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Stored Grain Advisor Pro: Decision support system for insect management in commercial grain elevators ☆

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Abstract

A decision support system, Stored Grain Advisor Pro (SGA Pro) was developed to provide insect pest management information for wheat stored at commercial elevators. The program uses a model to predict future risk based on current insect density, grain temperature and moisture. A rule-based system was used to provide advice and recommendations to grain managers. The software was tested in a research program conducted at commercial grain elevators in Kansas and Oklahoma, USA. A vacuum-probe sampler was used to take ten 3-kg grain samples in the top 12 m of each bin that contained wheat. After the insect species and numbers were determined for each sample, the data were entered into SGA Pro. A risk analysis and treatment recommendation report for all bins was presented to the grain managers every 6 weeks. SGA Pro correctly predicted for 71–80% of bins whether the grain was safe or at high risk of dense infestation and grain damage. SGA Pro failed to predict "unsafe" insect densities in only 2 out of 399 Kansas bins (0.5%) and in none of 114 bins in Oklahoma. Grain managers who followed SGA Pro's recommendations tended to fumigate only the bins with high insect densities instead of fumigating all bins at their facility. This resulted in more efficient insect pest management because fumigating bins only when insect densities exceeded economic thresholds and treating only the bins that required fumigation minimized the risk of economic losses from insects, reduced the cost of pest management, and reduced the use of grain fumigant.
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Keywords: *Rhyzopertha dominica*; *Cryptolestes ferrugineus*; Decision support system; Model; Integrated pest management; Stored grain; Area-wide

1. Introduction

Most cereal grain produced in the USA is stored in commercial facilities known locally as grain elevators. Major insect pests of stored wheat in the USA include *Rhyzopertha dominica* (F.), *Sitophilus oryzae* (L.), *Cryptolestes ferrugineus* (Stephens), *Tribolium castaneum* (Herbst), and *Oryzaephilus surinamensis* (L.). The first two species cause the most grain damage because the immature stages develop inside the grain kernels. These internal feeding insects are a major cause of insect contamination in wheat flour because the immature stages and pre-emergent adults cannot be completely removed from the wheat before it is milled. Grain managers and regulators use the number of insect-damaged kernels (IDK) in wheat as an indirect measure of the density of internally-infested kernels. If more than 32 IDK are found per 100 g of wheat, the grain is classified as "sample grade" and unfit for human consumption (Hagstrum and Subramanyam, 2006). At most domestic flour mills, the wheat purchasing specifications include a maximum IDK count of either 3 or 5/100 g. *Cryptolestes ferrugineus* is a very common insect pest that often reaches high densities near the grain surface. Young larvae of this species frequently feed on the germ of whole kernels and on fine material in the grain (Rilett, 1949). They leave the germ before becoming adults and do not cause IDK. Nevertheless, grain infested with this species is likely to receive a lower price than uninfested grain.

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Typically, control of stored-grain insects in grain elevators in the USA includes monitoring of grain temperature and calendar-based fumigations using phosphine fumigant (Hagstrum et al., 1999). This approach often fails to distinguish between bins with high and low insect densities and does not optimize the timing of the fumigation treatment. Therefore, grain may be unnecessarily fumigated, or the fumigation may not be timed to prevent high insect populations and grain damage from occurring. Although careful monitoring of grain temperature often alerts the manager to potential mold and insect problems (Reed, 2006), large populations of insects or severe mold problems can develop before a temperature increase is noted.

In contrast to traditional insect control practices currently used for most stored grain, the integrated pest management (IPM) approach uses sampling to determine if insects have exceeded an economic threshold (Hagstrum and Flinn, 1992). Adapting IPM principles to insect control in a grain elevator is complicated by the structure and operation of the facility. A large elevator may have over 100 bins, and the bins may contain different types of grain, stored for different durations. The grain temperature and moisture often vary greatly between bins, which affects the rate at which insects and molds grow and damage the grain.

To facilitate the development and implementation of IPM practices in stored grain in the USA, the USDA's Agricultural Research Service recently funded a 5-year demonstration project for area-wide IPM for stored wheat in Kansas and Oklahoma (Flinn et al., 2003). This project was undertaken by a collaboration of researchers at the Agricultural Research Service (Manhattan, Kansas), Kansas State University (Manhattan, Kansas), and Oklahoma State University (Stillwater, Oklahoma). We used two elevator networks, one in each state, for a total of 28 grain elevators. One of the project goals was the development of a decision support system for insect pest management for grain stored in commercial elevators.

A validated insect population growth model was previously developed for *R. dominica* in concrete elevator storage (Flinn et al., 2004). This model was used in a decision support system to make management recommendations based on current insect density, grain temperature and grain moisture. A decision support system (Stored Grain Advisor) was developed previously for farm-stored grain in the USA (Flinn and Hagstrum, 1990b). However, that software was not suitable for large commercial elevators because the grain sampling methods and recommendations were specific for farm-stored grain.

Decision support systems for stored grain have been developed in several countries. In Canada, CanStore, was developed to assist farmers in stored grain management (www.res2.agr.ca/winnipeg/storage/pages/cnstr_e.htm). In Australia, Pestman ranks insect pest management recommendations by their cost and provides a graphical site plan that allow a manager to quickly find information about any bin (Longstaff, 1997). In the UK, Integrated Grain Storage Manager (Knight et al., 1999) is a new version of Grain Pest Advisor (Wilkin and Mumford, 1994) that was developed with input from farmers and storekeepers to better suit their needs. Grain Management Expert System (Zonglin et al., 1999), was developed from Pestman for use in China. QualiGrain is an expert system for maintaining the quality of stored malting barley (Ndiaye et al., 2003; Knight and Wilkin, 2004).

None of the previously mentioned systems fit the requirements of the USA commercial grain storage system. We needed a management program that was based on intensive grain sampling for insect pests in each elevator bin (at least ten 3-kg grain samples per bin to a depth of 12 m). In addition, the system needed to be able to predict insect population growth for up to 3 months, based on current insect density in the bin, grain temperature, and grain moisture. In this paper, we describe the validation of a decision support system that was developed as part of an area-wide IPM demonstration project. The decision support system uses current and predicted insect density estimates to provide grain managers with an overall risk analysis for the grain at their facility and recommended treatment options.

2. Materials and methods

2.1. Grain sampling

An area-wide IPM program for grain elevators was started in 1998. Investigators collected data from two elevator networks in south-central Kansas and central Oklahoma. Each network consisted of at least 10 rural elevators and at least one terminal elevator. The rural elevators typically receive grain from farmers and store it for a shorter period of time compared to the terminal elevators, where most grain is received from rural elevators. Storage bins at these elevators were either upright concrete bins, typically 6–9 m in diameter and 30–35 m tall, or metal bins that are shorter and wider. Maize and other grains were stored in the project elevators, but only the wheat was sampled during this project.

Various sampling methods to estimate insect density in upright concrete grain bins were tested: probe traps placed at the grain surface, samples taken as the grain was moved on transport belts, and samples taken from grain discharged from the bins onto a stationary transport belt. Samples taken with a vacuum probe as the grain was at rest in the storage bins provided the best estimate of insect density. Data collected with the vacuum probe were highly correlated with grain samples taken as the bin was unloaded ($r^2 = 0.79$, $N = 16$, $P = 0.001$). In addition, unlike the other sampling methods, the power probe allowed the grain to be sampled at any time, and it provided a vertical profile of the insect distribution for each bin. We used a Port-A-Probe (Grain Value Systems, Shawnee Mission, Kansas), which consists of a vacuum

pump powered by a 5.3 KW gasoline engine connected by flexible plastic tubing to sections of rigid aluminum tubes 1.2 m long by 3.5 cm wide. The probe was inserted vertically into the grain and a 3.9 l (about 3 kg) sample of wheat was taken during every 1.2 m transect of grain to a depth of 12 m. In the concrete upright bins, the grain was sampled through the entry port. In metal bins, the probe was inserted at 3–5 locations across the surface. Grain samples were extracted from the grain mass by suction and collected in a cyclone funnel.

Samples were processed twice over an inclined sieve (89 × 43 cm, 1.6 mm aperture) (Hagstrum, 1989) to separate insects from the wheat. Material that passed through the screen was collected on a pan below the screen, which then slid into a funnel at the bottom of the pan. A resealable plastic bag was attached to the funnel to collect the material that was separated from the grain sample. A hopper above the screen held the grain sample and a funnel at the base of the screen directed material passing over the screen into a plastic bucket. The sieve was inclined 24° from horizontal and the opening of the hopper was adjusted such that the sample passed over the screen in about 25 s. Each sample was passed over the sieve two times. Validation data for SGA Pro were selected from bins that were sampled at least twice, starting in autumn, in which the wheat was not moved or fumigated. In a typical bin (6–9 m wide and 30–35 m tall), the sampling rate for vacuum probe samples was 0.07–0.13 kg/t of grain sampled. In most cases, only the grain in the top 12 m of the bin was sampled.

2.2. Decision support software

The Stored Grain Advisor Pro (SGA Pro) software was initially developed using Microsoft Access. The program was then modified and re-written using Visual Basic 6.0. We designed a graphical user interface that provides a bin diagram for each elevator location (Fig. 1). Data were entered using three data-entry forms: insects, grain quality, and grain temperature. Data entered in the insect form were: sample type (bottom, moving sample, probe trap, or vacuum sample) and the number of insects found in each sample for five primary stored-grain insects (*Cryptolestes* spp., *R. dominica*, *O. surinamensis*, *Sitophilus* spp., and *Tribolium* spp.) (Fig. 2). Data entered for grain quality were: grade, % dockage, test weight, moisture, foreign material, % shrunken or broken kernels, insect damaged kernels, % protein (Fig. 3). Grain temperature data were also entered into the database for each bin (data entry is similar to the grain quality form and is not shown here). Most elevator bins were equipped with one or more cables containing up to 20 thermocouple-type sensors per cable. In bins not equipped with temperature sensors, investigators inserted temporary probes to collect information on grain temperature.

The SGA Pro system will recommend either fumigation, aeration, or waiting until the next sampling period based on current insect density in the bin, grain temperature, aeration capability, time of year, and predicted insect density in 1, 2, and 3 months. For example,

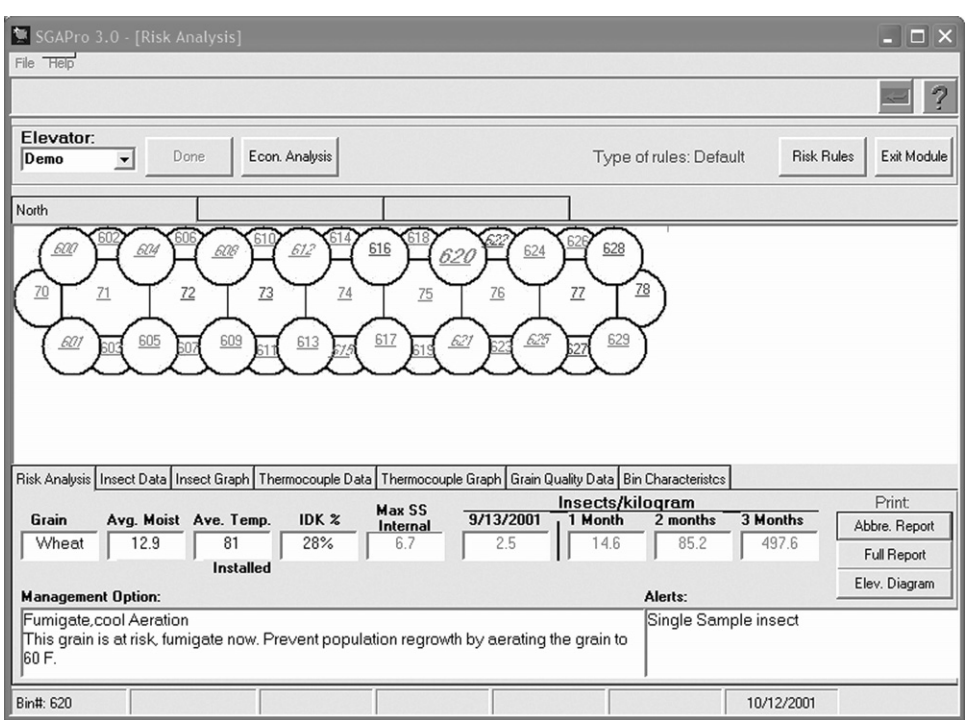
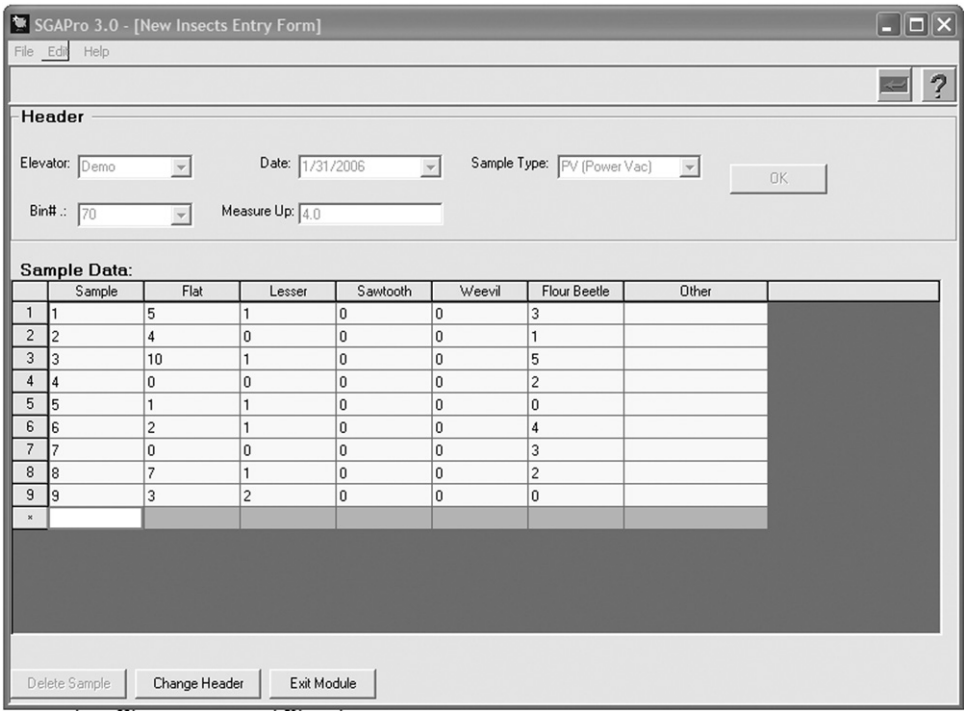
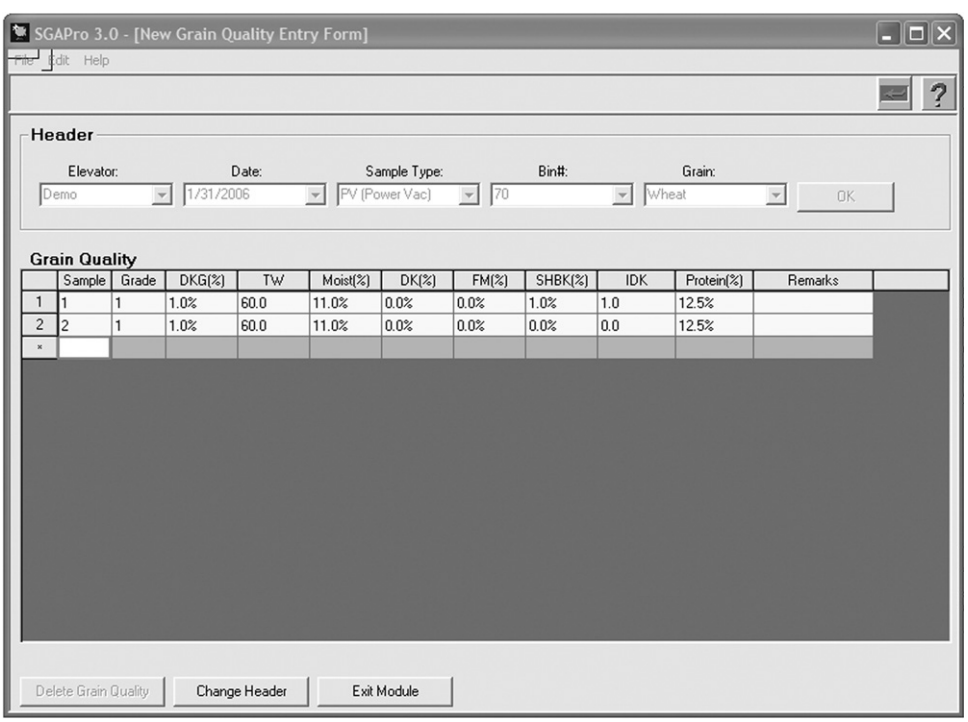


Fig. 1. Elevator bin diagram from Stored Grain Advisor Pro; on the computer screen, bins of grain at high, moderate, and low risk for insect problems are shown in red, blue and green, respectively. In this figure, bin numbers that are light grey are at low risk, bins 615, 620 and 621 are at high risk, and the rest are at moderate risk. Bin 620 is currently selected (using the mouse), and the information for this bin is shown in the bottom half of the screen.



	Sample	Flat	Lesser	Sawtooth	Weevil	Flour Beetle	Other
1	1	5	1	0	0	3	
2	2	4	0	0	0	1	
3	3	10	1	0	0	5	
4	4	0	0	0	0	2	
5	5	1	1	0	0	0	
6	6	2	1	0	0	4	
7	7	0	0	0	0	3	
8	8	7	1	0	0	2	
9	9	3	2	0	0	0	

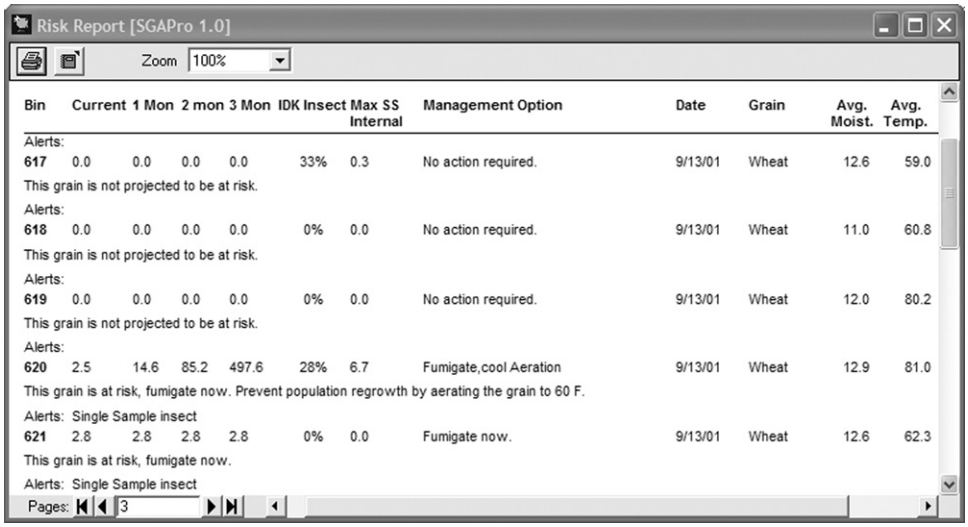
Fig. 2. Insect data entry form for Stored Grain Advisor Pro. The number of insects for each 3-kg sample were entered into the form. For simplicity, common names are used for the insect species (flat = *Cryptolestes* spp., lesser = *R. dominica*, sawtooth = *O. surinamensis*, weevil = *Sitophilus* spp., flour beetle = *Tribolium* spp.).



	Sample	Grade	DKG(%)	TW	Moist(%)	DK(%)	FM(%)	SHBK(%)	IDK	Protein(%)	Remarks
1	1	1	1.0%	60.0	11.0%	0.0%	0.0%	1.0%	1.0	12.5%	
2	2	1	1.0%	60.0	11.0%	0.0%	0.0%	0.0%	0.0	12.5%	

Fig. 3. Grain quality data entry form for Stored Grain Advisor Pro (grade = grain grade, DKG(%) = % dockage, TW = test weight, moist(%) = % grain moisture, DK(%) = % damaged kernels, FM(%) = % foreign material, SHBK(%) = % shrunken or broken kernels, IDK = number of insect damaged kernels per 100 g, protein(%) = % protein).

for bin 620 (Fig. 4), the program indicated that the current insect density was 2.5 kg^{-1} and predicted a density of 14.6 insects/kg in 1 month. Twenty-eight percent of the insects from the samples were species that caused IDK, so SGA Pro recommended fumigation followed by aeration to cool the grain.


Risk Report [SGAPro 1.0]

Zoom 100%

Bin	Current	1 Mon	2 mon	3 Mon	IDK Insect	Max SS Internal	Management Option	Date	Grain	Avg. Moist.	Avg. Temp.
Alerts:											
617	0.0	0.0	0.0	0.0	33%	0.3	No action required.	9/13/01	Wheat	12.6	59.0
This grain is not projected to be at risk.											
Alerts:											
618	0.0	0.0	0.0	0.0	0%	0.0	No action required.	9/13/01	Wheat	11.0	60.8
This grain is not projected to be at risk.											
Alerts:											
619	0.0	0.0	0.0	0.0	0%	0.0	No action required.	9/13/01	Wheat	12.0	80.2
This grain is not projected to be at risk.											
Alerts:											
620	2.5	14.6	85.2	497.6	28%	6.7	Fumigate,cool Aeration	9/13/01	Wheat	12.9	81.0
This grain is at risk, fumigate now. Prevent population regrowth by aerating the grain to 60 F.											
Alerts: Single Sample insect											
621	2.8	2.8	2.8	2.8	0%	0.0	Fumigate now.	9/13/01	Wheat	12.6	62.3
This grain is at risk, fumigate now.											
Alerts: Single Sample insect											

Pages: 3

Fig. 4. Stored Grain Advisor recommendation report. The report shows alerts for five elevator bins (Current = average insects per kg grain, 1 Mon = predicted insect density in 1 month, 2 Mon = predicted insect density in 2 months, IDK insect = % of the insects in the sample that cause IDK, Max SS internal = highest number of internal insects in any single sample, and management option = recommended actions for the elevator manager).

An equation was developed to predict insect population growth based on current insect density, grain temperature and moisture by running simulations for a model of *R. dominica* (Flinn and Hagstrum, 1990a), over temperatures from 21.5 to 33.5 °C and moistures from 9.5 to 13.5%. Tablecurve 3D version 3 (SPSS, 1997) was used to fit an equation to the model-generated data, where Z is the rate of increase over 30 days, X is temperature, and Y is moisture:

$$Z = (9.2004 - 1.6898X + 0.0787^2 - 0.0011X^2 + 0.1841Y)/(1 - 0.0197X - 0.0161Y). \quad (1.0)$$

This equation fitted the data well ($R^2 = 0.98$, $N = 25$). Because we needed to predict only 1–3 months ahead, this equation was adequate for quickly estimating future populations for many bins present in the database (often more than 100). Although *C. ferrugineus* was often the most numerous species during the first month of storage, we based Eq. (1.0) on *R. dominica* because it is the more damaging species, it was more common than *C. ferrugineus* later in the season, and the predicted rates of increase for both species were fairly similar (Hagstrum and Flinn, 1990). We did not use a model for *S. oryza*e because this species was found in about 1% of the wheat samples, whereas, *R. dominica* was found in approximately 60% of the samples.

SGA Pro used a rule-based algorithm to determine whether bins were safe, moderate, or at high risk of having insect densities that exceed certain thresholds, based on the current and predicted insect density, grain temperature, and grain moisture. Insect economic thresholds can be adjusted by the user (Fig. 5). In addition, alerts can also be set for: high grain moisture, high thermocouple readings, and high numbers of internally feeding insects in an individual sample.

SGA Pro was tested during the final 2 years of the area-wide IPM study. Bins at each elevator were sampled at approximately 6-week intervals, data were entered into SGA Pro, and the report recommendations were shown to the elevator managers. SGA Pro was validated by comparing predicted insect densities and control recommendations with actual insect densities in the same bins 6 weeks later. Validation data came from bins in which the grain had not been turned or fumigated for at least two sampling periods.

3. Results

In the Kansas data set from 2002, SGA Pro correctly predicted that bins were "safe" or at "high risk" in 285 out of 399 cases (Table 1). Forty-seven of the 399 bins required fumigation. SGA Pro failed to predict "unsafe" insect densities in only two bins (0.5%), and the insects in these isolated instances were mostly near the surface, suggesting recent immigration. The simple growth model used by SGA Pro tended to overestimate insect densities in bins that were at medium risk (112 out of 399 bins). All of the bins that the software predicted to be at high risk contained insect densities greater than the threshold at the next sampling period. In Oklahoma, SGA Pro correctly predicted bins that were "safe" or at "high risk" in 107 out of 133 total bins. Forty-five of the 133 bins needed to be fumigated. All of the bins that the program determined as being "safe" turned out to have insect densities below the threshold of 2 insects/kg 6 weeks later. As in Kansas, SGA Pro tended to overestimate insect densities in bins that were at medium risk (26 out of 131 bins).

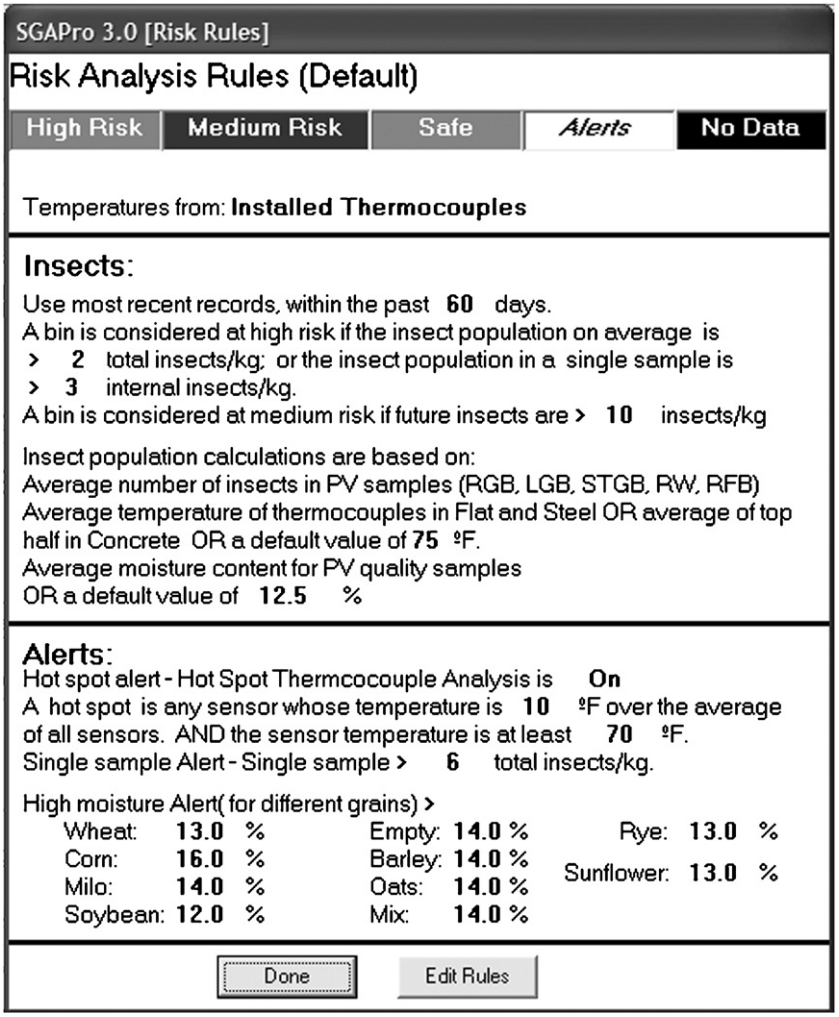


Fig. 5. Economic thresholds used by Stored Grain Advisor Pro are adjustable by the user. In addition to settings thresholds for average and single sample insect counts, alerts can also be set for temperature hotspots or high-moisture grain samples.

Table 1
Number of correct predictions by Stored Grain Advisor Pro, and type A and B errors for elevator bins in Kansas and Oklahoma

Location	Total	Correct		Type A[a]		Type B[b]	
	N	*N*	%	*N*	%	*N*	%
Kansas	399	285	71.4	2	0.5	112	28.1
Oklahoma	133	107	80.5	0	0.0	26	19.5

[a]Type A errors: software predicts "safe" (< 2 insects/kg) and actual density in 6 weeks was >2 insects/kg of wheat.
[b]Type B errors: software predicts "medium risk" (>10 insects/kg) and actual density in 6 weeks was less than 10 insects/kg of wheat.

4. Discussion

Compared to other decision support systems for large commercial grain stores, SGA Pro is the first that uses intensive sampling of the grain to determine if insect densities exceed economic thresholds. In countries where this type of software has been developed, for example UK, Australia, and Canada, the grain trade operates on a "zero tolerance" for insects in stored grain. This makes it difficult to implement economic thresholds for insect pests. SGA Pro is also the first decision support system for commercial grain storage that has been field validated, certainly to the extent presented here. Integrated Grain Storage Manager (Knight et al., 1999) was revised with input from store keepers (a type of validation), and Grain Storage Information System (Mann et al., 1997) was verified by several experts.

We demonstrated that the use of SGA Pro resulted in a low type A error (SGA Pro predicts < 2 insects/kg, and actual density in 6 weeks is > 2 insects/kg of wheat), but a rather moderate type B error (SGA Pro predicts > 10 insects/kg, and actual density in 6 weeks is < 10 insects/kg). A low type A error and moderate type B error translates in practice to a low probability of grain deterioration. Although unnecessary expenditure on grain fumigation occurs from time to time, the cost of such errors is minimal. Experience with companies that adopt a data-based decision model has shown that the

"unnecessary" grain turning may have a hidden benefit. Grain managers, because they are conditioned to turn and fumigate wheat at a certain time of year, seem to feel more secure using the new approach if it recommends some "insurance" grain turning. They are therefore more likely to adopt the new approach compared to a program that recommends little or no turning and fumigation for long periods of time.

SGA Pro provides a comparison of the cost of fumigating grain in all bins vs. sampling in all bins and fumigating only grain with high insect densities (Fig. 6). For example, fumigating all 33 bins at an elevator storing 17,600 tonnes (646,698 bushels) of wheat could cost $5220 USD (electrical costs for turning per bushel = $0.0033 USD, phosphine fumigant = $0.002 per bushel, loss in wheat volume = $0.0028 per bushel). However, if the elevator manager knows that only eight of these bins have high insect densities, fumigating only these eight bins plus the cost of sampling ($0.00205 USD per bushel) all 33 bins is $3,053 USD for a savings of $2,167 USD.

SGA Pro software is freely available to the public at the Grain Marketing and Production Research Center web site (www.ars.usda.gov/npa/gmprc/bru/sga). Learning to use the software is fairly easy; however, using the sampling equipment and identifying the insects does require some training.

A private company is using SGA Pro with the sampling methods developed in this project, and has provided scouting services to more than 70 elevators in Kansas, Oklahoma, and Nebraska. Industry response to the availability of grain scouting services for IPM in stored grain appears to parallel that of farmers' initial responses to crop consultants that first offered IPM services for production agriculture. Most grain managers resist the change to data-based decision making. A few early adopters of grain scouting, those who appeared to be open to the increased use of computer technology in grain management, have embraced the entire information-based decision-making concept. Several managers perceived value in parts or components of the services offered by the grain scouting company. For example, several of the company's clientele initially purchased only the services that had obvious benefits to the grain merchandiser, such as the wheat protein data generated by vacuum probe sampling. Over time, these users began to perceive the potential benefits of the insect scouting service.

To quantify the effect of the information-based approach to insect pest management, the incidence and density of insect-damaged wheat kernels in samples collected in the autumn of 2003, the first year of the scouting company's operation, were compared with samples collected during the same time period 1 year later.

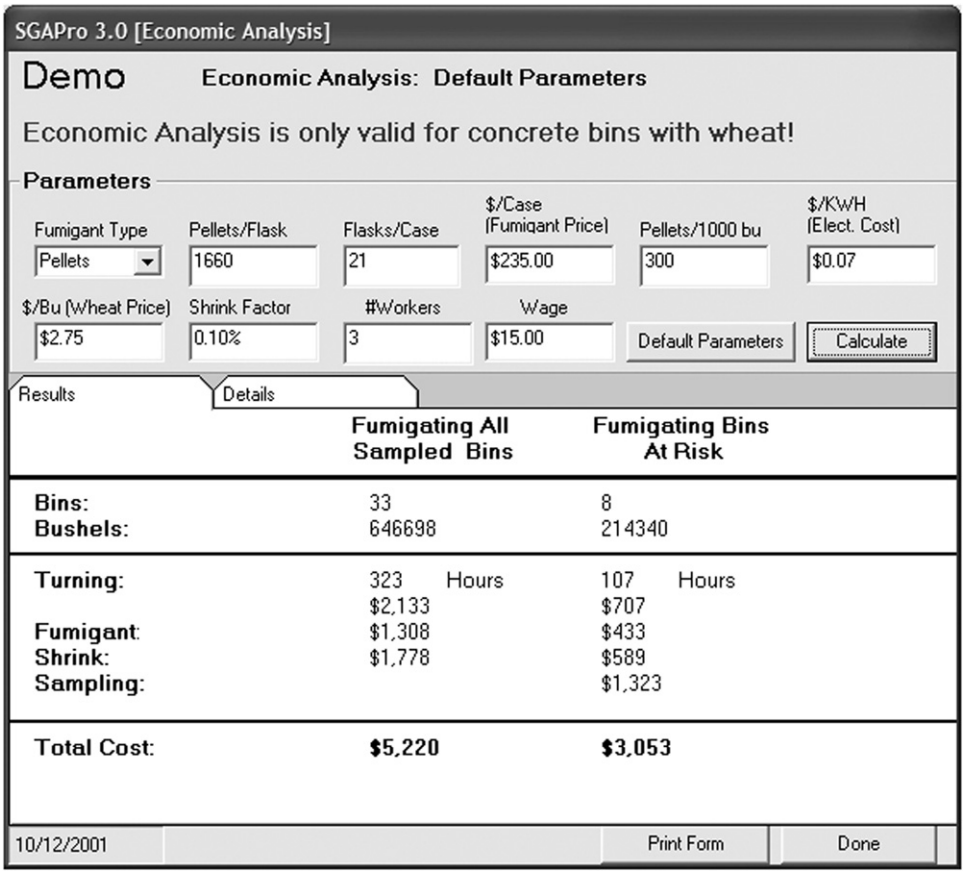


Fig. 6. Economic analysis calculated by Stored Grain Advisor Pro. Users can change costs for electricity, fumigant, wheat price, shrink factor (height of grain lost by turning and fumigating grain), and sampling.

Data from four elevators were used in this analysis, providing 2132 data points. The frequency of samples with a high density (>10/100 g) of kernel damage was reduced by 24% (chi square = 34.8, $P \leqslant 0.01$), and the mean density of kernel damage (2.5/100 g vs. 1.9/100 g) was significantly different ($P \leqslant 0.05$).

A case study that illustrates the value of the IPM approach used by SGA Pro was created accidentally when a scouting report was not relayed to a grain manager. Twenty-four bins of wheat were scouted at an elevator that was manned only part of the year. The manager was away during the scouting and was unaware of the scouting report. When the manager returned, he began treating the grain based on his traditional approach. When the scouting company's crew returned 6 weeks later to conduct routine re-sampling, seven bins had been turned and fumigated. Based on vacuum probe sampling, the tradition-based decisions were "correct" in three of the seven bins; that is, the grain that was fumigated did, in fact, require fumigation. In two cases, grain containing too few insects to warrant fumigation was treated. For two of the fumigated bins, the data were inconclusive regarding the validity of the traditional approach. Of the 17 bins that had not been fumigated, the previous scouting report had recommended "no action until further sampling" in 10 bins. In three of these bins, insect densities had increased in the intervening period such that fumigation was warranted and would be more effective than if it had been done prematurely, but no significant grain damage occurred. In all grain for which SGA Pro recommended no action, no grain damage had occurred in 6 weeks. In the remainder (7) of the 17 untreated bins, the previous report by SGA Pro had recommended immediate fumigation. In six of seven, the second sampling showed insect populations exceeding acceptable levels, and grain damage had occurred because fumigation had not been done when recommended. In one bin, insect numbers had not increased significantly and no significant grain damage had occurred. The results of this case study closely parallel those of the analysis described above from data taken during the research project. That is, SGA Pro recommended immediate action in all cases where it was needed but slightly over-estimated the number of grain lots requiring fumigation in 6 weeks.

Investigators recognized that area-wide IPM will be adopted by grain elevator managers only if it is more effective and profitable than the traditional approach, and if it fits into their current marketing and grain management practices. We tried to determine how elevator managers might use insect-monitoring information to manage insect problems in their grain bins. The findings of the area-wide IPM project have been communicated to managers through nine newsletters, at training programs in Kansas, Oklahoma, Nebraska, and Minnesota, and at two recent International Grain Elevator and Processing Society (GEAPS) annual meetings. Information gathered in this study was used to develop extension publications for stored-grain integrated pest management.

The sampling routines and decision support software that we developed have several advantages over calendar-based fumigation. Treating bins only when insect densities exceed economic thresholds and treating only the bins that need to be treated minimizes the risk of economic losses from unexpected insect problems, reduces the cost of pest management, and reduces the use of fumigant. Minimizing the use of fumigant improves worker safety by reducing exposure to phosphine, and reduces the probability that insect populations will develop resistance to phosphine.

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