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Stored-grain insect control costs in varying climates and levels of insects' phosphine resistance

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Introduction

Insect resistance to phosphine, the primary fumigant used to combat stored grain pests, is a major problem in many countries such as Australia, Brazil, China and India (Collins et al. 2005; Daghli 2004; Rajendran 1999; Sartori and Vilar 1991; and Zeng 1999). The development of resistance in these countries is believed to have resulted from poor fumigation practices over time. Inadequate insect exposure to phosphine made multiple treatments necessary, allowing pests to develop resistance (Semple et al. 1992). Once the genes responsible for resistance were present in an insect population, increased phosphine use resulted in higher proportions of resistant pests (Emery, Collins and Wallbank 2003; Collins et al. 2005; Daghli 2004; Newman 2010; Schlipalius et al. 2008). As the levels of resistance increase, the frequency, concentration, and/or duration of fumigation must also increase. Additionally, the problem of pest resistance developing has been compounded by the Montreal Protocol which mandated that methyl bromide be phased out (Van Graver and Banks 1997). For many uses, phosphine has been the only economically available alternative.

Although there currently are no economical alternatives to phosphine as a stored grain fumigant (Collins et al. 2005), other grain management strategies, such as integrated pest management (IPM), have been adopted that help slow the development of phosphine resistance (Lorini and Filho 2004; Mori et al. 2006). IPM combines different tools in a way that is intended to reduce need for fumigation. IPM is a balanced use of multiple control tactics – biological, chemical, and cultural – as is most appropriate for a particular situation in light of careful study of all factors involved (Way 1977).

For example, a storage manager may sample grain to determine if fumigation is necessary instead of using a calendar-based approach of routinely and automatically fumigating. In some countries where insect resistance is problematic, stored grain managers have had success combating resistance by using IPM (Lorini and Filho 2004; Mori et al. 2006).

Although concerns about phosphine-resistant pests have been primarily focused on Australia, Brazil, China, India and a number of other developing nations, recently, phosphine resistance has been detected in the US (Opit et al. 2012). Stored grain managers in the U.S. can learn from the experience gained in countries currently combating phosphine resistance by adopting some of the available IPM tools. In order to determine whether IPM is cost effective, however, a model that includes the costs associated with increased pest resistance to phosphine is needed. It is hypothesized that accounting for resistance costs will increase the economic attractiveness of IPM approaches relative to conventional fumigation approaches.

Objectives

The overall objective is to determine how phosphine resistance affects cost of controlling *Rhyzopertha dominica*, or lesser grain borer (LGB), in stored grain.

The specific objectives are to:

- 1) Determine the effect of reduced fumigation frequency on costs of LGB control in stored grain when resistance genes are present.

- 2) Determine how assumptions about emigration to refuge populations and immigration from secondary populations affect growth of resistant populations of LGB and their control costs in stored grain.
- 3) Determine how alternative rates of fumigation effectiveness affect control costs of LGB populations in stored grain when resistance genes are present.
- 4) Determine how alternative beginning levels of phosphine resistant phenotypes affect control costs of LGB populations in stored grain.
- 5) Determine how weather affects LGB control costs in stored grain when phosphine resistant populations are present.

In this study, additional costs associated with changes in pest resistance are modeled and included in the cost-benefit analysis of a calendar-based fumigation strategy, sampling-based IPM, and aeration-based IPM. The model is applied to the weather and grain conditions in two climates representative of those in major US wheat-growing areas, Oklahoma City, OK, and Goodland, KS.

Literature Review

Pest Resistance Models

Most researchers recognize that pest resistance is a global problem (Collins et al. 2005; Laxminarayan 2003; Semple et al. 1992); however, the economic costs of pest resistance remain unclear. Many view pest susceptibility to an insecticide as a common property resource (Carlson 1977; Cowan and Gundy 1996; Hueth and Regev 1974; Fleischer 1998; Laxminarayan 2003). Since many firms contribute to the resource depletion over time, it is difficult for individual firms to internalize their contribution to the total cost. However, much of the work leading to the view of pest susceptibility as a common property resource has occurred with crop pests. Campbell et al. (2007) has provided evidence that individual stored grain firms bear a large portion of the cost associated with resistant LGB because LGB do not migrate far. Thus, there may be an incentive for stored grain firms to manage levels of phosphine resistance within their firms.

Several conceptual models have been proposed to explain how pest management strategies impact pest resistance. For example, Hueth and Regev (1974) demonstrated how farm level decision makers can influence changes in the resistance levels of a crop-pest population. Their model included a single crop with one pest and one gene responsible for resistance. Analysis centered on the economic threshold for pesticide application, the known point when a pesticide must be used to prevent economic loss from crop damage. They showed that the economic threshold is variable depending on decisions made in the current year. In some cases, however, it increases in succeeding years. Therefore, pest resistance should be modeled dynamically because changes in resistance are the direct result of previous choices. This result was supported by Lichtenberg and Zilberman (1986) who showed that use of products contributing to resistance increases the future amounts of product needed to achieve earlier results. This increased product use leads to increased treatment costs.

Hurley, Babcock, and Hellmich (2001) incorporated the Hardy-Weinberg principle (which states that the proportion of particular genotypes remain constant in a population unless there is a disturbance) into an economic model that was designed to determine optimal crop refuge size.

Refuge is the designated portion of the crop land where pesticide application does not occur. The purpose of the refuge is to maintain some level of pest susceptibility as a means to control the development of pest resistance. They found that the levels of susceptibility are significantly affected by pest mobility and the ability of refuge and non-refuge pests to mate.

Genetics of Pest Resistance

To date, economic models used to demonstrate the development of pest resistance have assumed that a single gene (or allele at two levels) is responsible for resistance to a fumigant. However, these conceptual models may oversimplify the problem of resistance in stored grain pests. For example, Daghli (2004) identified two levels of LGB resistance to phosphine. Collins et al. (2005) found that LGB exhibiting strong resistance to phosphine had an additional mechanism not present in the weak resistant LGB. These two results led to the discovery by Schlipalius et al. (2008) that two different alleles are responsible for LGB resistance. Further, the genotypes possible from each allele interact in such a way that LGB exhibit four different levels of phosphine resistance (phenotypes) which range from about 2.5 to more than 250 times the resistance of susceptible LGB. These three studies are of potential significance for economic modeling, especially since the level of fumigation effectiveness impacts the surviving phenotypes. In other words, when fumigation effectiveness is low, weak resistant pests would dominate the population; when fumigation effectiveness is high, strong (and some moderate) resistant pests would dominate.

A common finding reported by Collins et al. (2005), Daghli (2004), and Schlipalius et al. (2008) is that phosphine resistant LGB did not suffer any fitness cost associated with the increased resistance. In essence, fitness costs are the tradeoffs that result when one genetic trait is given up for another. However, Sousa et al. (2009) reported that resistant LGB, in the absence of phosphine exposure, may indeed suffer fitness costs compared to susceptible LGB. Further, the fitness costs associated with resistant pests may allow previous levels of susceptibility to be regained once phosphine use is substantially reduced. Therefore, use of phosphine-reducing strategies such as IPM may do more than slow resistance development: they may actually reverse it.

Conceptual Framework

This paper estimates the cost of controlling LGB in stored wheat under alternative specifications of phosphine resistance and insect population dynamics. According to Schlipalius et al. (2008), LGB resistance is the result of two different alleles, each at two levels, which leads to the five possible phenotypes (susceptible LGB, plus four different levels of resistance). They found that one of the alleles responsible for resistance can occur as a heterozygote (weak 1 resistance level, which is 2.5-12.5 times more resistant than susceptible LGB), while the other must occur as homozygote in order for resistance to be expressed (weak 2 resistance level, which is 12.5-25 times more resistant than susceptible LGB). When no resistant genes are present, or when the alleles responsible for the weak 2 resistance level occur as a heterozygote, then the LGB phenotype is susceptible. Schlipalius et al. also found that when the alleles responsible for weak 1 resistance level occur as a heterozygote and those responsible for weak 2 resistance level occur as a homozygote, moderate resistance results (25-50 times more resistant than susceptible). However, they discovered that an interaction between the two alleles occurs when the genes

responsible for weak 1 and weak 2 resistance levels both occur as homozygotes. This results in a strong resistance (250 times more resistant than susceptible LGB).

One consideration made in this study is that differences in fumigation effectiveness may affect which of the five phenotypes dominates the population and, therefore, has the strongest impact on costs. For example, where fumigation effectiveness is high enough to eliminate the susceptible and weak resistant pests, strong resistant LGB (and potentially some moderately resistant LGB) would eventually dominate the population, and be the main driver of changes in cost. However, if fumigation effectiveness were low enough, only some susceptible pests and a small fraction of weak and moderate pests would be eliminated. The result in this case would be that weak and moderately resistant pests would eventually dominate the population (the primary driver of changes in cost) and strong resistant pests would remain in relatively small proportions.

This paper also considers the impact of three grain management strategies on levels of LGB resistance, and the effect that changes in resistance have on the strategy costs. In particular, costs of calendar-based fumigation, sampling-based IPM, and aeration-based IPM resulting from LGB resistance are compared. A typical practice used for wheat in the U.S. Great Plains region is calendar-based fumigation, under which a grain elevator manager fumigates all structures at approximately the same time every year. In contrast, a sampling-based IPM approach is to periodically sample the grain in a storage structure, and to fumigate only if the information, combined with known insect growth patterns, possibly using decision support software, suggests that insects are likely to cause damage in the future (Flinn et al., 2007). The assumption with this IPM strategy is that some or all bins within a storage structure might have sufficiently low insect population growth that fumigation is not required.

Insect population growth in a grain storage structure depends on environmental conditions (particularly grain temperature and moisture), condition of the grain, and rate of immigration of grain-damaging insects into the structure (which itself depends on environmental conditions such as wind and temperature as well as cleanliness and structural integrity of the facility). The effectiveness of insect control treatments depends on environmental conditions, cleanliness and structural integrity of the facility, and on how thoroughly and carefully a particular practice is implemented.

If the insect population in stored grain is not controlled effectively, the insects will damage grain, which in turn triggers large discounts. *Rhyzopertha dominica*, in particular, cause insect damaged kernels (IDK). *R. dominica* larvae feed inside the kernel until they mature into adults and burrow out of the kernel, which results in an IDK. The life cycle of *R. dominica* is approximately five weeks at 32°C, so there is approximately a five-week lag between immigration of an adult insect until appearance of new adults.

Also, if two or more live insects are detected in a one-kilogram grain sample at time of sale, the U.S. Department of Agriculture (USDA) does not permit the grain to be sold for human consumption. Since this prohibition can be overcome by fumigating to kill the live insects, this results in a live insect discount that is commonly larger than the cost of fumigating itself. Often, in practice, this discount is imposed by commercial firms even if only one live grain-damaging insect is detected in a one-kg sample.

The model specified below includes costs of discrete insect management and control activities that can be combined into both IPM and non-IPM strategies. Using the model together with a population dynamics model, we simulate and compare costs of alternative insect control strategies, including conventional, calendar-based fumigation approaches and IPM sampling-based approaches to managing stored-grain insects.

Cost Model

The strategy cost of insect control in time p can be expressed as

$$1(a) \quad SC_p = C(F_p, S_p, A_p, IDK_p, INF_p),$$

where $C(\cdot)$ is a function of the number of fumigations (F), number of samplings (S), use of aeration (A), insect damaged kernels (IDK), and infestation discount (INF) at the end of period p .

The net present value (NPV) of costs over P periods is:

$$1(b) \quad NPV = \sum_{p=1}^P \frac{SC_p}{(1+d)^{p-1}},$$

where d is the discount rate.

The cost of treatment is estimated using economic engineering methods in a partial-budgeting approach, and the cost of failing to control insects is estimated by simulating insect growth under various environmental conditions and treatments. Adding these costs provides an estimate of the total cost of using each insect control strategy (IPM vs. calendar-based).¹

The elevator manager using calendar-based fumigation is assumed to fumigate at nearly the same time every year. Under a sampling-based approach, however, it is assumed a manager samples the grain, and fumigates a particular bin only if the number of insects from a sample of that bin exceeds a threshold level.

Population Dynamics Model

The development of LGB resistance to phosphine in Australia (see Emery, Collins, and Wallbank 2003; Newman 2010) appears more similar to scenarios of crop-pest resistance development when a refuge population is present (see Hurley, Babcock, and Hellmich 2001), than to scenarios with no refuge (see Hueth and Regev 1974). However, there are currently no economic studies in the context of stored grain that depict the potential movement of LGB populations with different proportions of resistance phenotypes.

Implementing a model based on this proposition is difficult, though, because there is uncertainty regarding: 1) how many LGB with each level of resistance exist in and around a stored grain facility; and 2) the manner in which insects from each of these levels combine in and around the storage facility. For example, after fumigation the population inside the stored grain would have proportions of phosphine resistance different from those of the population nearby the facility. There may also be LGB that linger within the stored grain facility after grain is removed and that population would have proportions of resistance levels different from those of the population nearby the facility. Further, when grain is moved there may be an opportunity for some LGB in

¹ In a partial budgeting approach, only cost components that might differ between approaches are evaluated. For example, although the cost of loading and unloading grain is an important storage cost, it is not considered here because it is assumed to be the same for both the calendar-based and the sampling-based approaches.

the grain to flee back outside the facility. Finally, when new grain is received, LGB immigrating into the stored grain could be coming from populations of LGB that potentially have different proportions of resistance levels.

Consider the following model:

$$\begin{aligned}
 2(a) \quad & \mathbf{a}_p = (\mathbf{\alpha}_{p-1} + \omega \boldsymbol{\gamma}_p)(1 + \omega)^{-1} \\
 2(b) \quad & \boldsymbol{\gamma}_p = \boldsymbol{\lambda}_p [\mathbf{I}^T \boldsymbol{\lambda}_p]^{-1} \\
 2(c) \quad & \boldsymbol{\lambda}_p^T = (1 - F)^{n_p} [(1 + \delta)^{-1} (\mathbf{\alpha}_{p-1} + \delta \boldsymbol{\gamma}_{p-1})]^T \mathbf{R}^{n_p} \\
 & \text{s. t. } \lambda_{jp} \leq (1 + \delta)^{-1} (\alpha_{j,p-1} + \delta \gamma_{j,p-1})
 \end{aligned}$$

- \mathbf{a}_p is a vector of the resistant proportions of the LGB population (based on Schlipalius et al. 2008)
- p is the storage period (only one period is allowed per year), for $p = 1, \dots, P$
- $\mathbf{\alpha}_{p-1}$ is a vector of the resistance proportions at the end of the previous period and represents the refuge proportion of the pest population
- $\alpha_{j,p-1}$ is the proportion of LGB with resistance level j , for $j = 1, \dots, 5$, and $\sum_j \alpha_{j,p-1} = 1$
- $\boldsymbol{\gamma}_p$ is a vector of the resistant proportions inside the stored grain at the end of period p
- ω is the ratio at which the inside and refuge populations mix
- $\boldsymbol{\lambda}_p$ is a vector of the proportions of the j resistance levels remaining at the end of the period
- λ_{jp} is the proportion of resistance level j surviving fumigation, and $\boldsymbol{\lambda}_p$ is not standardized to one, i.e. $\sum_j \lambda_{jp} \leq 1$
- F is the fumigation effectiveness and is defined as the proportion of susceptible LGB that are eliminated during fumigation; and the proportion of resistant LGB eliminated is based on their level of phosphine resistance relative to susceptible pests
- n_p is the number of fumigations
- δ is the ratio by which the two populations inside the stored grain mix
- \mathbf{R}_p is a diagonal matrix of the resistance levels based on Schlipalius et al. (2008) and each level, r_{jp} , is defined in terms of a distribution such that $r_{jp} \sim N(\mu_j, \sigma_j^2)$, where j is the resistance level, $\mu_j = \frac{\text{lower limit}_j + \text{upper limit}_j}{2}$, and $\sigma_j = \frac{\text{upper limit}_j - \text{lower limit}_j}{6}$
- \mathbf{I} is a vector of ones

The insect population dynamics model presented here is sufficiently general to permit three different scenarios about refuge populations. The first scenario identifies three distinct LGB populations (see Figure 1). The primary (refuge) population (α_p) is similar to a refuge population described by Hurley, Babcock, and Hellmich (2001) and exists within a region where one or more stored grain facilities operate. A portion of this refuge population immigrates into new grain after it is stored. A secondary population (γ_{p-1}) remains inside the stored grain facility after grain is moved. When new grain shipments arrive, this population also immigrates into the new grain. A tertiary population (γ_p) grows inside newly stored grain and is a mix (at rate δ) of the refuge and secondary populations. When grain is sold and removed from storage, a portion of the tertiary (in-bin) population emigrates (at rate ω) back to the refuge population, and the remaining portion of the population makes up the secondary population.

A distinction between the three populations is important when proportions of resistance are considered since each population would have different proportions of resistance levels. The tertiary (in-bin) population is the only population exposed to phosphine; therefore, that population would have the highest levels of resistance. The secondary population only exists after the storage-bin is emptied and would have the same levels of resistance as the tertiary population in the previous period. The refuge population would have the lowest levels of resistance.

This first scenario appears to best model the situation in Australia. Without the presence of an “accidental” refuge of LGB near Australian stored grain facilities as suggested by Emery, Collins, and Wallbank (2003) and Newman (2010), the Hueth and Regev (1974) model predicts that susceptible LGB would have disappeared much more rapidly (in just a few seasons) and LGB populations would only be composed of weak and strong phosphine resistant LGB (see also Hurley, Babcock, and Hellmich 2001). Avoiding this type of occurrence was the primary motivation behind utilizing crop refuges (Hurley, Babcock, and Hellmich 2001). Further, as the number of fumigations and/or the concentrations of fumigant increased, the proportion of weak resistant LGB would have dwindled, allowing strong resistant LGB to dominate the population. Based on the evidence provided by Emery, Collins, and Wallbank (2003) and Newman (2010), this was not the case.

The second scenario considers only two populations, the refuge and the tertiary population. In this case, no secondary population exists (and $\delta = 0$). The third scenario considers three populations but assumes that no portion of the tertiary population returns back to the refuge (i.e. $\omega = 0$). Instead, it makes up the secondary population. This scenario allows for a steady state of resistance level proportions since the refuge acts to continually dilute the tertiary population, while the proportion of the resistant levels in the refuge population never change.

Factors Driving Resistance and Costs

Higher frequencies of phosphine application by stored grain managers result in more rapid development of resistant LGB (Collins et al. 2005; Hueth and Regev 1974; Lichtenberg and Zilberman 1986). As the resistance to phosphine increases, more frequent applications are needed to control economic damage. Therefore, factors that contribute to more rapid resistance development should also contribute to higher costs. There are five different factors considered in this study that potentially affect the speed of resistance development, which in turn impacts insect control strategy costs: fumigation effectiveness, the relative proportion of the tertiary population returning back to the refuge (ω), the relative proportion of the secondary population entering the grain (δ), starting proportions of resistance levels, and the weather.

Schlupalius et al. (2008) identified four different levels of resistance and depending on the fumigation effectiveness (and potentially the weather which drives LGB growth) rapid development of resistance could occur by one of two ways. If fumigation effectiveness was high enough, only strong (and some moderate) resistant LGB would survive. Therefore, the costs associated with increased resistance would be the result of increased strong resistance LGB. On the other hand, if fumigation effectiveness was low enough then higher portions of weak resistant LGB, relative to strong resistant LGB, would survive. In this case, the costs associated

with resistance would initially be attributed to weak resistant LGB, and later with strong resistant LGB (as the number of fumigations per period increased).

Under scenarios 1 and 2, the higher the rate of emigrating (ω in Figure 1) tertiary LGB, the faster the refuge develops resistance. This also depends on the fumigation effectiveness (i.e. the surviving proportions of resistance levels) as well as the weather. Similarly, under scenarios 1 and 3, higher rates of immigration (δ in Figure 1) of the secondary population would lead higher proportions of strong and moderate resistant pests inside the grain. This would also potentially lead to faster rates of resistance development. Again, this will depend on the fumigation effectiveness and weather. The rates of emigration and immigration are potentially important considerations if other conditions, such as fumigation effectiveness and weather, are such that one grain management strategy is more cost effective than the other. However, the specific threshold for each of these other considerations (fumigation effectiveness, and weather) must also be determined.

When the proportion of weak, moderate and strong LGB resistance is very low in the LGB population, there is a potential opportunity for cost differentiation between grain management strategies that fumigate at different rates per period. In other words, it may be possible that the strategy which fumigates the least would also cost the least if LGB resistance is not well established. This is one of the motivating factors for using sampling-based IPM (Adam et al. 2006). However, the difference in the frequency of fumigations under each strategy, in this case calendar-based and sampling-based, would have to be such that the costs associated with the sampling-based IPM would be less than those associated with calendar-based fumigation over a limited time horizon.

In general, warmer weather encourages LGB growth in stored grain (Flinn et al. 2004). Therefore, strategies that are cost effective in cooler climates may not have the same costs and benefits in warmer climates. For example, Adam et al. (2010) demonstrated that sampling-based IPM was only cost effective in cooler climates, or when grain was stored for a shorter period of time. This was because LGB growth was high enough in the locations considered that fumigation was always necessary. Although the present study only considered a single storage season (1989-1990), it may be the case that using sampling-based IPM will never be cost effective in warmer climates (where LGB growth is potentially higher) when storage periods are longer. However, in warmer climates with moderate storage periods and once LGB resistance is introduced into the model, sampling-based IPM may be cost effective over a time horizon.

Methodology

The objective in this study is to determine how the cost of grain management is impacted by the proposed LGB population dynamics model, fumigation effectiveness, starting proportions of LGB resistance, and weather. The proposed LGB population dynamics model considers three scenarios: (1) after grain is sold, LGB surviving fumigation emigrate (at rate ω) to a refuge population, and then immigrate into new grain while a secondary population remains in the storage facility that also immigrates (at rate δ) into new grain, (2) after grain is sold, LGB surviving fumigation emigrate to a refuge population and no secondary population exists ($\gamma_{p-1} = 0, \delta = 0$), (3) after grain is sold, LGB surviving fumigation do not emigrate ($\omega = 0$) to the refuge population, but become the secondary population (see Figure 1). It is important to point

out that the impact on cost from immigration of a general LGB population into stored grain was demonstrated by Adam et al. (2010). In their study, the term “immigration” referred to the rate at which LGB entered the stored grain. Their immigration rate generated an actual number of pests per kg and was based on the Flinn et al. (2004) model. In this study, immigration and emigration are relative terms and used to describe the proportions of each LGB populations relative to the refuge population.

Since the same LGB growth model (Flinn et al. 2004) is used in this study, immigration based on the Adam et al. (2010) definition is considered part of the LGB growth rate. Additionally, a fixed immigration rate of “low,” based on the Flinn et al. (2004) model was used for all LGB growth. The reason this “low” rate was used is because Adam et al. (2010) had previously demonstrated that fumigation was always necessary in warmer climates and when immigration into the grain was “normal.” Therefore, when LGB resistance is included in the model, the only case where calendar-based fumigation and sampling-based IPM impact changes in the development of resistance differently is when the immigration rate used in the Flinn et al. model is low.

To accomplish the objective set out in this study, a simulation was designed such that each scenario could be examined given variations of the five factors (model parameters). In the simulation, grain is received and stored shortly after harvest. LGB enter the grain according to what the Flinn et al. (2004) model predicts, and based on the specific scenario and set of factors (model parameters) used.

Under calendar-based fumigation, grain is fumigated at the same time each season. At the conclusion of the storage period, grain is moved. Since the development of LGB resistance is included in the model, at some point in time the residual LGB remaining after fumigation will trigger the need for additional fumigation. In the simulation, if residual LGB population is greater than the acceptable threshold at the time grain is sold, the simulation adds an additional fumigation for all subsequent crop years. Once an additional fumigation event is added, under calendar-based fumigation it will always occur, so the number of times fumigation occurs per period only increases and never decreases.

Under sampling-based fumigation, the process of receiving grain and LGB growth is the same as under calendar-based fumigation. In place of automatic fumigation, however, grain is automatically sampled. Fumigation will only occur if sampling determines it is necessary to avoid LGB growth reaching the acceptable threshold. Similar to calendar-based fumigation, at some point in time additional sampling and fumigation becomes necessary due to the increase of LGB resistance. In place of one additional sampling event occurring automatically, the initial sampling will determine if fumigation and the further sampling is necessary. Once the threshold is reached, if sampling determines fumigation is necessary then one an additional sampling is also necessary. However, if the initial sampling determined fumigation was unnecessary then no further action is taken during the particular period. As was the case with calendar-based fumigation, this is a stepwise process. Therefore only the addition of one sampling and fumigation is allowed per period.

The specific simulation parameters and the sources for model inputs are described in the next section (Data and Simulation Parameters). What follows in this section is the specification and

explanation of the general model used in the simulation as well as a discussion about how LGB population genetics were handled in the simulation.

Change in Levels of Resistance from Fumigation

Determining periodic changes in grain storage costs from corresponding increases in LGB resistance to phosphine depends on identifying how resistance increases the number of fumigations (or fumigations and sampling) needed per period. Hueth and Regev (1974) demonstrated that use of a pesticide in period P to control crop pests would reduce the proportion of susceptible pests in period $P + 1$ making pesticide use in successive periods less effective. Greater amounts of pesticide would be necessary to achieve the same level of pest control obtained in previous periods thereby increasing the cost of crop pest control. Similarly, an increase in the cost of stored grain management during any period would result from additional fumigation or additional fumigation and sampling.

Although fumigation selects for resistant pests, the impact of a single fumigation also depends on the effectiveness of pesticide application (fumigation effectiveness), the proportions of pest resistance levels in the population, and the genetic mechanisms responsible for resistance. The analysis by Hueth and Regev (1974) assumed that a single allele was responsible for resistance. However, for *R. dominica* Schlipalius et al. (2008) have identified two loci, each with two alleles, responsible for resistance. The possible combinations of their alleles result in four levels of LGB phosphine resistance, plus full susceptibility.

As previously discussed, the specific population dynamics that account for LGB phosphine resistance levels within the framework of stored grain management are unclear. The model proposed in equations 2(a)-2(c) is similar to what Hurley, Babcock and Hellmich (2001) have described with crop-pests: that LGB surviving fumigation in a given period mix with another population not fumigated (refuge population) in the same period. In this case, the overall change in resistance is diluted down, relative to what Hueth and Regev (1974) predicts. To set up the model following the proposed LGB population dynamics, an initial LGB refuge population with specific proportions of each resistance level is defined, \mathbf{a}_p (also see Figure 1). Then LGB immigrate into the stored grain, potentially from two sources if the secondary population (\mathbf{y}_{p-1}) exists, and are defined by, \mathbf{y}_p . This population in the stored grain will potentially have different proportions of resistance levels relative to \mathbf{a}_p . If fumigation occurs, then the surviving pests inside the grain will have different proportions of resistance levels relative to \mathbf{a}_p . Once grain is sold and depending on the particular scenario considered, a portion of the population inside the stored grain may return to the refuge (at rate ω), while the remainder will make-up the secondary population for the next period.

Based on the model's construction, the secondary population and the refuge will mix at rate δ during the fumigation step in equation 2(c). This is simply for convenience. The restriction in the model assures that the proportion of a particular resistance level after fumigation is not greater than what is actually possible. Additionally when $\delta = 0$, the model fits scenario 2, and when $\omega = 0$ and $\delta > 0$ the model fits scenario 3. Equation 2(a) is used to develop the recursive model that is used to identify changes in proportions of resistance over the time-horizon of P periods:

$$2(d) \quad \mathbf{a}_p = \mathbf{a}_0(1 + \omega)^{-P} + \omega \sum_{p=1}^P \boldsymbol{\gamma}_p(1 + \omega)^{-P+p-1}$$

where \mathbf{a}_0 is a vector of the initial resistance proportions at the start of the simulation.

Determining the Number of Fumigations

A distinction is made between the number of fumigations for calendar-based fumigation and sampling-based IPM. Under a calendar-based approach, fumigation occurs regularly and the number of fumigations will increase by up to one per storage period, as the number of LGB surviving fumigation is at, or above, a predetermined economic threshold. This threshold is based on the acceptable number of pests that are found in the grain on a per kg basis (Adam et al. 2010). Under a calendar-based strategy the number of fumigations per period is determined as follows:

$$3(a) \quad n_p = \begin{cases} n_{p-1} + 1 & \text{if } G_{p-1} \mathbf{I}^T \boldsymbol{\lambda}_{p-1} \geq \tau \\ n_{p-1} & \text{otherwise} \end{cases}$$

where G_p is the LGB growth based on Flinn et al. (2004) and τ is the economic threshold.

For sampling-based IPM, the number of fumigations is determined by sampling in the current period as well as the number of fumigations in the previous period and whether or not pest growth exceeded τ in the previous period, that is:

$$3(a) \quad m_p = m(n_p | s_p, n_{p-1}, \tau)$$

where m_p is the number of fumigation under sampling-based IPM and s_p is the number of samplings. As n_{p-1} increases, the number of potential sampling and fumigation increases. For example, if $n_{p-1} = 3$ and $G_{p-1} \mathbf{I}^T \boldsymbol{\lambda}_{p-1} \geq \tau$ then the possible number of sampling is $s_p \in \{1, 2, 3, 4\}$, while the possible number of fumigations is $n_p \in \{0, 1, 2, 3, 4\}$. Note that $n_p \leq s_p \forall p$. For this same example of $n_{p-1} = 3$, if the first sampling determines that fumigation is not necessary during period p , then $s_p = 1$ and $n_p = 0$. On the other hand, if the first sampling determines fumigation is necessary, then the number of samplings in period p will continue to increase until $s_p = 3$ (and the number of fumigations will also continue to increase until $n_p = 3$) or until sampling determines no more fumigation is necessary.

Aeration-based IPM

In this study, aeration-based IPM is also examined in the context of resistance and compared to the other two strategies. Under an aeration-based strategy, grain is cooled shortly after it is received in order to suppress pest growth. Previous simulations of LGB growth under aeration-based IPM and with a “low” rate immigration (based on the Adam et al. 2010 definition of immigration), demonstrated that fumigation would not ever occur (see Adam et al 2006; Flinn et al. 2004). This is the case because aeration, under the conditions given above, is able to suppresses pest growth well below τ . Since fumigation is not needed under these particular circumstances, LGB resistance remains constant. Therefore, the costs associated with aeration-based IPM are also constant.

Adam et al. 2010 also pointed out that many grain storage facilities in Oklahoma and Kansas (the course of weather data used in this model) are not properly equipped to aerate grain. Therefore the costs associated with aeration under the conditions or low aeration is simply for comparison.

Estimating Costs

The specific cost for calendar-based fumigation in period p is determined as follows:

$$4(a) \quad SC_p = C_F n_p + \mathbf{C}_{D1}^T \mathbf{D1}_p + \mathbf{C}_{D2}^T \mathbf{D2}_p$$

where SC_p is the strategy cost, C_F is costs of fumigation, \mathbf{C}_{D1} and \mathbf{C}_{D2} are vectors of IDK and infestation costs respectively, and $\mathbf{D1}_p$ and $\mathbf{D2}_p$ are vectors of indicator variables for IDK and infestation respectively. Similarly, the cost of IPM is given by:

$$4(b) \quad SC_p = (1 - A)C_F m_p + (1 - A)C_S s_p + C_A A + \mathbf{C}_{D1}^T \mathbf{D1}_p + \mathbf{C}_{D2}^T \mathbf{D2}_p$$

where C_S is the cost of sampling, C_A is the cost of aeration, and A is an indicator variable for the use of aeration.

In this study, changes in the NPV of costs are examined under three different pest population scenarios, $\omega > 0$ and $\delta > 0$ (scenario one), $\omega > 0$ and $\delta = 0$ (scenario two), and $\omega = 0$ and $\delta > 0$ (scenario three), and utilizing one of three grain management strategies (calendar-based fumigation, sampling-based IPM, and aeration-based IPM). In the third scenario, the primary population (refuge population) is unchanged after grain is sold and only the secondary population experiences changes in resistance levels. This allows for a potential steady state of resistance level proportions which are dependent on F and δ .

Stabilizing Allele Frequencies after Fumigation

In the basic Hueth and Regev (1974) model the effect of the remaining allele frequencies, after fumigation, on the genetic make-up of future pest population is not a necessary consideration since the model only considers one gene responsible for resistance. Since the findings of Schlipalius et al. (2008); however, there is a need for a two-allele (each at two levels) economic model to determine the impact of changes in LGB resistance on the cost of stored grain management over a time horizon. One of the challenges in developing such a model is determining how quickly the LGB population stabilizes after fumigation based on the remaining allele frequencies. The main concern is that stabilizing the population under the circumstances of fumigation and different groups of populations mixing violates the Hardy-Weinberg principle (Lush 1994). Additionally, Hurley, Babcock and Hellmich (2001) demonstrated how a violation of the Hardy-Weinberg principle, non-random mating, might also occur when pest populations made up of different resistance levels (the refuge population and the population where fumigation has occurred) are unable to combine due to their proximity to one another.

In the case of stored grain in this study, it is assumed that mating only occurs inside the stored grain and after the population has sufficiently mixed (random mating). Further, fumigation effectiveness is not 100% successful meaning that some susceptible LGB will remain after fumigation. The distribution throughout the grain of all LGB, both susceptible and resistant is assumed to be random. Since the allele frequency stabilization after fumigation and potential violations of the Hardy-Weinberg principle are beyond the scope of this paper, two extreme cases will be examined: 1) no stabilizing and 2) stabilization after every shock.

If one were to assume that allele frequencies remain constant after fumigation and until the next round of pesticide is applied (one extreme), then the increase in resistance occurs much faster compared to when allele frequencies in the population are stabilized after each shock (fumigation or mixing) (see Lush 1994). Stabilizing the population after each shock also assumes that at least one generation of reproduction occurs and that the population is large enough for stabilization to

occur. In the first extreme, the five proportions of resistance levels only change when fumigation occurs or when the two populations mix. However, the levels of resistance are never stabilized based on allele frequencies (Lush 1994). For the second extreme, the allele frequencies are assumed to stabilize after each shock (fumigation or populations mixing). In this case, the genotypes have a multinomial distribution (see Lush 1994) and are grouped into their respective phenotypes based on the results of Schlipalius et al. (2008).

Data and Simulation Parameters

LGB growth was simulated with the Flinn et al. (2004) model for Oklahoma City, OK, using NOAA weather data for years 1961-1990 and Goodland, KS, using NOAA weather data for years 1997-2004. The storage facility and grain condition inputs for the growth model as well as grain management costs and τ were identical to what Adam et al. (2010) (see Tables 1 and 2) specified. The rate of LGB immigration (based on the Adam et al. 2010 definition) into the grain was assumed to be low. Although ω is unknown, pre-test simulations with large values of ω (>0.5) resulted in development of resistance that far exceeded what was observed by Emery, Collins and Wallbank (2003) and Newman (2010). However, parameter values in the model were still determined *ad hoc* since there are no other studies to support choosing different values.

The particular parameter values selected in this study were based on pre-testing attempts to replicate the development of resistance in Australia, given the model presented in equation 2(a)-(c). During pre-testing, it was determined that the rate at which the development of resistance occurred was due to a combination of all parameters considered (including weather). Therefore, it was possible to replicate the Australian data presented by Emery, Collins and Wallbank (2003) and Newman (2010) by different combinations of parameters and parameter values. The range of values used in this study includes these values, as well as values that result in resistance developing more slowly (specifically low ω and δ). The reason for the use of low values in this study is because resistance in the U.S. has potentially occurred more slowly than in Australia. Therefore, parameters reflecting this possibility were selected and included.

Values for ω of 0.05, 0.20 and 0.35 were used in scenarios 1 and 2. For each scenario, low (0.65), medium (0.80) and high (0.95) values of F were used. For scenarios (1) and (3), low (0.20) and high (0.80) values for δ were used. Additionally, starting values for the allele frequency of the gene responsible for resistance at each locus were set at either 1% for each resistant gene (lower levels of resistance) or at 3% for each resistant gene (higher levels of resistance).

Two methods were considered to simulate grain management cost and changes in LGB phosphine resistance. The first method utilized a non-parametric bootstrap and simulated LGB growth for two different storage periods in each location, June 1 - February 1 and June 1 - April 1. An LGB growth year was selected at random and with replacement from the pool of simulated values for each city to create a 25-year period of estimated changes in phosphine resistance. Then, 1,000 25-year periods were generated and used to estimate a mean NPV of costs for each location and under each strategy, scenario and set of model parameters.

For the second method, a frequency of fumigation (i.e. having to fumigate about 71% of the time) given τ was selected and the distribution of LGB growth for each location that matched the

frequency of fumigation was estimated. The storage periods that matched the frequency of fumigation were June 1-January 27 (Oklahoma City) and June 1-February 9 (Goodland). Using a parametric bootstrap procedure, the growth distribution was used to create a 25-year period. Again, 1,000 25-year periods were generated and used to estimate a mean NPV of costs for each location and combination of strategy, scenario, and model parameters.

Results and Discussion

Impact of Fumigation Effectiveness

In general, higher fumigation effectiveness resulted in lower cost relative to moderate and low fumigation effectiveness (see Tables 3-14). However, the type of LGB resistance driving costs was different depending on fumigation effectiveness. To demonstrate this difference, three plots (one for each level of fumigation effectiveness) were generated showing the proportions of resistance levels and the corresponding average period costs over a 35-season time horizon (Data in Tables 3-15 are based on a 25-season time horizon, but this extended time horizon for the three plots was necessary to clearly see what happens when the fumigation effectiveness level is high.) Figures 1-3 show how average costs per period change as the proportions of the five phenotypes (susceptible plus the four resistant levels) under a calendar-based strategy. The specific parameters used to generate these figures are based on scenario 1: LGB population stabilized after each shock, Oklahoma City weather, a storage period July 1 to February 1, high (Figure 2), medium (Figure 3) and low (Figure 4) values of fumigation effectiveness (F), high tertiary population emigration (ω), high secondary population immigration (δ), and a 3% beginning frequency of each gene responsible for resistance (also see Figure 1).

When fumigation effectiveness is high (Figure 2), a change in the average cost does not occur until the end of the time-horizon (about period 25). The main driver for these changes is the rapid increase in the proportion of the strong resistance phenotype (and to a lesser extent the moderate resistance phenotype). The changes in cost under calendar-based fumigation are the result of an increase in the number of fumigations each period. The change in the number of fumigations per period is triggered once the residual LGB (LGB remaining after fumigation) and their offspring are at or above the acceptable number of pests per kg of grain (τ). When fumigation effectiveness is high, only strong resistant LGB can survive in large proportions and it's the strong resistant LGB that are responsible for the increase in residual LGB.

When fumigation effectiveness is moderate and low (Figures 3 and 4, respectively), the weak 1 resistant phenotype is driving the increase in the average cost per period. In fact, the other resistant phenotypes (including strong resistance) do not account for a significant proportion of the total LGB resistance. This is the case since large proportions of weak 1 resistant LGB are able to survive fumigation when the effectiveness is low or moderate. It is also important to point out in Figures 3 and 4 that by season 20, the simulation reaches its preset maximum limit of possible fumigations per period (10 fumigations).

In all three figures the proportion of susceptible LGB falls substantially within the first 5-10 seasons (below 25%). Further, susceptible LGB are replaced by weak 1 as the dominant phenotype by period 5. This is an important point, especially when fumigation effectiveness is high, since this shift dramatically increases the rate at which strong resistant LGB are produced.

Although these snapshots (Figure 2-4) may not accurately characterize how grain managers in Oklahoma would respond over the time horizon, piecing together these figures can potentially explain, at least in part, what occurred in Australia as well as other countries where LGB resistance is problematic. The development of pest resistance is believed to have occurred as the result of low and repeated pest exposure to fumigants (Semple et al. 1992). As weak LGB resistance became problematic (as demonstrated in Figures 3 and 4), improvements resulting in increased fumigation effectiveness occurred (see Emery, Collins and Wallbank 2003; Newman 2010). Based on the results in Figure 2, high proportions of weak resistant LGB combined with high fumigation effectiveness resulted in a rapid increase in the proportions of strong resistant LGB.

Impact of immigration (ω) and/or emigration (δ)

When values for immigration (ω) and/or emigration (δ) were increased, costs also increased (this result is a generalization that can be seen in Tables 3-14). However, the rate at which costs increased depended on fumigation effectiveness as well as on the interaction between immigration (ω) and emigration (δ). For example, as emigration (δ) is increased from zero to high and/or when immigration (ω) is increased from low to high, weak 1 resistance is able to develop much more rapidly for low and moderate values of fumigation effectiveness. However, under scenario 3 when immigration (ω) was zero, a steady state of resistance proportions was possible and per period costs stabilized (or began to stabilize, since in some cases a time horizon longer than 25-season was needed to see this result). In this third scenario, costs were lowest when the fumigation effectiveness was high.

In cases when the residual LGB and offspring remained consistently below the acceptable threshold τ (see results for Goodland with the storage period of July 1 to February 1), the effect of immigration (ω) and/or emigration (δ) on costs were negligible. This result occurred regardless of the fumigation effectiveness or grain management strategy. Given the 25-season time horizon and low LGB growth in these cases, resistance was not able to develop in sufficient proportions to necessitate additional fumigation.

Comparison of Scenarios

Scenario 1 resulted in the highest potential costs since the combination of immigration (ω) and emigration (δ) allowed for the most rapid development of resistance. However, when immigration (ω) and emigration (δ) are low, the costs across the three scenarios are very close to one another. This cost similarity occurred especially when the phenotype population was stabilized in the model. Costs for all three scenarios are also relatively close when the storage period is July 1 to February 1, and the fumigation frequency was high. When the storage period was expanded (July 1 to April 1), resistance was able to further develop and the costs under each scenario diverged.

Distinguishing the highest cost scenario between scenarios 2 and 3 is not as straightforward. Under scenario 2, costs, in some cases, are higher (relative to scenario 3) when the storage period is July 1-February 1. Under scenario 3, costs are frequently higher (relative to scenario 2) when the storage period is extended to April 1.

Grain Management Strategy, Location, and Sale Date

In this study, selecting an optimal grain management strategy supported many of the findings of Adam et al. (2010). When the storage period was July 1 to February 1 (February 28 in Adam et al. 2010), sampling-based IPM was optimal when Goodland weather data was used (relatively cooler weather). Calendar-based fumigation was frequently optimal when Oklahoma City weather data was used (with relatively warmer weather). In some cases under scenarios 1 and 2, however, use of a sampling-based IPM strategy with Oklahoma City weather data resulted in enough slowed LGB resistance development (compared to calendar-based fumigation) that the costs between the two strategies were very close. This was even true with the higher discount rate (10%). This occurrence can be seen in the results tables with both the stabilized and non-stabilized LGB population models as well as allele frequencies of 1% and 3%.

Regarding aeration-based IPM, the findings in this study support the results of Adam et al. (2006) and Adam et al. (2010). With a “low” immigration rate used to determine LGB growth, aeration frequently cost less than sampling-based IPM and always cost less than calendar-based fumigation (see Table 15). However, many storage facilities in Oklahoma and Kansas are not equipped with aeration.

Comparing Costs at the Two Locations

The non-parametric results (Tables 3-10) demonstrate that, in general, locations with cooler weather will experience lower grain management costs regardless of the strategy employed. This result occurs because LGB growth is lower where weather is cooler and the rate at which additional fumigation is needed is also lower relative to where weather is warmer. However, these results do not distinguish between the impacts of mean LGB growth and the frequency of pesticide use on the development of resistance. To make this distinction, the use of a common fumigation frequency, 71% (or 0.71 probability that fumigation was needed), was used to compare strategies and scenarios across the two locations (see Tables 11-13). The common fumigation frequency was based on the distribution of the LGB growth data for each location (the corresponding storage periods were June 1 to January 27 for Oklahoma City, and June 1 to February 9 for Goodland).

The average untreated LGB growth is higher in Oklahoma City (1.17 LGB per kg) than in Goodland (1.11 LGB per kg). Therefore, the number of LGB surviving fumigation needed to trigger additional fumigation is lower in Oklahoma City than Goodland (holding other factors the same). As a result, resistance (and costs) develop more rapidly in Oklahoma City. As was the case with many earlier results, when fumigation effectiveness, immigration (ω) and emigration (δ) are low, costs in the two locations are very close. However, as immigration (ω) and emigration (δ) are increased, the difference in costs between the two locations also increases. This observance is most pronounced under the parametric scenario 1 and less so in the parametric scenario 2. In the parametric scenario 3, the costs for the two locations remained close despite the increase in immigration (ω) and emigration (δ). This is because LGB growth is still low enough that very little resistance develops over the 25-season time horizon.

Allele Frequencies and Population Stabilization

A stark contrast can be drawn between the results where the proportions of resistant allele frequencies were stabilized and those where they were not stabilized. Where allele frequencies

were not stabilized, LGB resistance developed much faster, especially as the immigration (ω), emigration (δ) and fumigation effectiveness were increased. The increased rate of resistance development between the stabilized and non-stabilized allele frequencies was also reflected in increased costs.

For example, the discounted cost of \$22.52 reported in Table 7 reflects the impact of stabilized allele frequencies after every shock, under a calendar-based fumigation strategy, with a starting allele frequency of 1%, a storage period of July 1 to February 1, and with high levels of immigration (ω), emigration (δ) and fumigation effectiveness. The corresponding cost when allele frequencies were not stabilized (but all other parameters remained the same) is \$67.82 (see Table 3). When the starting allele frequency was increased to 3%, the difference between costs of stabilized and non-stabilized allele frequency results is much greater. On the other hand, when the model parameters are adjusted such that resistance development occurs slowly due to low levels of immigration (ω) and emigration (δ) the cost differences between the stabilized and non-stabilized allele frequency results are very small. Additionally, the costs diverged much more rapidly when the allele frequencies were not stabilized and as the rate of resistance increased compared to when allele frequencies were stabilized.

Summary and Conclusion

The primary motivation for this study is that recently pest resistance in stored grain has been detected in parts of the US (Bonjour 2010). Significant economic damage from LGB resistance to phosphine has already occurred in countries such as Australia and Brazil (Emery, Collins, and Wallbank 2003; Collins et al. 2005; Dargatzis 2004; Newman 2010). Currently there are no economical alternatives to phosphine as a fumigant against stored grain pests (Collins et al. 2005). The main challenge is to extend the useful life of phosphine by developing and adopting strategies that can reduce pest exposure to the fumigant. However, grain managers in the US have been reluctant to adopt many of these strategies potentially since many of these strategies have not been shown to be cost effective, especially in warm climates (Adam et al. 2010).

The overall objective of this study was to determine how the cost of controlling LGB in stored grain is affected by LGB resistance. Three scenarios were proposed that depicted LGB population dynamics. Under each scenario, changes in specific parameters were examined in the context of their individual impact on LGB resistance and the corresponding change in the costs of controlling LGB. The particular parameters considered were: rates of LGB emigration from the stored grain to a refuge population; rates of LGB immigration from a secondary population into stored grain; levels of fumigation effectiveness; weather; grain storage periods; and starting levels of the frequency of alleles responsible for resistance. Additionally, changes in costs resulting from changes in LGB resistance were modeled and incorporated into the cost benefit analysis of three grain management strategies (calendar-based fumigation, sampling-based IPM, and aeration-based IPM).

When costs associated with LGB resistance are incorporated into the cost model, results from the simulation suggest that in Oklahoma, where the weather is considered warm relative to what encourages pest growth, sampling-based IPM is only cost-effective when the development of LGB is much slower than what occurs under calendar-based fumigation. In Kansas, where the weather is relatively cooler, sampling-based IPM is cost-effective much more frequently.

Additionally, aeration-based IPM was found to be the most cost-effective strategy since LGB growth was suppressed enough that fumigation was never found to be necessary. Although these results only reflect the case of “low” immigration (based on the definition used by Adam et al. 2010 and Flinn et al. 2004), they justify further research into the application of different IPM technologies and the impact of such technologies on LGB resistance and the corresponding costs from changes in resistance.

The results also indicate that high fumigation effectiveness has a potential long-term externality associated with the type of LGB resistance that develops. In short, large portions of strong resistant LGB survived when the fumigation effectiveness was high. Given a particular value for “high” fumigation effectiveness (in this study 95%), once strong resistant LGB have a foothold, the value of “high” will have to be increased in order to maintain the same level of effectiveness. However, increasing fumigation effectiveness will only delay the development of strong resistant LGB.

Another strategy may be to incorporate alternative means, such as aeration, to suppress pest growth. Although aeration will not eliminate the need for fumigation in all regions (especially where weather is favorable to insect growth), it could further extend the useful life of phosphine. The use of aeration may also make sampling-based IPM more useful in warm and hot climates. Combined, these two strategies could potentially extend the useful life of phosphine further than either strategy alone.

Another important consideration is the population dynamics of LGB in and around stored grain facilities. Although the impacts on resistance development from emigrating LGB back to a refuge population and the immigrating LGB into grain from a secondary population are intuitive, they present another area that could be exploited by grain managers to control pest populations. For example, when emigration and immigration were low, the development of resistance occurred much slower compared to when these levels were high. Controlling the entry and exits of pests as well as controlling the potential multiple pest populations may have added benefit when resistance is taken into account. Although the proposed scenarios of LGB population dynamics are hypothetical, the potential cost savings from reduced resistance development justify more research into this area.

For grain managers, one symptom of increased pest resistance is the need for increased fumigation effectiveness (via more frequent fumigations or higher concentrations). If controls are in place such that the fumigation effectiveness is relatively high (see the example in Figure 2), then the symptoms of pest resistance may be initially overlooked. In warmer climates where sampling-based IPM has been shown to be too expensive, grain managers may be unaware of current levels of resistance. If the development of LGB resistance is on the threshold, such as the example of Figure 2 near the end of the 35-season storage period, then the current strategies employed may lead to significant economic loss. Once past this threshold, the options for grain managers to make alternative strategy decisions are further reduced.

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Table 1. Treatment Cost for Stored Wheat

Treatment	Cost (\$/t)
Fumigation	0.911
Sampling	0.345
Aeration	0.671

source: Adam et al. (2010)

Table 7. NPV of Grain Management Strategy Costs (\$/t): Oklahoma City, 1% Discount Rate, Non-parametric Bootstrap, Stabilized

		Beginning resistance alleles present at 1%											
		Calendar-based fumigation					Sampling-based IPM						
		$\omega = 0$	$\omega = 0.05$	$\omega = 0.2$	$\omega = 0.35$	$\omega = 0$	$\omega = 0.05$	$\omega = 0.2$	$\omega = 0.35$	$\omega = 0.2$	$\omega = 0.35$		
June 1 to February 1	65% F	-	27.29	36.47	55.43	-	29.41	32.04	48.00	-	29.41	32.04	48.00
	80% F	-	21.35	41.31	70.02	-	27.12	39.46	73.04	-	27.12	39.46	73.04
	95% F	-	20.84	21.25	21.84	-	27.02	27.28	27.42	-	27.02	27.28	27.42
	65% F	26.69	27.27	44.29	66.13	29.23	29.23	37.47	62.62	29.23	29.23	37.47	62.62
	80% F	20.84	23.80	55.91	82.32	27.00	27.88	52.92	90.40	27.00	27.88	52.92	90.40
	95% F	20.84	20.84	21.51	22.08	27.02	27.02	27.33	27.52	27.02	27.02	27.33	27.52
	65% F	28.19	35.93	70.74	89.58	29.38	31.77	66.75	98.29	29.38	31.77	66.75	98.29
	80% F	26.43	39.64	85.78	100.71	28.71	34.16	92.59	117.91	28.71	34.16	92.59	117.91
	95% F	20.84	20.94	22.05	22.52	27.12	27.18	27.50	27.65	27.12	27.18	27.50	27.65
	65% F	-	127.48	154.13	158.53	-	166.65	209.89	216.28	-	166.65	209.89	216.28
80% F	-	124.73	152.87	157.46	-	166.28	208.22	214.38	-	166.28	208.22	214.38	
95% F	-	29.11	40.42	44.06	-	34.89	50.37	54.75	-	34.89	50.37	54.75	
65% F	132.74	152.73	158.99	160.90	148.06	207.50	217.06	219.77	148.06	207.50	217.06	219.77	
80% F	125.50	148.89	156.39	158.22	133.53	202.52	213.15	215.48	133.53	202.52	213.15	215.48	
95% F	26.25	34.45	42.80	45.93	30.70	41.94	53.12	56.69	30.70	41.94	53.12	56.69	
65% F	159.47	160.15	160.98	162.08	218.12	219.08	219.97	221.45	218.12	219.08	219.97	221.45	
80% F	153.15	153.51	155.73	157.11	208.75	209.63	212.53	214.42	208.75	209.63	212.53	214.42	
95% F	38.04	41.88	46.27	47.82	44.00	51.49	57.10	58.75	44.00	51.49	57.10	58.75	
		Beginning resistance alleles present at 3%											
June 1 to February 1	65% F	-	27.58	44.96	70.27	-	29.41	37.82	65.35	-	29.41	37.82	65.35
	80% F	-	23.15	53.56	80.78	-	27.77	48.62	87.17	-	27.77	48.62	87.17
	95% F	-	20.84	21.46	22.03	-	27.02	27.33	27.50	-	27.02	27.33	27.50
	65% F	26.69	28.20	56.00	81.24	29.23	29.46	47.45	82.69	29.23	29.46	47.45	82.69
	80% F	20.84	26.55	68.14	92.73	27.00	28.89	65.31	103.86	27.00	28.89	65.31	103.86
	95% F	20.84	20.85	21.65	22.31	27.02	27.02	27.38	27.64	27.02	27.02	27.38	27.64
	65% F	28.31	42.51	84.31	101.22	29.40	34.65	84.11	115.37	29.40	34.65	84.11	115.37
	80% F	27.89	45.24	93.81	108.45	29.23	36.93	103.56	128.21	29.23	36.93	103.56	128.21
	95% F	20.87	21.04	22.41	23.33	27.12	27.20	27.68	28.12	27.12	27.20	27.68	28.12
	65% F	-	147.46	162.30	165.10	-	198.85	221.74	225.55	-	198.85	221.74	225.55
80% F	-	139.72	159.30	161.65	-	189.19	217.61	220.69	-	189.19	217.61	220.69	
95% F	-	32.78	43.42	49.57	-	39.04	53.36	59.62	-	39.04	53.36	59.62	
65% F	154.15	161.50	165.61	166.66	196.06	220.74	226.40	227.70	196.06	220.74	226.40	227.70	
80% F	145.64	156.72	161.36	162.51	179.50	213.92	220.36	221.84	179.50	213.92	220.36	221.84	
95% F	28.15	37.06	47.19	57.27	31.63	45.09	56.82	67.39	31.63	45.09	56.82	67.39	
65% F	165.21	165.50	166.35	166.73	226.02	226.44	227.32	227.79	226.02	226.44	227.32	227.79	
80% F	158.76	158.59	160.68	160.53	216.43	216.62	219.36	219.09	216.43	216.62	219.36	219.09	
95% F	67.38	59.07	68.80	79.91	66.56	65.41	80.67	95.97	66.56	65.41	80.67	95.97	

Table 2. Discount f

of insect damage k

- 1 < IDK 5
- 6 < IDK 20
- 21 < IDK 31
- 32 < IDK 70
- 71 < IDK 100
- 101 < IDK 140
- 140 < IDK

source: Adam et al. (

Table 11 Table 14. NPV of Grain Management Strategy Costs (\$) : Goodland, Parametric Bootstrap, Stabilized

	1% Discount Rate											
	Calendar-based fumigation					Sampling-based IPM						
	No ω	Low ω	Medium ω	High ω	No ω	Low ω	Medium ω	High ω	No ω	Low ω	Medium ω	High ω
65% F	-	20.84	21.51	57.06	-	22.67	22.60	23.33	-	22.67	22.60	23.33
80% F	-	20.84	25.50	80.66	-	22.64	23.10	26.92	-	22.64	23.10	26.92
95% F	-	20.84	20.84	41.68	-	22.55	22.72	22.64	-	22.55	22.72	22.64
65% F	20.84	20.84	20.84	34.68	22.67	22.67	22.74	24.67	22.67	22.67	22.74	24.67
80% F	20.84	20.84	31.04	49.23	22.64	22.64	24.11	30.70	22.64	22.64	24.11	30.70
95% F	20.84	20.84	20.84	20.84	22.55	22.55	22.65	22.64	22.55	22.55	22.65	22.64
65% F	20.84	21.27	36.92	51.94	22.59	22.58	25.17	31.42	22.59	22.58	25.17	31.42
80% F	20.84	22.40	48.95	67.04	22.64	22.58	29.67	41.70	22.64	22.58	29.67	41.70
95% F	20.84	20.84	20.84	20.84	22.65	22.66	22.60	22.56	22.65	22.66	22.60	22.56
65% F	-	20.84	24.02	35.60	-	22.67	22.82	25.15	-	22.67	22.82	25.15
80% F	-	20.84	29.10	47.08	-	22.64	23.85	29.90	-	22.64	23.85	29.90
95% F	-	20.84	20.84	20.85	-	22.55	22.72	22.64	-	22.55	22.72	22.64
65% F	20.84	20.84	28.32	43.57	22.67	22.67	23.44	27.61	22.67	22.67	23.44	27.61
80% F	20.84	20.86	35.19	56.21	22.64	22.64	25.44	34.58	22.64	22.64	25.44	34.58
95% F	20.84	20.84	20.84	20.88	22.55	22.55	22.65	22.64	22.55	22.55	22.65	22.64
65% F	20.84	22.33	44.40	62.06	22.59	22.62	27.93	37.46	22.59	22.62	27.93	37.46
80% F	20.84	23.55	55.21	73.59	22.64	22.68	32.75	47.11	22.64	22.68	32.75	47.11
95% F	20.84	20.84	20.88	21.10	22.65	22.66	22.60	22.60	22.65	22.66	22.60	22.60
10% Discount Rate												
65% F	-	9.36	9.47	10.64	-	10.14	10.14	10.28	-	10.14	10.14	10.28
80% F	-	9.36	10.10	12.80	-	10.09	10.19	10.76	-	10.09	10.19	10.76
95% F	-	9.36	9.36	9.36	-	10.18	10.21	10.14	-	10.18	10.21	10.14
65% F	9.36	9.36	9.89	11.88	10.10	10.16	10.19	10.42	10.10	10.16	10.19	10.42
80% F	9.36	9.36	11.17	14.85	10.15	10.15	10.32	11.54	10.15	10.15	10.32	11.54
95% F	9.36	9.36	9.36	9.36	10.16	10.10	10.12	10.15	10.16	10.10	10.12	10.15
65% F	9.36	9.43	12.19	15.32	10.14	10.11	10.54	11.63	10.14	10.11	10.54	11.63
80% F	9.36	9.61	14.81	18.83	10.09	10.13	11.39	13.87	10.09	10.13	11.39	13.87
95% F	9.36	9.36	9.36	9.36	10.18	10.08	10.11	10.14	10.18	10.08	10.11	10.14
65% F	-	9.36	9.88	12.05	-	10.14	10.18	10.61	-	10.14	10.18	10.61
80% F	-	9.36	10.81	14.38	-	10.09	10.36	11.31	-	10.09	10.36	11.31
95% F	-	9.36	9.36	9.36	-	10.18	10.21	10.14	-	10.18	10.21	10.14
65% F	9.36	9.36	10.69	13.74	9.77	10.16	10.32	10.96	9.77	10.16	10.32	10.96
80% F	9.36	9.36	12.07	16.57	9.79	10.15	10.56	12.34	9.79	10.15	10.56	12.34
95% F	9.36	9.36	9.36	9.36	9.80	10.10	10.12	10.15	9.80	10.10	10.12	10.15
65% F	9.36	9.61	13.98	17.77	9.79	10.12	11.03	12.84	9.79	10.12	11.03	12.84
80% F	9.36	9.82	16.23	20.64	9.76	10.15	12.04	15.07	9.76	10.15	12.04	15.07
95% F	9.36	9.36	9.36	9.39	9.81	10.08	10.11	10.14	9.81	10.08	10.11	10.14

Table 15. Discounted Aeration-Based IPM Costs

1% Discount	10% Discount
14.93	6.70

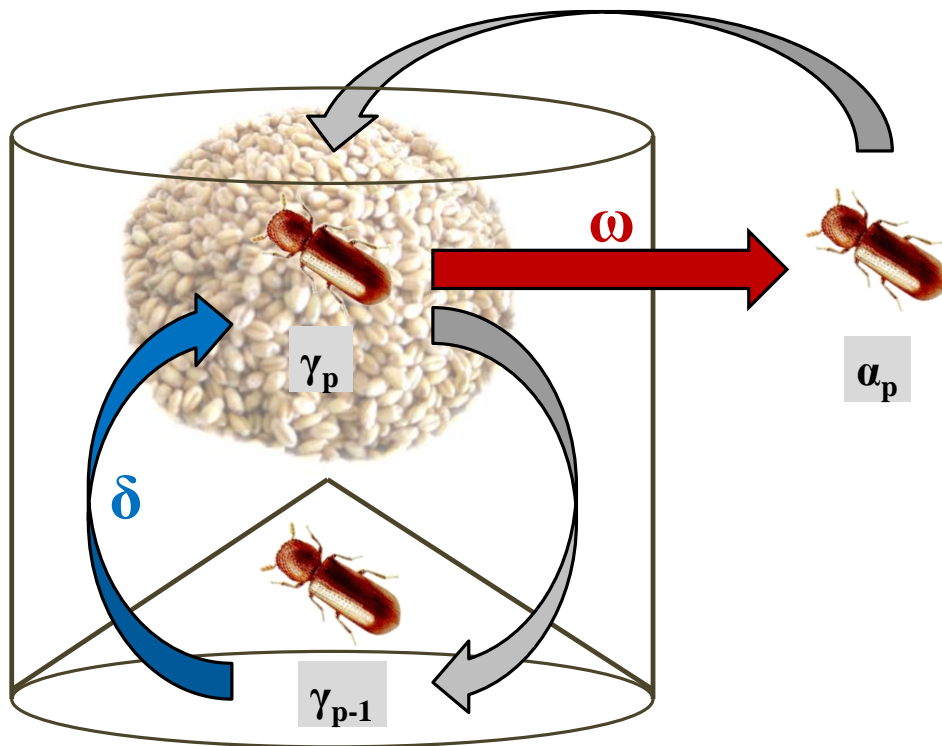


Figure 1. Hypothesized Population Dynamics of Lesser Grain Borer in Stored Wheat.

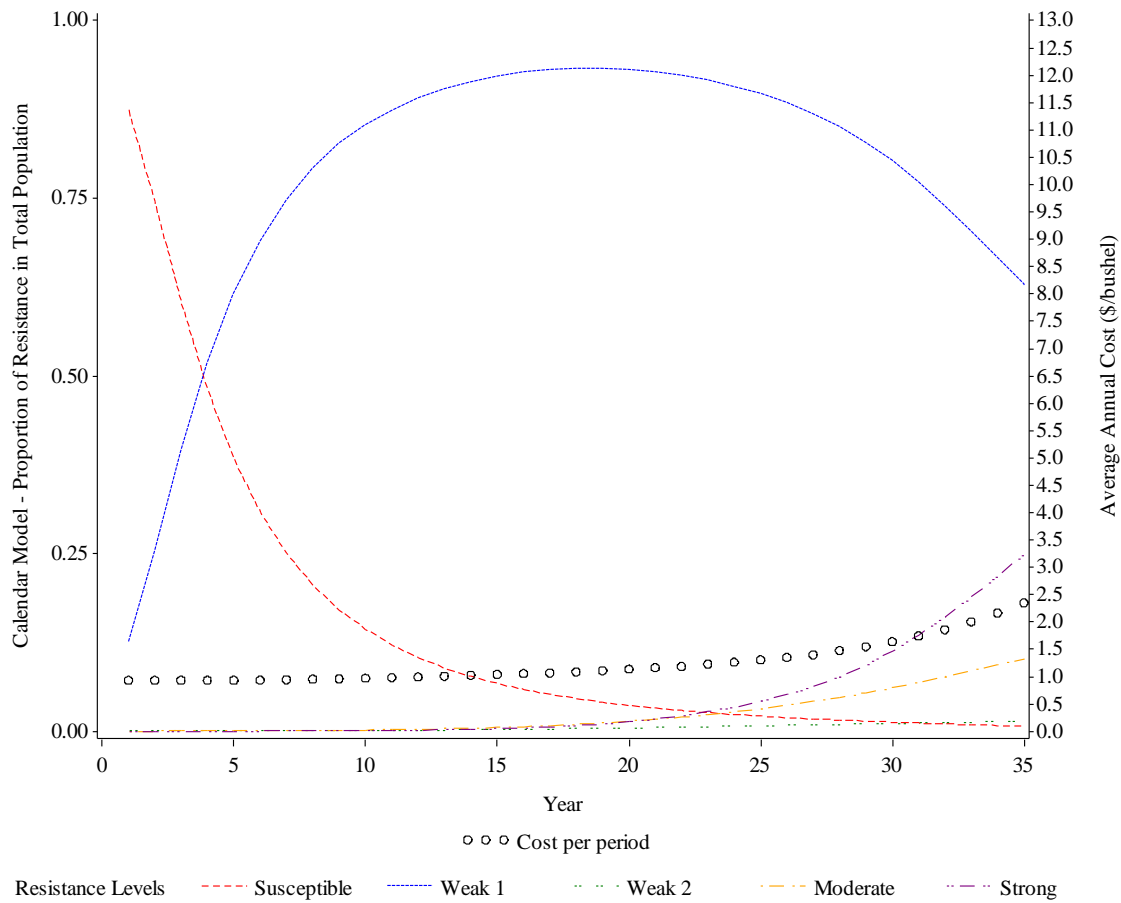


Figure 2. Resistance Development and Costs of Calendar-Based Fumigation for Oklahoma City, Under Scenario 1, Stabilized, Non-parametric Model, with 95% F, $\omega = 0.35$, $\delta = 0.8$, and 3% Allele Starting Frequencies

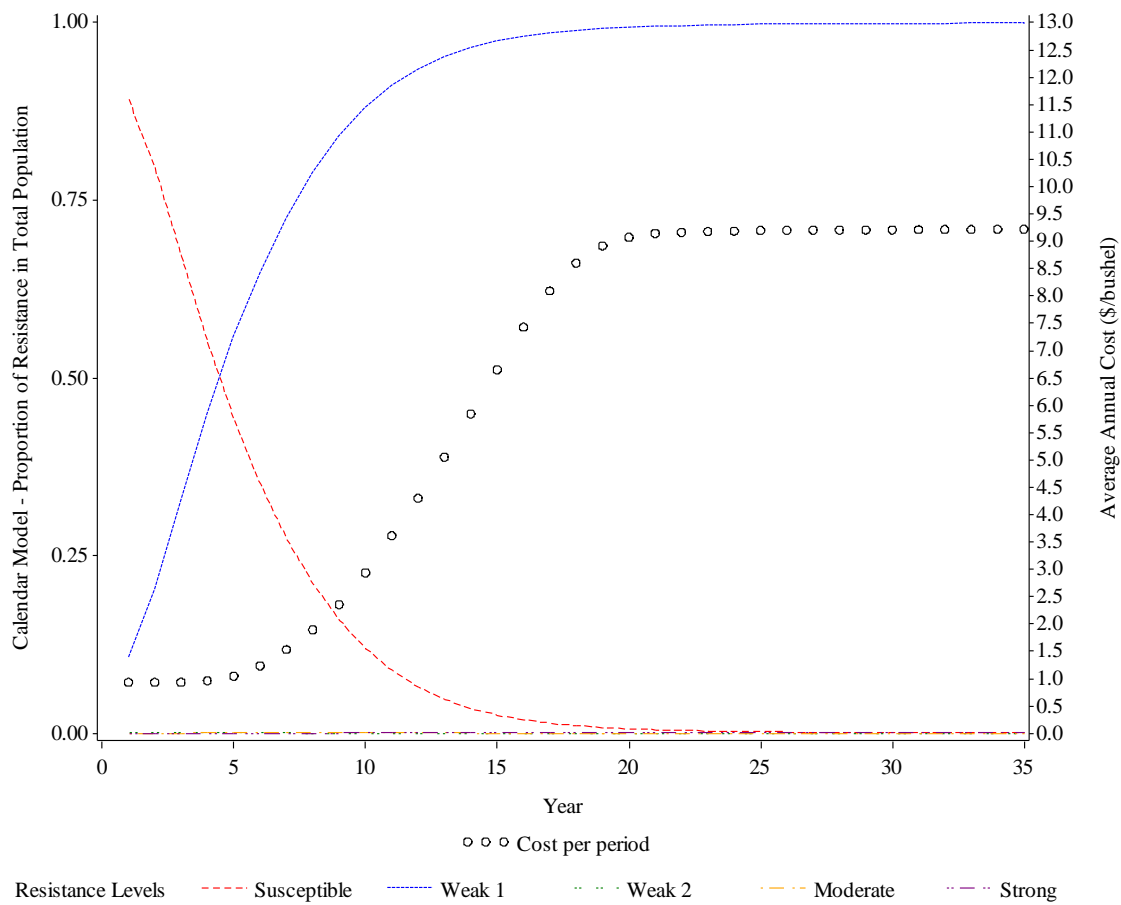


Figure 3. Resistance Development and Costs of Calendar-Based Fumigation for Oklahoma City, Under Scenario 1, Stabilized, Non-parametric Model, with 80% F, $\omega = 0.35$, $\delta = 0.8$, and 3% Allele Starting Frequencies

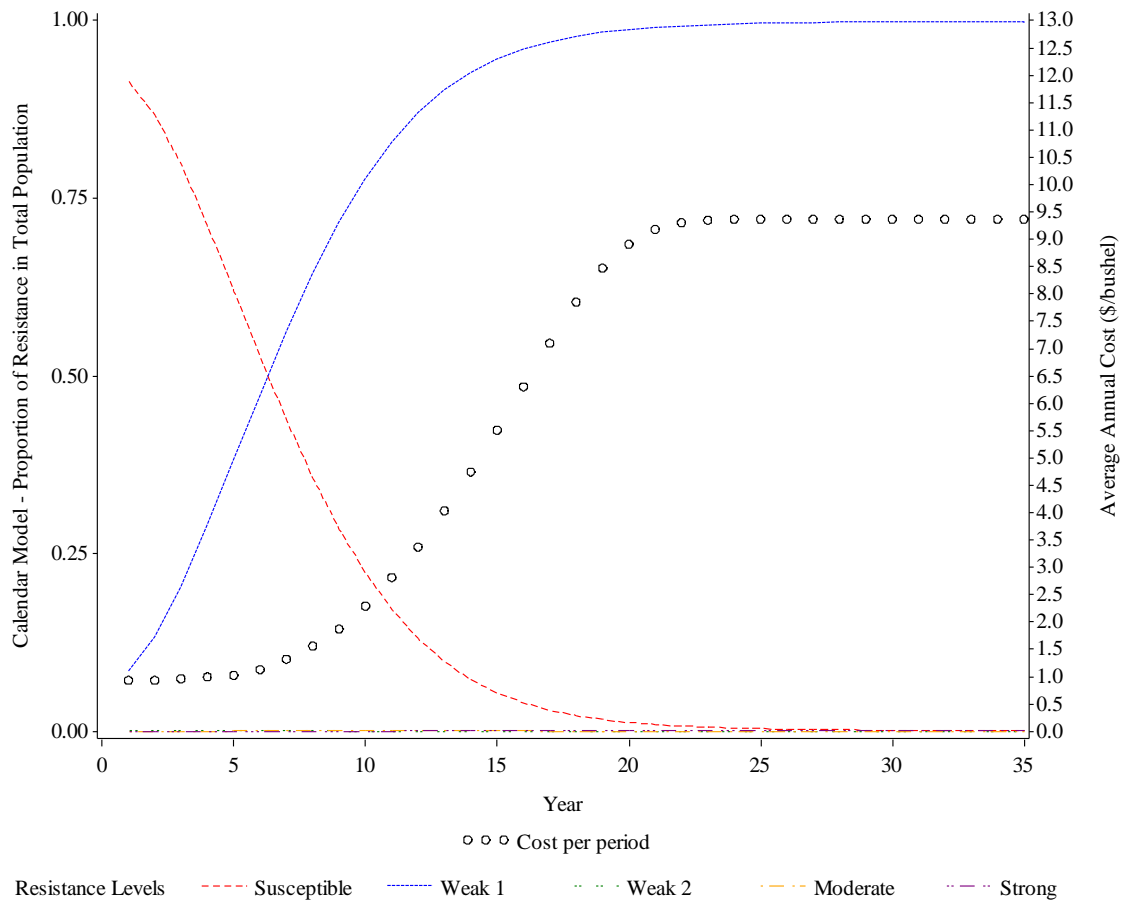


Figure 4. Resistance Development and Costs of Calendar-Based Fumigation for Oklahoma City, Under Scenario 1, Stabilized, Non-parametric Model, with 65% F, $\omega = 0.35$, $\delta = 0.8$, and 3% Allele Starting Frequencies