumigations (Oct & Mar 31st)	1.66		1.66		**1.66**		1.66		1.66		1.66		1.66	
		1.66	1.66	1.66	1.66	**1.66**	**1.66**	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66
Sampling-based Strategies															
IV	One sampling-based fumigation (no optimal dates)	1.11		1.11		2.95		1.85		1.72		1.48		1.11	
		1.11	1.11	1.11	1.11	2.95	2.95	1.85	1.85	1.72	1.72	1.48	1.48	1.11	1.11
V	Monthly Sampling with 0.5/kg threshold (Sep-Mar 31st)	1.23		1.23		1.96		1.52		1.47		1.38		1.23	
		1.23	1.23	1.23	1.23	1.96	1.96	1.52	1.52	1.47	1.47	1.38	1.38	1.23	1.23
VI	Monthly Sampling with a 0.75/kg threshold (Sep-April 19th)	1.28		1.28		2.00		1.57		1.52		1.42		1.28	
		1.28	1.28	1.28	1.28	2.00	2.00	1.57	1.57	1.52	1.52	1.42	1.42	1.28	1.28
Combination Strategies															
VII	Fumigation Oct 31st , One Sample (Mar 31st)	1.11		1.11		1.83		**1.40**		**1.35**		**1.25**		1.11	
		1.11	1.11	1.11	1.11	1.83	1.83	**1.40**	**1.40**	**1.35**	**1.35**	**1.25**	**1.25**	1.11	1.11
VIII	Fumigation Oct 31st , Monthly Sample (Nov-Mar 31st)	1.15		1.15		1.87		1.44		1.39		1.294		1.15	
		1.15	1.15	1.15	1.15	1.87	1.87	1.44	1.44	1.39	1.39	1.294	1.294	1.15	1.15
VX	Fumigation Oct 31st , Two Samples (Feb 28, Mar 31)	1.14		1.14		1.87		1.43		1.38		1.29		1.14	
		1.14	1.14	1.14	1.14	1.87	1.87	1.43	1.43	1.38	1.38	1.29	1.29	1.14	1.14

Table 4.24 Average, Minimum and Maximum Cost ($/tonne) of Alternate Strategies across 29 Storage Periods under Unknown Weather Conditions and Alternative Immigration Rates, Wichita, Sampling Cost Halved

Strategies	Description	Low		Normal		High		0.3Low, 0.3Normal, 0.4High		1/3Low, 1/3Normal, 1/3High		0.4Low, 0.4Normal, 0.2High		0.5Low, 0.5Normal	
I	Doing Nothing	1.08		2.90		19.2		8.87		7.72		5.43		1.99	
		0	1.84	1.84	4.59	8.55	29.3	3.97	13.7	3.46	11.9	2.45	8.43	0.919	3.21
Calendar-based Strategies															
II	One Fumigation (Dec 4th)	**0.937**		**0.937**		1.95		1.34		1.28		**1.14**		**0.937**	
		0.937	**0.937**	**0.937**	**0.937**	0.937	2.77	0.937	1.67	0.937	1.55	**0.937**	**1.30**	**0.937**	**0.937**
III	Two Fumigations (Oct & Mar 31st)	1.66		1.66		**1.66**		1.66		1.66		1.66		1.66	
		1.66	1.66	1.66	1.66	**1.66**	**1.66**	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66
Sampling-based Strategies															
IV	One sampling-based fumigation	0.809		1.11		2.13		1.43		1.35		1.19		0.96	
		0.388	1.11	1.11	1.11	1.11	2.95	0.89	1.85	0.868	1.72	0.820	1.48	0.75	1.11
V	Monthly Sampling with 0.5/kg threshold (Sep-Mar 31st)	1.01		1.23		1.69		1.35		1.31		1.23		1.12	
		0.510	2.35	1.23	1.23	1.23	3.07	1.01	2.31	0.994	2.21	0.944	2.04	0.87	1.79
VI	Monthly Sampling with a 0.75/kg threshold (Sep-April 19th)	1.05		1.28		1.87		1.45		1.41		1.31		1.16	
		0.552	1.28	1.28	1.28	1.28	2.01	1.06	1.56	1.03	1.51	0.982	1.42	0.912	1.28
Combination Strategies															
VII	Fumigation Oct 31st, One Sample (Mar 31st)	1.11		1.11		1.57		**1.30**		**1.27**		1.20		1.11	
		1.11	1.11	1.11	1.11	1.11	2.95	**1.11**	**1.85**	**1.11**	**1.72**	1.11	1.48	1.11	1.11
VIII	Fumigation Oct 31st, Monthly Sample (Nov-Mar 31st)	1.15		1.15		1.61		1.33		1.30		1.23		1.15	
		1.15	1.15	1.15	1.15	1.15	3.71	1.15	2.17	1.15	2.00	1.15	1.66	1.15	1.15
VX	Fumigation Oct 31st, Two Samples (Feb 28, Mar 31)	1.14		1.14		1.60		1.33		1.30		1.23		1.14	
		1.14	1.14	1.14	1.14	1.14	2.98	1.14	1.88	1.14	1.75	1.14	1.51	1.14	1.14

CHAPTER V

CONCLUSION

Summary and Discussion

In this study we have estimated and summarized optimal treatment dates and costs for various insect control strategies simulated under uncertain weather conditions and unknown immigration rates. We considered eight strategies, in addition to doing nothing, grouped into calendar-based, sampling-based and combination strategies.

For current cost estimates, under most situations for which insect immigration rate was known, the optimal strategy (one that achieves lowest cost of insect control) was one or two fumigations. Strategies including sampling were not preferred. For example, under Oklahoma City weather conditions with low or normal insect immigration rates, the strategy with the lowest combined treatment cost and insect damage cost was to fumigate once per storage period. Two fumigations were preferred with a high insect immigration rate. Similar results were realized for Wichita.

In contrast, when insect immigration rate was not known, a strategy of one fumigation plus sampling after that became dominant for Oklahoma City. For Wichita, no one strategy became dominant, because a fumigation was not needed in every year in Wichita. Following the same strategy in Wichita that was dominant in OKC, however, would have provided insect control that was as good as or better than in OKC because of the cooler temperatures, at a cost no higher than incurred in OKC.

To determine the sensitivity of these results to underlying assumptions, we examined the effects of reducing sampling cost by 50%, and of doubling the live insect discount. Sampling cost might be reduced if sampling technology could be improved, and live insect discount might be significantly higher if a buyer rejects a load because of the presence of live insects.

Results show that if cost of sampling was reduced by 50%, there was greater incentive to conduct more sampling after fumigating, to increase confidence that insects were in fact controlled. Also, if live insect discount was doubled, strategies using sampling became the least cost strategy under a greater range of scenarios.

Anecdotal reports suggest that many elevators in the Central and Southern Plains fumigate more often than once per year. Fumigating once at a strategic time, and then sampling for follow up might reduce the number of fumigations to one in a given year, even when some bins have a high immigration rate. This could reduce costs, and would also provide assurance that insect populations would not grow unchecked in the event that bins have a high immigration rate.

Implications for Future Study

There are several things could be considered in future study. First of all, this study used a simplified version of insect growth model. Further estimation with full model by Flinn, Hagstrum, and Phillips would obtain more realistic result. Even more, the sampling result might be more predictable.

Second, sampling results are sensitive to sampling date and threshold, especially for monthly sampling. Further research could better determine best sampling time and threshold. Improving insect sampling in this way could reduce the risk managers face by not fumigating, increasing their confidence that they will detect insects in time to control them. This could make IPM methods more attractive to elevator managers.

Third, the two locations considered, Oklahoma City and Wichita, are only 160 miles apart. Further research should consider how optimal insect control strategies would change for locations farther north or south in the hard red winter wheat growing area of the U.S. It may also be useful to evaluate strategies for locations even farther north, in the area of the U.S. that grows spring wheat.

Fourth, the measures of risk considered here were simple. More complete measures of the risk involved in these strategies could be obtained through estimating distributions of the random variables modeled here and using Monte Carlo techniques. This would help ensure that any strategy recommendations had more carefully considered the risk faced by grain storage managers.

Finally, we have assumed that all the bins are in the same situation except immigration rate. But in a storage facility, bins in different locations could face different weather conditions. For example, sunshine time could influence a specific bin’s temperature. Also, immigration rate may have special influence among all bins. If one bin is observed with high immigration rate, the nearby bins are more likely to have high immigration rate. So this should be considered when estimating immigration rate.

REFERENCES

Adam, Brian D. and Corinne Alexander. 2012. “Economics of IPM Decisions.” Ch. 28 in “Stored Product Protection," edited by David W. Hagstrum, Thomas W. Phillips and Gerrit Cuperus. Available at http://www.ksre.ksu.edu/bookstore/pubs/S156.pdf.

Adam, B.D., Edmond Bonjour, and Jim Criswell. 2010. "Cost Comparison of Methyl Bromide and Sulfuryl Fluoride (ProFume®) for Fumigating Food Processing Facilities, Warehouses, and Cocoa Beans." In: Carvalho, O.M, Fields, P.G., Adler, C.S., Arthur, F.H., Athanassiou, C.G., Campbell, J.F., Fleurat-Lessard, F., Flinn, P.W., Hodges, R.J., Isikber, A.A. Navarro, S., Noyes, R.T., Riudavets, J., Sinha, K.K., Thorpe, G.R., Timlick, B.H., Trematerra, P., White, N.D.G. (Eds), *Proceedings of the Tenth International Working Conference on Stored Product Protection*, 27 June-2 July, Estoril, Portugal, Julius-Kuhn-Archiv, Berlin, Germany, pp.314-321.

Adam, B. D., T. W. Phillips, and P.W. Flinn. 2006. “The Economics of IPM in Stored Grain: Why Don’t More Grain Handlers Use IPM?” *Proceedings of the 9th International Working Conference on Stored Product Protection.* Edited by I. Lorini et al.. Campinas, Sao Paulo, BRAZIL: ABRAPOS, pp.3-12.

Adam, B.D., M. Siaplay, P.W. Flinn, B.W. Brorsen, and T.W. Phillips. 2010. "Factors influencing economic profitability of sampling-based integrated pest management of wheat in country elevators." *Journal of Stored Products Research* 46:186-196.

Arthur, F. H., J. A. Johnson, L. G. Neven, G. J. Hallman, and P. A. Follett. 2009. Insect pest management in postharvest ecosystems in the United States of America. *Outlooks on Pest Management*, *20*(6), 279-284.

Campbell, J.F., M.A. Mullen, and A.K. Dowdy. 2002. "Monitoring Stored-Product Pests in Food Processing Plants with Pheromone Trapping, Contour Mapping, and Mark-Recapture." *Journal of Economic Entomology*.

Fields, P.G., and N.D.G. White. 2002. "Alternatives to methyl bromide treatments for stored-product and quarantine research." *Annu. Rev. Entomol* 47:311.

Flinn, P.W. Weather Data provided in spreadsheet.

Flinn, P.W., D.W. Hagstrum, C.R. Reed, and T.W. Phillips. 2007. "Stored Grain Advisor Pro: Decision support system for insect management in commercial grain elevators." *Journal of Stored Products Research* 43:8.

Hagstrum, David W., and Paul W. Flinn. 2012. “Insect Pest Management for Raw Commodities During Storage”, Ch. 18 in “Stored Product Protection," edited by David W. Hagstrum, Thomas W. Phillips and Gerrit Cuperus. Available at http://www.ksre.ksu.edu/bookstore/pubs/S156.pdf.

Hagstrum, D.W., and B. Subramanyam (2000) "Monitoring and decision tools." *Alternatives to pesticides in stored-product IPM*., Springer US, 2000. pp. 1-28.

Harein, P.K., and R. Meronuck. 1991. "Stored grain losses due to insects and molds and the importance of proper grain management." Ch. 4 in "*Stored Product Management*," edited by Krischik, V., G. Cuperus, and D. Galliart

Krischik, Vera. and Wendell Burkholder. 1991. "Stored -product Insects and Biological Control Agents." Ch. 13 in "*Stored Product Management*," edited by Krischik, V., G. Cuperus, and D. Galliart.

Mah, P.M. 2004. "Cost of Controlling (or Failing to Control) Insects in Stored Grain: A comparison of Chemical-Based and Integrated Pest Management Strategies." Oklahoma State University.

Mason, Linda J., and Marissa McDonough. 2012 "Biology, Behavior, and Ecology of Stored Grain and Legume Insects", Ch. 2 in "Stored Product Protection," edited by David W. Hagstrum, Thomas W. Phillips and Gerrit Cuperus. Available at http://www.ksre.ksu.edu/bookstore/pubs/S156.pdf.

Reed, Carl. 2013. Phone and email conversations.

Roesli, R., and B. Subramanyam. "Insect Populations before and after Heat Treatment of a Pilot Flour Mill."

Tilley, D.R., F.H. Arthur, M.E. Casada, and M.R. Langemeier. 2007. "Cost and Risk Analysis of Heat and Chemical Treatments." *Journal of Economic Entomology* 100(2):604-612.

Way, M.J. 1977. "Integrated control-practical realities." *Outlook on agriculture* 9(3):127-135.

VITA

Suling Duan

Candidate for the Degree of

Master of Science

Thesis: INSECT CONTROL UNDER UNCERTAINTY: ECONOMICAL STRATEGIES THAT ARE ROBUST TO VARYING WEATHER CONDITIONS AND INSECT IMMIGRATION RATES

Major Field: Agricultural Economics

Biographical:

Education:

Completed the requirements for the Master of Science in Agricultural Economics at Oklahoma State University, Stillwater, Oklahoma in July, 2014.

Bachelor of Science in Turfgrass Management at Michigan State University, East Lansing, Michigan in 2010.

Bachelor of Science in Turfgrass Management at Sichuan Agricultural University, Yaan, China in 2010.

Experience:

Employed as a research assistant at Oklahoma State University; Department of Agricultural Economics, 2010-2014