Journal of Stored Products Research 46 (2010) 186–196

Contents lists available at ScienceDirect

Journal of Stored Products Research

journal homepage: www.elsevier.com/locate/jspr

Factors influencing economic profitability of sampling-based integrated pest management of wheat in country elevators☆

B.D. Adam[a,*], M. Siaplay[a], P.W. Flinn[b], B.W. Brorsen[a], T.W. Phillips[c]

[a] Dept. of Agricultural Economics, Oklahoma State University, Stillwater, OK 74078, USA
[b] USDA-ARS, Grain Marketing and Production Research Center, Manhattan, KS, USA
[c] Dept. of Entomology, Kansas State University, KS, USA

ARTICLE INFO

Article history:
Accepted 2 April 2010

Keywords:
Integrated pest management
Economics
Grain elevators
Costs and benefits
Fumigation

ABSTRACT

Integrated pest management (IPM) in stored wheat could increase worker safety, reduce environmental concerns, and may reduce the chances of loss in grain quality. Managers of many country elevators, however, continue to use chemical-based approaches. To determine if this choice is economically justified, total costs (including both costs of implementation and costs of failing to control insects) for sampling-based IPM and calendar-based chemical approaches were simulated and compared for country elevators operating under typical conditions in the Central and Southern Plains of the United States.

When we simulated a constant insect immigration rate into all bins at an elevator, results suggested that managers of country elevators storing hard red winter wheat under standardized assumptions and typical conditions have little economic incentive to switch from conventional calendar-based fumigation to sampling-based fumigation when both cost of treatment and cost of failing to control insects are considered. Under these assumptions, the reason sampling was not profitable was that fumigation eventually became necessary in all the bins, so sampling was just an extra cost. However, changing some of the standardized assumptions can make sampling-based fumigation profitable. In particular, the simulation suggests that if an elevator has some bins with a low rate of immigration and others with a medium rate of immigration, sampling-based fumigation becomes an economically attractive alternative. Other factors such as increased sanitation, reducing the cost of sampling, and storing the grain for shorter periods may also make a sampling-based approach more economical.

© 2010 Elsevier Ltd. All rights reserved.

1. Introduction

Two aspects of consumer preferences for food conflict with one another. On the one hand, consumers demand wholesome products, free of insects and other pests. On the other, consumers are increasingly concerned about pesticide and herbicide residues on their food (Senauer et al., 1991; Magnusson and Cranfield, 2005).

Because of food safety as well as worker safety and environmental concerns, many of the pesticides currently used to control pests in stored products such as grain are being phased out or significantly restricted by regulations (Ramaswamy et al., 2000). Also, in order to reduce the potential for pesticide residues on their food products, some food manufacturers severely limit the amount of pesticides that can be applied to inputs they purchase (Phillips et al., 2002). Moreover, insects are developing resistance to some of the pesticides currently used (Zettler and Cuperus, 1990; Zettler and Beeman, 1995; Bridgeman et al., 2000; Bell, 2000; Benhalima et al., 2004; Daglish, 2004; Athie and Mills, 2005; Pimentel et al., 2007).

The reduced arsenal of pest control tools combined with demands for wholesome and pest-free food poses a challenge for managers of food processing firms and stored-grain facilities. Some authors have proposed Integrated Pest Management (IPM) as a solution to this dilemma. The expanded set of information-based tools available with IPM provides the potential for better insect management as well as increased worker safety and reduced environmental concerns.

As Yigezu et al. (2008) note, there has been little analysis of the economics of stored-product pest management. Fox and Hennessy (1999) developed a theoretical model to analyze post-harvest food quality control and the tradeoff between cost of intervention and cost of damage, and applied it to infestations of *Rhyzopertha dominica* (F.) in stored wheat. Although their theoretical model is

☆ This article reports the results of research only. Mention of a proprietary product or trade name does not constitute a recommendation or endorsement by the US Department of Agriculture, Oklahoma State University, or Kansas State University.

* Corresponding author. Tel.: +1 405 744 6854; fax: +1 405 744 8210.
E-mail address: brian.adam@okstate.edu (B.D. Adam).

0022-474X/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jspr.2010.04.004

adaptable to a number of alternative specifications, including varying weather conditions or insect immigration rates, the analysis assumed that levels of insects were correctly predicted by the model so that no monitoring costs were incurred.

In contrast, Yigezu et al. (2008) focused on prevention and monitoring, and found that a monitoring-based optimal mold management strategy for food-grade corn would be profitable for producers who have signed contracts with a food processor because the premium and storage cost reimbursement associated with such contracts would more than offset the cost of monitoring.

In the case of wheat in the Central and Southern Plains region of the U.S., few grain elevator managers have adopted a monitoring, or sampling-based, IPM approach to insect control (see Cuperus et al., 1990). The purpose of this article is to determine if there is an economic explanation for this reluctance.

Approximately two-thirds or more of wheat storage in the Central and Southern Plains (including Kansas and Oklahoma) is in commercial, off-farm facilities (Anderson and Noyes, 1989). Much of this wheat is stored in country elevators. Country elevators are the primary point of first assembly for wheat, buying wheat from producers and either selling the wheat immediately or storing it for later sale. Some of the wheat stored by country elevators is owned by producers, who pay a monthly charge for storage and who plan to sell the wheat to the elevator at some future time.

Environmental conditions in this region promote rapid insect growth in grain. Although automatic aeration[1] to cool grain as quickly as outside temperatures permit is a recommended IPM practice that controls insects inexpensively (Adam et al., 2006), most commercial grain storage structures in the region do not have aeration capability. A typical structure is a group of concrete silos joined with interstices. In contrast to corn and soybean elevators in the U.S. corn belt, storage structures for wheat in the Plains states were built with smaller bins to segregate the wheat for more diverse quality characteristics (Schnake and Stevens, 1983). Few of these structures were fitted for aeration capability, so most elevator managers resort to phosphine fumigation one or more times per year to control insects, either after an insect infestation has been detected or on a pre-determined schedule (Hagstrum et al., 1999).

A typical practice used in this region is calendar-based fumigation, under which a grain elevator manager fumigates all structures at approximately the same time every year. In contrast to this calendar-based fumigation, 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 in 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 a lower insect population and thus would not need to be fumigated along with the other bins.

Managers may be concerned that IPM is too costly, that it requires more management time and expertise than is available, or that it is not as reliably effective in controlling insects. There is little published evidence that IPM is cost-effective. Although it reduces pesticide use and associated costs, it requires more management skill and more labor, both expensive inputs. However, Lukens (2002) found that the costs of several specific IPM practices compared favorably with those of conventional, non-IPM practices, even when the extra labor time is considered.

While measurable costs of IPM practices compare favorably, the less measurable demands on management expertise may be higher if IPM practices are to be used effectively. Some managers may not have the inclination or ability to follow recommended IPM practices for maximum effectiveness. Even if IPM decision-making were shown to be as effective as calendar-based decisions when practiced correctly, there is a risk that a manager would fail to apply IPM methods correctly, resulting in higher insect numbers than if conventional practices were followed. Or, sampling too infrequently may not detect insects that calendar-based fumigation would have killed whether or not they were detected. Thus, calendar-based pesticide applications provide "insurance" against insect damage (Feder, 1979), while grain managers may view IPM as increasing risk.

Some of the perceived risk of IPM, however, may result from storage managers over-estimating the reliability of calendar-based decisions, which are susceptible to failure as well. Fumigation may be applied too early or too late for effective control. Some managers, though, likely have adopted calendar-based fumigation in an attempt to avoid this problem. They are seeking a balance between fumigating too early, which would allow insect populations to rebound by time of sale, and fumigating too late, allowing population densities to exceed the economic threshold. In addition, Noyes (2002) argued that conventional phosphine fumigations (the most commonly used control method in stored wheat) "…are typically poorly managed due to leaky [storage facilities], improper application methods, incorrect dosages, and incorrect timing. These poor fumigation practices have resulted in failure to kill all life stages of stored grain insects, contributing to breeding new generations of stored grain insects with increased vigor and resistance to phosphine." Other factors complicate both calendar-based and sampling-based fumigation: insects may have developed resistance to a particular chemical; temperature and moisture conditions may be favorable to insect growth so that control is difficult; a particular treatment may be effective only for a certain part of the insect growth cycle, leaving insects at different stages free to grow and reproduce; or a particular treatment may be incorrectly applied, reducing its effectiveness.

Whereas routinely applying chemical treatments may have a range of effectiveness (for example, a fumigation may be 90% effective, or 50% effective), a sampling-based IPM approach in which a range of non-chemical and chemical treatments is available may come down to an "either/or" decision. A key feature of a sampling-based IPM approach is sampling or monitoring the grain, and depending on results of sampling, a (possibly chemical) treatment is either recommended or not (Flinn et al., 2007). If sampling fails to detect an insect problem, and no treatment is applied, extensive damage may result. A grain elevator manager may not wish to bear that risk when conventional methods are working, such as calendar-based fumigation without sampling, even though perhaps at a sub-optimal level.

Thus, a possible reason for so few elevator operators adopting IPM methods may be the large costs they face if they fail to control insects effectively. Although applying treatments when they are not needed adds unnecessary costs, those costs are relatively small. However, not applying treatments when they are needed results in large costs, because of the nonlinear relationship between insect population and grain discounts and because of the exponential nature of insect population growth. Moreover, the monitoring, or sampling, that IPM practices use to decide when treatments are needed is itself costly.

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,

[1] Automatic aeration refers to aeration in which fans operate only when outside temperatures are a set number of degrees cooler than the grain. Yigezu et al. (2008) refer to this as conditional aeration.

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* larvae feed inside the kernel until they mature into adults and burrow out of the kernel, which results in insect-damaged kernels (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.

Here, we simulate and compare a conventional, calendar-based fumigation approach and an IPM sampling-based approach to managing stored-grain insects. For each, we estimate both the expected costs of the treatment and the expected cost of failing to effectively control insects: the discounts result from insect-damaged grain and from live insects present at the time of marketing.

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).[2]

The elevator manager using calendar-based fumigation is assumed to fumigate at nearly the same time every year, with its associated costs. Under a sampling-based approach, however, it is assumed a manager would sample the grain during storage, and fumigate a particular bin only if the number of insects from a sample of that bin exceeded a threshold level.

Adam et al. (2006) showed that under typical environmental conditions and insect growth and immigration rates, based on the model described by Flinn et al. (2004), elevators in the study region with concrete storage structures and no aeration capability would always require fumigation at some point in the storage period. In other words, even if sampling at a particular date would have indicated that some bins did not need fumigation, those bins eventually would have sufficient insect growth that fumigation would be required at a later date. Thus, sampling as an IPM practice would have added cost but provided no benefit because it would have changed only the timing of fumigation, but not the need for it.

However, Adam et al. (2006) assumed a constant immigration rate of insects into each bin within a storage facility. Immigration rates actually differ from bin to bin, so their approach would underestimate the attractiveness of sampling relative to routine fumigation since varying immigration rates might allow cases where fumigation is never needed.

Information received from continual on-site sampling at several grain elevators in Kansas and Oklahoma conducted as part of a regional study suggests that although the insect growth model described by Flinn et al. (2004) is calibrated for typical storage bins, its insect population predictions were too high for some bins. It was determined that these bins had a much lower insect immigration rate, so the model was calibrated to these bins by reducing the insect immigration rate specification (Hagstrum, personal communication; Flinn, personal communication).

Thus, the current study uses a more recent version of the insect growth model developed and validated by Flinn et al. (2004) to simulate insect growth. The revised version allows modeling lower immigration rates of grain-damaging insects into a storage structure. The "medium" rate of insect immigration specified here reflects the original calibration, while the "low" rate of insect immigration reflects the calibration appropriate for those bins whose populations the model over-predicted.

For this article, it is assumed initially that all storage bins within a grain elevator facility have either medium or low insect immigration rates. The results generated from these two baseline assumptions are then used to calculate the percentage of bins that would need to have a low immigration rate in order for IPM to be more profitable than conventional practice. In a future paper we will explore the consequences of differing rates of immigration across bins at the same elevator, which could increase the profitability of a sampling-based approach.

2. Materials and methods

2.1. Model development

The work was done in three steps. The first step was to estimate the cost of each component of insect control in grain storage using an economic-engineering approach. The second step was to predict the insect population that would result under various environmental conditions and under alternative insect control strategies. The insect growth model of Flinn et al. (2004), was used to simulate insect growth under various environmental conditions and under alternative treatments, as well as under alternative assumptions about fumigation effectiveness and insect immigration rate. This deterministic model predicts daily populations of *R. dominica* in the egg, larval, pupal, and adult stages as a function of the previous day's population, insect immigration rate, mortality rate due to fumigation and natural death, and grain temperature. Grain temperature is the most important variable for predicting insect population at various locations within a bin. The *R. dominica* model is coupled with a two-dimensional grain storage model that uses a thermal transfer equation to predict changes in grain temperature as a function of hourly observations of solar radiation, cloud opacity, dew point temperature, dry bulb temperature, relative humidity, barometric pressure, and wind speed.

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

$$\min_j E(C_j) = [\mathrm{TC}_j + E(D_j) + E(L_j)] \quad (1)$$

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; D_j is the discount due to damaged grain and L_j is the discount due to live insects at time of marketing. Further details are available in Mah (2004) and Adam et al. (2006).[3]

[2] In a partial-budgeting approach, only cost components that might differ between approaches are evaluated. For example, although the cost of loading and unloading grains 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.

[3] This specification does not stipulate that all managers make the mental calculations indicated here for every decision that they make, or that their decisions are always consistent with it. It simply asserts that decisions that correspond more closely with this model will reduce costs more than decisions that do not correspond as closely. Further, managers whose decisions do not correspond to this model will have a monetary incentive to adjust their decisions to more closely correspond to it.

2.2. Costs

Treatment cost for each strategy was estimated using an economic-engineering approach (see Lukens, 2002). Cost components include equipment, labor, chemicals, electricity, grain weight lost, and safety training. A grain elevator with a group of ten concrete bins, each 7.28 m in diameter and 24.4 m deep, holding 760 tonnes of wheat, is assumed.

Tables 1–4 show cost estimates of components of typical treatments. The cost of sampling (Table 1), for example, 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. Similarly, the cost of fumigation (Table 2) includes amortized equipment cost, insurance and training, labor, chemical costs, electricity used to turn grain, and value of grain lost in turning.

In concrete facilities, turning is usually required for effective fumigation; grain is emptied from one silo (bin) and transported on a moving belt to another silo within the facility. Fumigation is conducted by adding aluminum phosphide tablets into the moving grain as the bin is filled. It is assumed that 0.25% of grain weight is lost in turning (Kenkel, 2008).[4]

The analysis simulated conditions in four different locations in Oklahoma and Kansas (Oklahoma City in Oklahoma, and Wichita, Topeka and Dodge City in Kansas), using hourly weather data from 1989 and 1990. Figs. 1 and 2 show daily averages of the hourly observations for temperature (°C) and relative humidity (%) for the four locations. The only difference across these locations in the simulation is the weather, so one could think of these locations as representing four different sets of weather conditions.

It was assumed that any fumigation conducted was of average effectiveness, so that 90% of insects in the pupal stage, 99% of insects in the adult stage, and 99.9% of eggs and larvae were killed over a 5-day period. The model's prediction of adult *R. dominica* at time of sale is used to calculate the discount associated with the threshold of two or more live grain-damaging insects.[5] The model's prediction of insect-damaged kernels at time of sale is used to calculate IDK discount.

2.3. Simulation procedures

The simulation assumed that grain could be stored for three possible storage periods: (1) from June 20 to April 19 (304 days, or approximately ten months); (2) from June 20 to February 28 (254 days, or approximately eight months); or (3) from June 20 to December 20 (183 days, or approximately six months). The ten-month storage period reflects storage for nearly an entire crop year.

The six- and eight-month storage periods may be more representative of wheat stored in Oklahoma (see Cunningham et al., 2007). In fact, storing for six months and then selling may provide a storage manager with the highest price for wheat net of storage costs if practiced consistently over many years (see Klumpp et al., 2007). Accordingly, data presented by Anderson and Brorsen (2005) suggest that over the period 1992–2001, 40–60% of wheat in southern and central Oklahoma was sold before September, two to two-and-a-half months after harvest, but that 15–30% of wheat was held until after February.

However, any particular year may be quite different from the average; for example, managers storing wheat after the 2007 harvest would have received the highest price net of storage costs by storing until March, 9 months after harvest. Further complicating a manager's storage decisions, much of the wheat stored in commercial storage is owned by producers, not the storage firm. Thus, the storage manager may not have the flexibility to sell wheat as early as desired.

The insect growth model's grain temperature was set to 28.9 °C and the grain moisture to 12% on the initial date of storage, June 20. Insect numbers were predicted using the software SGAPro 3.0, based on the model by Flinn et al. (2004).

Table 1
Economic-engineering costs of sampling for insects in stored wheat ($/t).

Sampling cost components	Rate	$/tonne
Fixed		
PowerVac ($8000 amortized at 10% over useful life of 10 yrs + insurance + maintenance)	$2102/yr	$0.2760/t
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

Table 2
Economic-engineering costs of fumigating insects in stored wheat ($/t).

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
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

[4] If many managers were to adopt an IPM approach, or if many were to hire insect management services, these costs would likely change. The purpose of this paper is to quantify the current constraints faced by managers, so costs used here are appropriate. However, should such a widespread adoption of IPM or outsourcing of services occur, it would be straightforward to adjust the parameters of the economic-engineering approach used here.

[5] Rusty grain beetles (*Cryptolestes ferrugineus* (Stephens)) are also common in stored hard red winter wheat. Although the insect growth model used here has been calibrated for each species separately, it has not been calibrated for both together, so only *R. dominica* is modeled. Results from modeling *Cryptolestes* separately indicate that fumigation would be necessary under all assumptions of immigration rate and locations (weather) considered here, since population of *Cryptolestes* under each assumption is sufficiently large to incur a live insect discount. However, field observations indicate that when both *Rhyzopertha* and *Cryptolestes* are in a grain storage facility together, the *Rhyzopertha* population is dominant. The predicted numbers for *Rhyzopertha* – which are the most damaging because they cause (IDK) – should be viewed, then, as a lower bound for the total number of grain-damaging insects. Any bias resulting from omitting a *Cryptolestes* population in the ending population prediction would favor a sampling-based approach.

Table 3
Economic-engineering costs of aerating stored wheat ($/t).

Aeration cost components	Rate	$/tonne
Fixed		
5 HP fan (0.1 cfm/bu) $1500 amortized at 10% over 10 yrs + insurance + maintenance	$394/bin/yr	$0.5176/t
Electricity		
(hp/fan/0.748) * #fans * #hrs * $/kWh	$117/aeration/bin	$0.1536/t
Average cost (10 bins each 760 t)		$0.671/t

Three strategies were simulated. First, a baseline strategy assumed that insects grew unchecked during the storage period. A second strategy assumed a manager used calendar-based fumigation, fumigating on December 20. A third strategy assumed a manager used a sampling-based approach to determine whether to fumigate. The rule used in that strategy was to fumigate if sampling on December 20 detected 0.5 or more adult *R. dominica* per kilogram sample, except that if the grain was to be sold on December 20, the manager would fumigate only if sampling detected one or more *R. dominica* per sample. The December 20 sampling date was chosen late enough so that if sampling indicated fumigation was not necessary, no grain damage would in fact result before the grain was sold, and if sampling indicated fumigation was necessary, there would be insufficient time for the insect population to rebound enough to cause damage before the grain was sold. The criterion of 0.5 adult *R. dominica*/kg was set low enough so that no grain damage would occur before sampling was conducted, but high enough so that there was some possibility fumigation would not always be prescribed.

2.4. "Failure-to-control" discounts

Cost of failing to control insects is made up of three parts. First, a live insect discount is triggered if a one-kg sample taken at time of sale contains one or more adult *R. dominica*. Although a USDA designation of "infested" is triggered upon observation of two or more live grain-damaging insects per one-kg sample, since U.S. commercial trade increasingly appears to reject lots with even one live grain-damaging insect, one-insect-per-kg standard is used in this simulation. Here, a prediction of 1.0 adult *R. dominica*/kg by the model is assumed to result in a live insect discount of $1.837/t, primarily to cover the cost of commercially fumigating to kill all live insects.

Second, the number of insect-damaged kernels (IDK) in a 100-gram sample determines the amount of the IDK discount. A typical schedule of discounts charged by a terminal elevator to country elevators is shown in Table 5 and is the one used here. A third, additional, discount is triggered when the number of IDK reaches 32 in a 100-gram sample. At this level, the wheat is designated by USDA as "sample grade," and is no longer permitted to be sold for human consumption.

Table 4
Economic-engineering estimates of treatment costs for stored wheat ($/t).

	Sampling	Fumigation	Aeration	Turning
Equipment	$0.276	$0.131	$0.518	
Setup labor	$0.019			
Labor	$0.050	$0.126		$0.042
Chemicals		$0.189		
Electricity		$0.033	$0.154	$0.033
Grain weight lost		$0.375		$0.375
Safety training		$0.057		
Total ($/t)	$0.345	$0.911	$0.671	$0.450

3. Results

3.1. Treatment cost

The cost of each component of treatment cost is shown in Table 4 for sampling, fumigation, aeration, and turning. Tables 1–3 provide details of the economic-engineering calculations, and Table 4 summarizes them. Fumigation (with turning) costs just over $0.91/t. The component of fumigation that costs the most is the value of grain lost in turning (0.25% of the wheat, and assuming a wheat price of $150/t). Turning the grain makes up nearly 50% of the cost of fumigation (turning may have an added benefit, not quantified here, of cooling grain). The cost of sampling is $0.345/t, including variable costs of $0.069/t and amortized equipment costs of $0.276/t. Although Adam et al. (2006) found that automatic aeration would be an economical IPM strategy, since most elevators in the region do not have aeration capability, the focus of this paper is on non-aeration treatment strategies and aeration cost is included for comparison purposes.

3.2. Total costs – no treatment

Figs. 3–6 show the insect numbers and resulting IDK predicted by the insect growth model when no treatment strategies are used under baseline assumptions of low and medium rates of insect immigration for all bins at a storage facility. The simulated number of adult *R. dominica* reached nearly 4 per kg by April 19 in Oklahoma City under a low immigration rate (Fig. 3), and 10 times that many under a medium immigration rate (Fig. 4). IDK reached 1 IDK/100 g under low immigration (Fig. 5) and 12 IDK per 100 g under medium immigration (Fig. 6). The same figures show that adult *R. dominica* and IDK reached much lower numbers by February 28. By that date, the number of adult *R. dominica* had reached 1.2/kg and IDK had reached approximately 0.6 per 100 g-sample under low immigration. Under medium immigration, those numbers reached 12 adult *R. dominica*/kg, and 3.6 IDK/100 g. By December 20, though, the numbers had reached only 0.1 adult *R. dominica*/kg and 0.03 IDK/100 g under low immigration, and 1 adult *R. dominica*/kg and 0.3 IDK/100 g under medium immigration.

Scenario 1 in Tables 6 and 7 shows the simulated costs of doing nothing in all four locations under medium and low immigration rates for all bins at an elevator, assuming wheat is stored until April 19. There is no treatment cost, so all costs are due to failure to control insects. Insect numbers grow to a level high enough that there is a live insect discount of $1.837/t in all locations. Under a medium immigration rate (Table 6), IDK discounts range from more than $2.35/t to $4.740/t, depending on location. In contrast, with a low immigration rate (Table 7), no IDK discounts are incurred because insect numbers do not reach high levels until near the end of the storage period.

Scenario 2 in Tables 6 and 7 shows the costs of doing nothing in all four locations under medium and low immigration rates for all bins at an elevator, assuming wheat is stored until February 28. Under this assumption, no IDK costs are incurred under either low or medium immigration rates. Under a medium immigration rate (Table 6), all locations incur a live insect discount of $1.837/t. Under a low immigration rate (Table 7), three locations – Wichita, Topeka, and Dodge City – do not even incur a live insect discount.

Scenario 3 shows the costs of doing nothing in all locations assuming that wheat is stored only until December 20. Under

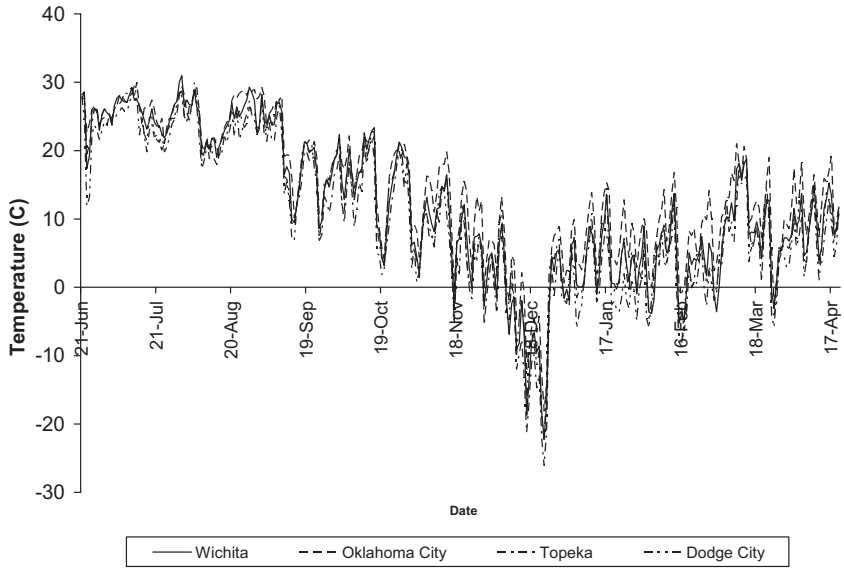

Fig. 1. Daily temperature readings (°C) in four locations, 1989–1990.

a medium immigration rate for all bins at an elevator, all locations incur a live insect discount, but no IDK discounts. Under a low immigration rate, no location incurs a discount.

3.3. Total costs – calendar-based fumigation

Figs. 7 and 8 show the adult *R. dominica* numbers and resulting IDK under scenario 4, a calendar-based fumigation on December 20, assuming a medium rate of insect immigration for all bins at an elevator and storage until April 19. Insect numbers begin to increase rapidly in November (even though outside temperatures cool considerably, the grain mass stays warm and favorable to insect growth, since aeration is not possible) until the fumigation on December 20.

With few new adult insects emerging after fumigation, IDK increases are halted. In March, the insects surviving fumigation renew population growth, but grain is sold before a problem develops. As shown in Tables 6 and 7, the cost in all locations for both medium and low immigration rates and for sale on February 28 or April 19 is a fumigation cost of $0.911/t.

3.4. IPM: total costs – sampling-based fumigation

Scenarios 5, 6, and 7 in Tables 6 and 7 show the cost of sampling on December 20, and fumigating only in those locations where the number of adult *R. dominica* is greater than 0.5/kg. Under a medium immigration rate for all bins at an elevator (Table 6), the insect population reaches this threshold at all locations, so fumigation is conducted at all locations. Thus, in addition to the sampling cost of $0.345/t, there is a fumigation cost of $0.911/t, but no costs due to grain damage regardless of the length of time grain is stored.

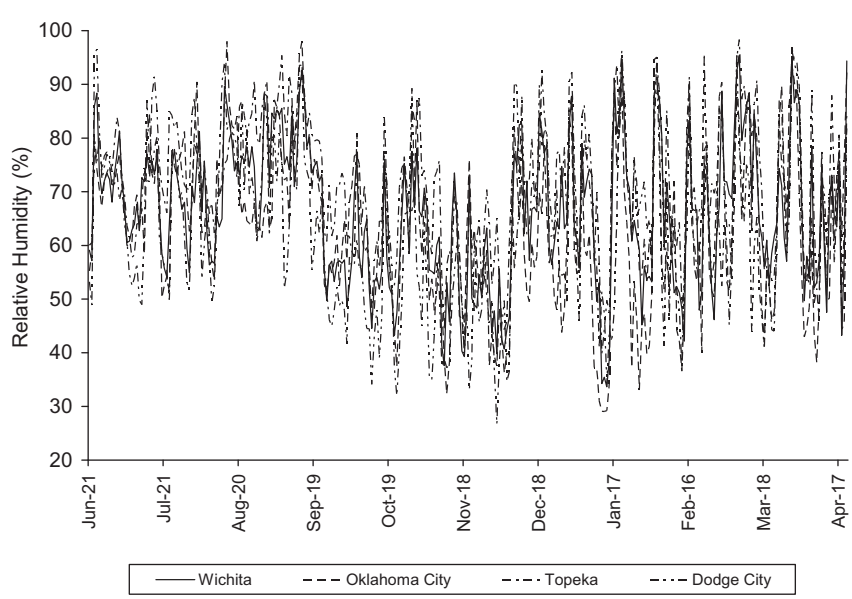

Fig 2. Daily relative humidity readings (%) in four locations, 1989–1990.

Table 5
Discount schedule for insect-damaged kernels (IDK).

# of insect-damaged kernels (IDK)	Discount ($/t)
1 < IDK < 5	0.00
6 < IDK < 20	0.367 × #IDK in sample
21 < IDK < 31	0.735/IDK in sample
32 < IDK < 70	14.70 cleaning charge
71 < IDK < 100	22.05 cleaning charge
101 < IDK < 140	33.07 cleaning charge
140 < IDK	0.367 × #IDK in sample

Source: Central Oklahoma terminal elevator.

Under a low immigration rate for all bins at an elevator (Table 7), the threshold is not reached at any of the locations by December 20, so no fumigation is conducted. However, storing grain in those locations until April 19 without fumigating results in enough insect growth to incur a live insect discount of $1.837/t, since sampling gives an incorrect signal that fumigating is not necessary.[6] Storing grain in those locations only until February 28 (Scenario 6) allows insects to grow to the point of a live insect discount only in Oklahoma City. Selling the grain on December 20 results in no additional costs in any of the locations.

Summarizing these results, under a medium immigration rate for all bins at an elevator (Table 6) the highest-cost approach in all locations is to use no treatment. When grain is stored until April 19, high IDK discounts and a live insect discount result. When grain is stored only until February 28, there are no IDK discounts but the grain incurs a live insect discount of $1.837/t. For all locations the lowest-cost approach is a calendar-based fumigation. Sampling-based fumigation is $0.345/t more expensive than a calendar-based fumigation because sampling does not change the treatment; the elevator manager pays for information that makes no difference.

Under a low insect immigration rate for all bins (Table 7), if grain is stored until April 19, the lowest-cost scenario is a calendar-based fumigation. Not fumigating results in a live insect discount of $1.84/t, while sampling (as in scenario 5) adds unnecessary cost of $0.345/t because sampling does not change the treatment.

However, the results change substantially for some locations if grain is stored only until February 28. For Wichita, Topeka, and Dodge City, fumigation would not have been needed with the low immigration rate. The lowest-cost approach would have been to do nothing, Sampling, though, provides the manager this information at a relatively low cost of $0.345/t.

For Oklahoma City, fumigation would have been needed. Thus, the lowest-cost approach for Oklahoma City is a calendar-based fumigation. A sampling-based approach adds $0.345/t to the treatment cost, but, even though fumigation ultimately was needed, sampling gave an incorrect signal to not fumigate (adult *R. dominica* did not reach the criterion of 0.5/kg until January 31), adding a live insect discount of $1.837/t to the cost.

Viewing the results from the perspective of an elevator manager in Wichita (or Topeka or Dodge City) who is uncertain of the insect immigration rate into each bin, and assuming that the immigration rate is the same for all bins at the elevator, doing nothing while storing until April 19 would cost $1.837/t for bins with a low immigration rate, and between $4.189/t and $5.328/t for bins with a medium immigration rate. A sampling-based approach would cost $2.183/t under a low immigration rate and $1.256/t under a medium immigration rate. A calendar-based fumigation would be the lowest-cost approach ($0.911/t) regardless of immigration rate. However, if grain were stored only until February 28, a sampling-based approach would have cost $0.345/t under a low immigration rate and $1.256/t under a medium immigration rate.

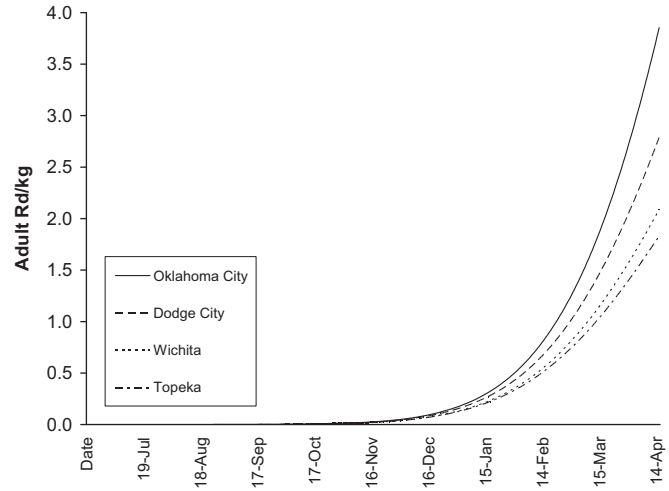

Fig. 3. Population of adult *Rhyzopertha dominica* F. in four locations (Adult Rd/kg), low immigration rate, no treatment.

Storing until December 20 would have the same result as storing until February 28 under either a low or medium immigration rate: sampling correctly signals that fumigation is needed under a medium immigration rate, and it correctly signals that fumigation is not needed under a low immigration rate.

In contrast, an elevator manager in Oklahoma City storing until February 28 would have found that a calendar-based fumigation was the least costly. Even with a low immigration rate, insects grew to a level at which fumigation was needed. Sampling unnecessarily adds $0.345/t to the cost, since the bins need to be fumigated anyway. Storing only until December 20, though, makes sampling valuable. It correctly signals that fumigation is needed under a medium immigration rate, and it correctly signals that fumigation is not needed under a low immigration rate.

Although assuming that all bins within an elevator have either low or medium immigration rates provides useful baseline estimates, a more realistic situation is that some of an elevator's bins have a low immigration rate and some have a medium immigration rate. Interpolating the results for medium and low immigration rates provides an estimate of situations under which an elevator manager would find sampling-based fumigation economical.

For example, as noted above for elevators in Wichita, Topeka, or Dodge City, if grain was stored only until February 28, a sampling-based approach would have cost $0.345/t with low immigration, and $1.256/t with medium immigration. The cost of a calendar-based fumigation ($0.911/t) under both low and medium immigration lies between these two costs, so there is a point between the two baseline assumptions (all bins with medium immigration rate or all bins with low immigration rate) at which the cost of a sampling-based approach equals the cost of a calendar-based approach. Here, if only 38% of an elevator's bins had a low immigration rate and did not need fumigation, a sampling-based approach would have cost the same as a calendar-based fumigation of all bins in the facility.[7] If more than 38% of the bins had a low immigration rate, the sampling-based approach would have been

[6] Sampling a second time several weeks later, as a comprehensive sampling-based IPM program likely would call for, would avoid the live insect discount, but would add a second sampling cost as well as a fumigation cost: in this scenario, fumigation is always necessary, and sampling adds unnecessary cost.

[7] Sampling all bins at $0.345/t + fumigating 62% of bins at $0.911/t = fumigating 100% of bins at $0.911/t ($0.345 + 62\% \times 0.911 \approx 0.911$).

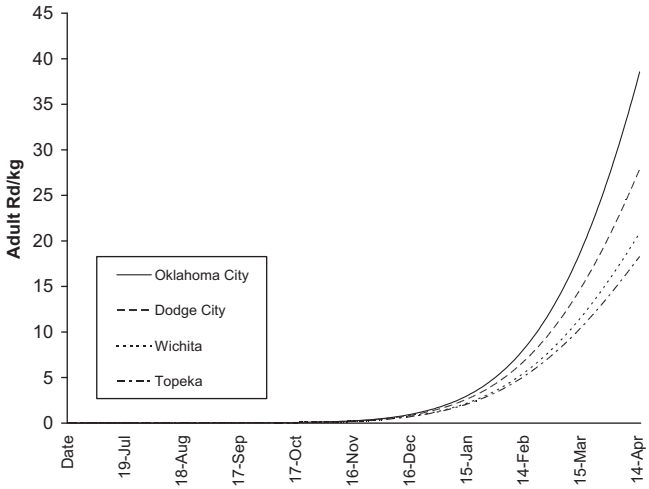

Fig. 4. Population of adult *Rhyzopertha dominica* in four locations (Adult Rd/kg), medium immigration rate, no treatment.

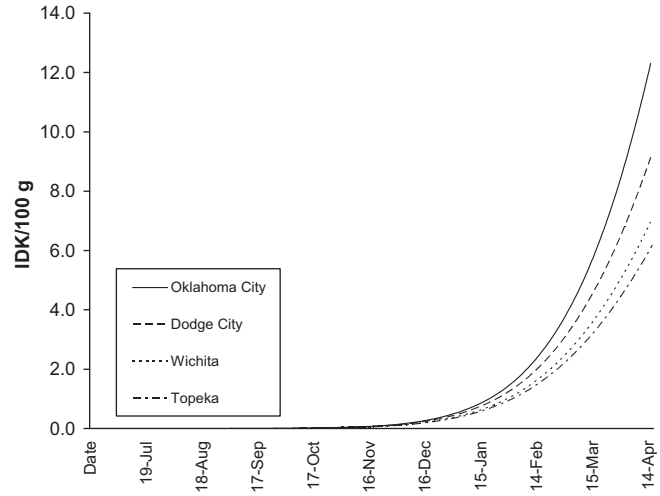

Fig. 6. Insect-damaged kernels (IDK) in four locations (IDK/100 g), medium immigration rate, no treatment.

less expensive than a calendar-based fumigation. The same calculations would apply for an elevator in Oklahoma City storing until December 20. Thus, these results indicate that an elevator manager who can achieve a low immigration rate in a portion of the elevator's bins may find a sampling-based approach economical.

4. Discussion

The purpose of this article was to determine if there is an economic explanation for the hesitation of some elevator managers to adopt a sampling-based approach to fumigation. By modeling the costs of alternative approaches, the extent to which managers have been making decisions based on incorrect information or perceptions can be identified. This study has shown that under some circumstances the cost of calendar-based fumigation is lower than the cost of sampling-based fumigation, explaining at least part of a manager's hesitation. It has also identified conditions under which the reverse is true, and specific cost factors that can be changed to lead to greater adoption of a sampling-based approach to insect management.

To the extent that elevator managers have, or believe they have, insects immigrating into all of the bins at their elevator at a medium rate, it is understandable that more of them have not adopted a sampling-based approach to fumigation. The results show that if insects immigrate into all of the bins at an elevator at a medium rate, fumigation is always needed; sampling adds unnecessary cost.

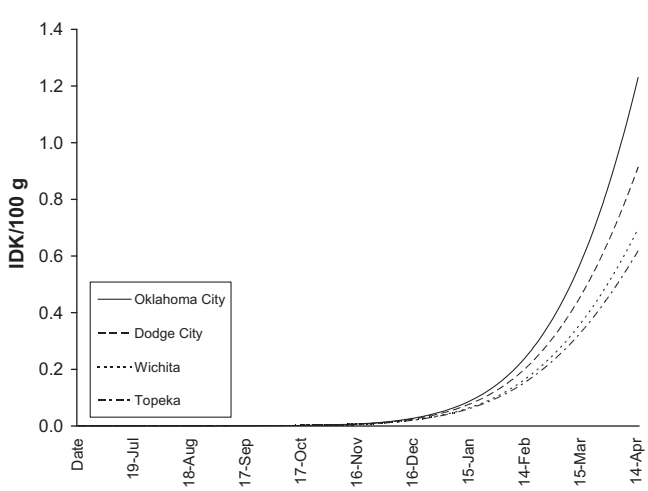

Fig. 5. Insect-damaged kernels (IDK) in four locations (IDK/100 g), low immigration rate, no treatment.

If insects immigrate into all of the storage bins at an elevator at a low rate, when weather conditions are similar to those represented by Wichita (or Topeka or Dodge City) in this simulation, the best approach is to do nothing, if storing only until February 28 or December 20. When weather conditions are similar to those represented by Oklahoma City in this simulation, a calendar-based fumigation is best.

A more realistic scenario is that an elevator has some bins with a low immigration rate and some bins with a medium immigration rate, but without sampling does not know which bins have these rates (see Flinn et al., 2004). In that situation, the results suggest that for weather conditions similar to those represented here by the locations Wichita, Topeka, and Dodge City, a sampling-based IPM approach may be economical for storage lengths of eight months or less. For the bins with a medium immigration rate, sampling would signal insect numbers would be high, and fumigation would be prescribed. For bins with a low immigration rate, sampling would signal insect numbers would be low, and fumigation would not be needed.

For weather conditions similar to those represented here by Oklahoma City, a sampling-based approach would be economical for storage lengths of six months or less. For eight- or ten-month storage periods, fumigation is always needed, even with low immigration rates, but for shorter storage periods sampling can help distinguish among bins that need to be fumigated and those that do not. In addition, to the extent that weather at an individual location differs from one year to the next, in some years the best approach might be the one that appears best for Wichita, whereas in warmer years the best approach might be the one best for Oklahoma City. Sampling may help distinguish among these situations.

For elevator managers considering a sampling-based approach to fumigation, at least some of the bins at the elevator must have low insect immigration rates. This might be a function of the elevator's location and environmental surroundings (which are not under the direct control of the elevator manager), but more likely it is a function of sanitation of the facility and integrity of

Table 6
Treatment and insect costs in four locations: medium immigration rate.

	Wichita	Oklahoma city	Topeka	Dodge city	Avg.
Scenario 1: no treatment, storing until April 19					
Sample grade	0.000	0.000	0.000	0.000	
IDK	2.646	4.740	2.352	3.491	
Live insect	1.837	1.837	1.837	1.837	
Total cost ($/t)	4.483	6.577	4.189	5.328	5.144
Scenario 2: no treatment, storing until Feb 28					
Sample grade	0.000	0.000	0.000	0.000	
IDK	0.000	0.000	0.000	0.000	
Live insect	1.837	1.837	1.837	1.837	
Total cost ($/t)	1.837	1.837	1.837	1.837	1.837
Scenario 3: no treatment, storing until Dec 20					
Sample grade	0.000	0.000	0.000	0.000	
IDK	0.000	0.000	0.000	0.000	
Live insect	1.837	1.837	1.837	1.837	
Total cost ($/t)	1.837	1.837	1.837	1.837	1.837
Scenario 4: calendar-based fumigation Dec 20, storing until April 19					
Sample grade	0.000	0.000	0.000	0.000	
IDK	0.000	0.000	0.000	0.000	
Live insect	0.000	0.000	0.000	0.000	
Fumigation	0.911	0.911	0.911	0.911	
Total cost ($/t)	0.911	0.911	0.911	0.911	0.911
Scenario 5: sampling-based fumigation, storing until April 19					
Sample grade	0.000	0.000	0.000	0.000	
IDK	0.000	0.000	0.000	0.000	
Live insect	0.000	0.000	0.000	0.000	
Fumigation	0.911	0.911	0.911	0.911	
Sampling	0.345	0.345	0.345	0.345	
Total cost ($/t)	1.256	1.256	1.256	1.256	1.256
Scenario 6: sampling-based fumigation, storing until Feb 28					
Sample grade	0.000	0.000	0.000	0.000	
IDK	0.000	0.000	0.000	0.000	
Live insect	0.000	0.000	0.000	0.000	
Fumigation	0.911	0.911	0.911	0.911	
Sampling	0.345	0.345	0.345	0.345	
Total cost ($/t)	1.256	1.256	1.256	1.256	1.256
Scenario 7: sampling-based fumigation, storing until Dec 20					
Sample grade	0.000	0.000	0.000	0.000	
IDK	0.000	0.000	0.000	0.000	
Live insect	0.000	0.000	0.000	0.000	
Fumigation	0.911	0.911	0.911	0.911	
Sampling	0.345	0.345	0.345	0.345	
Total cost ($/t)	1.256	1.256	1.256	1.256	1.256

Table 7
Treatment and insect costs in four locations: low immigration rate.

	Wichita	Oklahoma city	Topeka	Dodge city	Avg.
Scenario 1: no treatment, storing until April 19					
Sample grade	0.000	0.000	0.000	0.000	
IDK	0.000	0.000	0.000	0.000	
Live insect	1.837	1.837	1.837	1.837	
Total cost ($/t)	1.837	1.837	1.837	1.837	1.837
Scenario 2: no treatment, storing until Feb 28					
Sample grade	0.000	0.000	0.000	0.000	
IDK	0.000	0.000	0.000	0.000	
Live insect	0.000	1.837	0.000	0.000	
Total cost ($/t)	0.000	1.837	0.000	0.000	0.459
Scenario 3: no treatment, storing until Dec 20					
Sample grade	0.000	0.000	0.000	0.000	
IDK	0.000	0.000	0.000	0.000	
Live insect	0.000	0.000	0.000	0.000	
Total cost ($/t)	0.000	0.000	0.000	0.000	0.000
Scenario 4: calendar-based fumigation Dec 20, storing until April 19					
Sample grade	0.000	0.000	0.000	0.000	
IDK	0.000	0.000	0.000	0.000	
Live insect	0.000	0.000	0.000	0.000	
Fumigation	0.911	0.911	0.911	0.911	
Total cost ($/t)	0.911	0.911	0.911	0.911	0.911
Scenario 5: sampling-based fumigation, storing until April 19					
Sample grade	0.000	0.000	0.000	0.000	
IDK	0.000	0.000	0.000	0.000	
Live insect	1.837	1.837	1.837	1.837	
Fumigation	0.000	0.000	0.000	0.000	
Sampling	0.345	0.345	0.345	0.345	
Total cost ($/t)	2.183	2.183	2.183	2.183	2.183
Scenario 6: sampling-based fumigation, storing until Feb 28					
Sample grade	0.00	0.00	0.00	0.00	
IDK	0.00	0.00	0.00	0.00	
Live insect	0.00	1.84	0.00	0.00	
Fumigation	0.00	0.00	0.00	0.00	
Sampling	0.345	0.345	0.345	0.345	
Total cost ($/t)	0.345	2.183	0.345	0.345	0.805
Scenario 7: sampling-based fumigation, storing until Dec 20					
Sample grade	0.000	0.000	0.000	0.000	
IDK	0.000	0.000	0.000	0.000	
Live insect	0.000	0.000	0.000	0.000	
Fumigation	0.000	0.000	0.000	0.000	
Sampling	0.345	0.345	0.345	0.345	
Total cost ($/t)	0.345	0.345	0.345	0.345	0.345

the structures (which are under the control of the elevator manager).

Some caveats should be noted, though. First, these calculations do not recognize any environmental benefits from reducing the use of insecticides, since firm managers do not currently realize those benefits (taking into account environmental benefits might increase the attractiveness of an IPM approach; for this to affect a firm's decision, though, the firm must be able to internalize gains from environmental benefits). Similarly, these calculations have not considered benefits of slowing the development of insect resistance to insecticides.

Second, these simulations have used weather information from only one year. Although different locations may effectively represent varying weather possibilities in the same location, it is likely that weather variability in a single location is less than the differences between locations represented here. Future work should incorporate weather variability into the simulation.

Third, these calculations do not take into account probabilities that insects will or will not be detected in sampling procedures. Essentially, the simulation assumes that sampling is perfect. For example, if sampling occurs on December 31, the simulation assumes that the number of insects predicted by the growth model is the number that sampling detects. Also, the simulation assumes that when the grain is sold, the number of adult insects predicted by the simulation is the number that is detected by the purchaser.

Fourth, real-world fumigations may not achieve the mortality rates assumed here. A sampling-based management program could potentially detect less effective fumigations by monitoring the grain throughout the storage period even after the grain has been fumigated, thus avoiding loss due to insect damage.

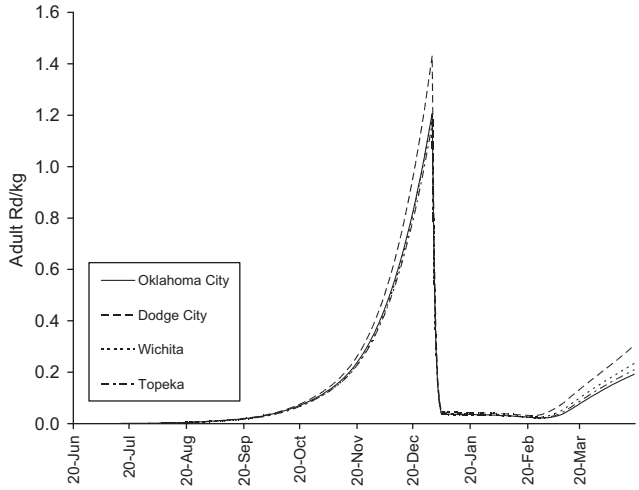

Fig. 7. Population of adult *Rhyzopertha dominica* (Rd) in four locations (Adult Rd/kg), medium immigration rate, fumigation on December 20.

Grain elevator managers in the Central and Southern Plains may hesitate to adopt a sampling-based approach to insect control if they believe they always face insect immigration rates such as the "medium" rate into all of the bins at their elevator, such as we simulated here, or weather conditions similar to those modeled here as "Oklahoma City." However, further testing is needed to determine the extent to which country elevators actually experience those immigration rates into all the bins at their elevator. Data from Flinn et al. (2010) show that many do not. If even as few as 38% of an elevator's storage bins experience low immigration rates and do not require fumigation, a sampling-based approach may be economical. Increased uncertainty in the need for pesticides – because of variations across an elevator's bins in insect
immigration rates or variations across years in weather conditions – would increase the cost effectiveness of a sampling-based approach. Similarly, reductions in sampling cost or increased cost of pesticide use would increase the attractiveness of sampling-based fumigation practices. Furthermore, elevator managers could increase the probability that sampling-based fumigation would be economical by reducing the insect immigration rate (by better sanitation practices or by sealing holes in grain bins), or by storing the grain a shorter amount of time. Sampling would help them assess the success of these efforts.

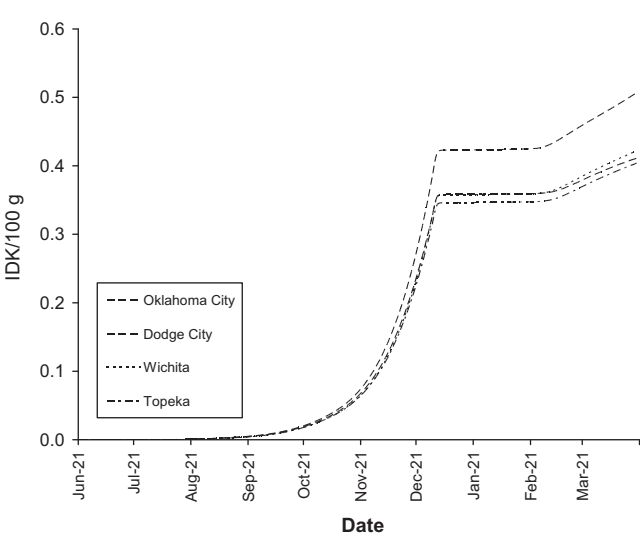

Fig. 8. Insect-damaged kernels (IDK) in four locations (IDK/100 g), medium immigration rate, fumigation on December 20.

Finally, elevator managers may wish to consider investing in automatic (conditional) aeration capabilities, retrofitting concrete facilities that currently do not have them. Use of conditional aeration would reduce the need for fumigation and potentially increase the profitability of sampling-based IPM. Work in progress is evaluating the payoff from such an investment.

Acknowledgments

The information contained in this publication was generated as part of a large-scale, long-term effort between Oklahoma State University, Purdue University, Kansas State University, and the USDA-ARS Grain Marketing & Production Research Center funded by the USDA-CSREES Risk Assessment & Mitigation Program (RAMP), Project No. S05035, entitled "Consortium for Integrated Management of Stored Product Insect Pests" (www.oznet.ksu.edu/spiramp) to investigate and develop alternative prevention, monitoring, sampling and suppression measures for organophosphate insecticides used directly on post-harvest grains that are under scrutiny as a result of the U.S. Food Quality Protection Act (FQPA) and for methyl bromide, which can only be used as a fumigant for pest control in U.S. grain processing facilities under Critical Use Exemption (CUE) as a result of the Montreal Protocol. The collaboration and participation of grain producers, handlers and processors as well as numerous equipment and service suppliers in this project across the U.S. has been greatly appreciated. The authors also benefited from discussions with members of the multi-state research project, NC-213 (The U.S. Quality Grains Research Consortium).

Comments by Phil Kenkel and anonymous reviewers are gratefully acknowledged.

References

Adam, B.D., Phillips, T.W., Flinn, P.W., 2006. The economics of IPM in stored grain: why don't more grain handlers use IPM? In: Lorini, I., Bacaltchuk, B., Beckel, H., Deckers, D., Sundfeld, E., dos Santos, J.P., Biagi, J.D., Celaro, J.C., Faroni, L.R.D'A., Bortolini, L. de O.F., Sartori, M.R., Elias, M.C., Guedes, R.N.C., da Fonseca, R.G., Scussel, V.M. (Eds.), Proceedings of the 9th International Conference on Stored-Product Protection, 15–18 October 2006, Campinas, Sao Paulo, Brazil. Brazilian Post Harvest Association, Campinas, Brazil, pp. 3–12.

Anderson, K.B., Brorsen, B.W., 2005. Marketing performance of Oklahoma farmers. American Journal of Agricultural Economics 87, 1265–1270.

Anderson, K.B., Noyes, R.T., 1989. Grain Storage Costs in Oklahoma. OSU Extension Fact Sheet AGEC-210. Division of Agricultural Sciences and Natural Resources, Oklahoma State University, Stillwater, Oklahoma.

Athie, I., Mills, K.A., 2005. Resistance to phosphine in stored-grain insect pests in Brazil. Brazilian Journal of Food Technology 8, 143–147.

Bell, C.H., 2000. Fumigation in the 21st century. Crop Protection 19, 563–569.

Benhalima, H., Chaudhry, M.Q., Mills, K.A., Price, N.R., 2004. Phosphine resistance in stored-product insects collected from various grain storage facilities in Morocco. Journal of Stored Products Research 40, 241–249.

Bridgeman, B., Ryan, R., Gock, D., Collins, P., 2000. High dose phosphine fumigation using on-site mixing. In: Donahaye, E.J., Navarro, S., Leesch, J.G. (Eds.), Proceedings of the International Conference on Controlled Atmosphere and Fumigation in Stored Products, 29 Oct.–3 Nov. 2000, Fresno, CA. Executive Printing Services, Clovis, CA, U.S.A., pp. 379–389.

Cunningham III, L.T., Brorsen, B.W., Anderson, K.B., 2007. Cash marketing styles and performance persistence. American Journal of Agricultural Economics 89, 624–636.

Cuperus, G.W., Noyes, R.T., Fargo, W.S., Clary, B.L., Arnold, D.C., Anderson, K., 1990. Successful management of a high risk stored wheat system in Oklahoma. American Entomologist 36, 129–134.

Daglish, G.J., 2004. Effect of exposure period on degree of dominance of phosphine resistance in adults of *Rhyzopertha dominica* (Coleoptera: Bostrychidae) and *Sitophilus oryzae* (Coleoptera: Curculionidae). Pest Management Science 60, 822–826.

Feder, G., 1979. Pesticides, information, and pest management under uncertainty. American Journal of Agricultural Economics 61, 97–103.

Flinn, P.W., Hagstrum, D.W., Reed, C., Phillips, T.W., 2004. Simulation model of *Rhyzopertha dominica* population dynamics in concrete grain bins. Journal of Stored Products Research 40, 39–45.

Flinn, P.W., Hagstrum, D.W., Reed, C.R., Phillips, T.W., 2007. Stored Grain Advisor Pro: decision support system for insect management in commercial grain elevators. Journal of Stored Products Research 43, 375–383.

Flinn, P.W., Hagstrum, D.W., Reed, C.R., Phillips, T.W., 2010. Insect population dynamics in commercial grain elevators. Journal of Stored Products Research 46, 43–47.

Fox, J.A., Hennessy, D.A., 1999. Cost effective hazard control in food handling. American Journal of Agricultural Economics 81, 359–372.

Hagstrum, D.W., Reed, C., Kenkel, P., 1999. Management of stored wheat insect pests in the USA. Integrated Pest Management Reviews 4, 127–142.

Kenkel, P., 2008. Grain Handling and Storage Costs in Country Elevators. The Cooperative Accountant. Winter.

Klumpp, J.M., Brorsen, B.W., Anderson, K.B., 2007. Determining returns to storage: does data aggregation matter? Journal of Agricultural and Applied Economics 39, 571–579.

Lukens, T.L., 2002. Cost and effectiveness of integrated pest management strategies compared to chemical methods in stored wheat. M.S. thesis, Oklahoma State University.

Magnusson, E., Cranfield, J.A.L., 2005. Consumer demand for pesticide free food products in Canada: a probit analysis. Canadian Journal of Agricultural Economics/Revue Canadienne d'agroeconomie 53, 67–81.

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. M.S. thesis, Oklahoma State University.

Noyes, R., 2002. Developing sustainable stored grain IPM systems in Oklahoma and Texas. Funded Proposal to Southern Region Sustainable Agriculture Research and Education.

Phillips, T., Adam, B., Cuperus, G., Danley, R., Kenkel, P., Lukens, T., Maier, D., Mason, L., Noyes, R., 2002. Integrated pest management for grain elevators that supply the breakfast cereal industry: case studies and economic analysis. A report to the Grocery Manufacturers of America and the National Foundation for IPM Education.

Pimentel, M.A.G., D'A Faroni, L.R., Totola, M.R., Guedes, R.N.C., 2007. Phosphine resistance, respiration rate and fitness consequences in stored-product insects. Pest Management Science 63, 876–881.

Ramaswamy, S., Phillips, T., Subramanyam, Bh., Arthur, F., Maier, D., 2000. Consortium for integrated management of stored product insect pests. A funded proposal to the U.S. Environmental Protection Agency.

Schnake, L.D., Stevens, J., 1983. Inland grain elevator operating costs and capital requirements. Kansas Agricultural Experiment Station Bulletin 83-219-B:32.

Senauer, B., Asp, E., Kinsey, J., 1991. Food Trends and the Changing Consumer. Eagan Press, St. Paul, MN.

Yigezu, Y.A., Alexander, C.E., Preckel, P.V., Maier, D.E., Woloshuk, C.P., Mason, L.J., Lawrence, J., Moog, D.J., 2008. Optimal mold management in stored corn. Agricultural Systems 92, 220–227.

Zettler, L., Beeman, R., 1995. Resistance to chemicals. In: Stored Product Management. Oklahoma State University Cooperative Extension Service Circular Number E-912, pp. 163–166.

Zettler, L., Cuperus, G., 1990. Pesticide resistance in *Tribolium castaneum* and *Rhyzopertha dominica* in wheat. Journal of Economic Entomology 83, 1677–1681.