Abstract. Management of insect pests of stored wheat is complex and involves many interacting factors, such as grain temperature and moisture, insecticide degradation, aeration, and fumigation. Determining whether or not insects will become a problem in stored grain is primarily a problem of predicting population increase under existing environmental conditions. We have developed computer models for all five of the major insect pests of stored wheat. These models predict insect population growth, as well as the degradation of insecticides and the effects of fumigating or aerating the grain in relation to storage temperature and moisture. Results from model simulations were incorporated into the rule base of the stored grain advisor (SGA) expert system. The SGA helps the manager identify insects or other problems, predicts the likelihood of insect infestation, and helps select the most appropriate prophylactic or remedial actions.

The SGA was developed on Apple Macintosh computers using the BruceShell (Pennsylvania State University). This is a frame-based shell that is used in conjunction with a C-language compiler. The shell has a graphic user interface, backward and forward chaining, explanation and help capabilities. The SGA also runs on MS-DOS compatible computers. This expert system should be valuable to producers, elevator operators, extension specialists, and others concerned with grain storage, and should greatly enhance our ability to store grain safely.

Stored Grain Advisor: A Knowledge-Based System for Management of Insect Pests of Stored Grain

Paul W. Flinn and David W. Hagstrum
U.S. Grain Marketing Research Laboratory
Agricultural Research Service
U.S. Department of Agriculture
Manhattan, Kansas 66502

Wheat is grown in 42 of the 50 states in the U.S. However 95 percent of the crop is grown in only 20 states. Harvest begins in mid-May in the south and lasts until mid-September in the most northerly states. Insects initially begin to migrate into wheat soon after it is stored on farm (Hagstrum 1989). The probability of insect populations reaching levels requiring control is directly related to grain moisture, temperature, and storage time (Hagstrum 1987, Hagstrum and Throne 1989). Four control practices account for a large percentage of insect pest management (Cuperus et al. 1990, Havein et al. 1985, Reed and Pederson 1987, Storey et al. 1984). Cleaning and insecticide treatment of bins prior to storing grain is the most widely used method. Fumigation is the next most popular method, but does not prevent reinfestation. Aeration has been less popular than fumigation largely because it has only been recommended in the fall. Recent studies by Hamer and Hagstrum (1990) suggest that judicious use of aeration can substantially reduce insect population growth. Finally, insecticides are frequently applied to wheat. However, unnecessary applications are often made because protectants must be applied at the time of storage.

Grain discounting policies at county elevators are highly variable (Reed et al. 1989). Thus, it is difficult to establish economic injury levels for infested grain. Often the additional costs of pest management are not justified due to inconsistent penalties that are often less than the cost of control measures (Barak and Harein 1981, Reed et al. 1989). However, two recent government acts have increased the risk of grain storage: the Clean Grain Act of 1986 and the
removal of the commonly used fumigant, ethylene dibromide, from the market by the Environmental Protection Agency. In addition, there is increased pressure from the milling industry for stricter regulations concerning wheat quality. This pressure should translate into more careful sampling of grain by elevator managers.

At present, extension manuals provide the primary source of information for grain managers in the U.S. While extension manuals and expert systems both provide advice on the four major control methods, the expert system described in this paper, the stored grain advisor (SGA), provides a much more quantitative interpretation of future insect population levels and the consequences of various management programs. The expert system has the added advantage of specifically tailoring the advice to the user's storage conditions.

Methods

The BruceShell (Pennsylvania State University) was selected for development and delivery of SGA. This is a frame-based shell that is used in conjunction with a C-language compiler (Think C or Turbo C). Development was done primarily on an Apple Macintosh computer. However, the expert system also runs on MS-DOS compatible computers. The shell has a graphic user interface, backward and forward chaining, explanation, and help capabilities. The graphics were created using an image scanner, Lightning Scan. Canvas was used to edit the images and to add text. The Apple utility ResEdit was used to store the images in a resource file where they can be called by the expert system. Currently, there is one main module, "insects," in SGA. Submodules of the insects module include management, identify, sampling, and fumigation.

Management. Determining whether or not insects will reach economic densities in stored grain is primarily a problem of predicting population increase under existing environmental conditions. The stored grain system is complex and involves multiple, dynamic interactions. For example, insect population growth is a function of time, grain temperature, and moisture. Other management factors, such as aeration, natural cooling, concentration of insecticide in the grain, and fumigation, also affect insect population growth. Human experts are unable to accurately forecast the quantitative effects that these variables will have on insects in stored grain. Thus, we turned to simulation modeling to give us the forecasting ability that was required for the SGA expert system.

Some expert systems have been developed that include simulation models. There are, however, certain drawbacks to this approach, the foremost of which is the time required to run a simulation. It takes approximately six to 12 minutes to run a simulation for one insect species with our model. Multiple species are usually present, and multiple management scenarios need to be investigated. This results in an expert system that is unattractive to the user because of the inordinate amount of time required to diagnose a problem and make a recommendation. To solve this problem, we used the models as a source of expertise to develop rules for the expert system. This allows the expert system to provide answers within a matter of seconds and also provides explanations for a particular diagnosis or recommendation. Validated models are available that accurately describe population growth for five of the most important insect pests of stored wheat, as a function of time, grain temperature and moisture (Hagstrum and Throne 1989, Flinn and Hagsstrum 1990, Hagsstrum and Flinn 1990). SGA differs from most expert systems in that the majority of the rules were derived from several hundred simulations conducted with sophisticated computer models of insect population growth. In addition, the models predict the effects of various management actions such as fumigation, aeration (cooling the grain with fans), and protectants (insecticides applied to the grain during bin filling) on insect populations (Flinn and Hagsstrum 1990). They can also predict the breakdown of insecticide in the grain as a function of time, temperature, and moisture, and the effects of insecticide concentration on insect survivorship. Thus, these models represent very powerful tools for forecasting if or when insects are likely to become a problem and the effects of management actions on the population.

The two most common insect species that are economically important in U.S. granaries were selected for running the simulations: the lesser grain borer, *Rhizopertha dominica*, and the rusty grain beetle, *Cryptolestes ferrugineus*. The results of these simulations are described in Flinn and Hagsstrum (1990) and Hagsstrum and Flinn (1990). They categorized the range of initial storage conditions into six possible combinations of temperature and moisture. In the simulations, grain could be treated with a protectant or aerated or both. The length of time that the grain is stored above 60°F, before it is either aerated in the fall or cools naturally, is a critical variable that affects population growth potential and it varies considerably between grain-growing regions of the U.S. For example, grain is usually harvested in June in Oklahoma, but in South Dakota grain is normally harvested in August. Three storage dates, June 1, July 1, and August 1, were used to simulate wheat storage in the southern, middle, and northern growing regions of the U.S.

The results of over 500 simulations were then translated into 54 rules that are contained within the
"insect" frame. We were able to reduce the number of rules in the expert system by combining rules whenever storage durations were within five days and the rules varied by only one other variable (an "or" could then be used to add the additional variable). Figure 1 shows the "and/or" diagram for one possible recommendation. The storage duration required for insect numbers to exceed set thresholds, under certain management conditions, were used to write the rules. The rules were generated by examining graphs of predicted insect density vs. time. Low, moderate, and high potentials for insect infestation were assigned if the predicted number of insects was less than one adult/bu, one to 100 adults/bu, and greater than 100 adults/bu, respectively. These thresholds came from interviews with three stored-grain experts. If a high probability of infestation is indicated, the manager is advised of several options: aerate if possible, consider selling the grain early, sample the grain for insects. If insect thresholds are exceeded, then fumigate if the grain temperature is above 60°F. If a moderate probability of infestation is diagnosed, the manager is advised that he or she should sample the grain for insects about 60 days after storage to see if treatment is needed. The manager also has the option of selling the grain earlier than planned. If a low probability of infestation is diagnosed, then the manager is advised that the grain will probably be safe and that it is unnecessary to sample the grain for insects unless the manager decides to sell the grain at a later date than planned.

If the manager has sampled the grain for insects, then the recommendation does not depend upon the insect frame. Instead, the management recommendation is based on the states of three other frames: insect-pest, time-vulnerable, and fumigate (Fig. 2a-d). The thresholds for the frame "insect pest" were the same as those previously described. The rules for the "time-vulnerable" frame came from an examination of the simulation results for reinestation of

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**Recommendation**

This bin has a high probability for infestation.

1) Sample the bin using traps or grain trier 60 days after the grain was stored to be sure you do not have an insect problem

2) Aerate the grain in early Oct. if you plan to hold the grain past the end of Oct. This may save you having to fumigate this bin.

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**Figure 1. An example of a recommendation given in the "management" submodule in the stored grain advisor in which the user has not yet sampled the grain for insects. In this case, "insect" is high and the user does not plan to aerate, but aeration equipment is available.**
Recommendation: you have caught enough primary insect pests to warrant fumigation. We advise:
1) Fumigating the grain as soon as possible.
2) Selling the grain either before or by the planned date of sale.

A

B

C

D

Figure 2. An example of a recommendation given in the “management submodule” in which the user has sampled the grain for insects. The expert system first checks if insect-pest is high, then if time vulnerable is less than 30 days, and finally if the grain is warm enough to fumigate.
the grain following fumigation under the worst grain storage temperature and moisture conditions. Fumigation has no residual protection, so the frame "time-vulnerable" is used to determine if the grain could become severely reinfested before it is either sold, aerated, or cooled naturally. If the state of the frame "insect-pest" is high and the state of "time-vulnerable" is <30, then the system determines the state of the frame "fumigate-ok" (Fig. 2d). If the bin has not been aerated and the temperature of the grain is above 60°F, then it is "ok to fumigate."

**Identify.** The purpose of this submodule is to help managers identify insects found in stored grain and thus is used in conjunction with the management submodule. It is important that insects be identified correctly because some insect species cause more damage to stored grain than others. Internal feeders cause the most damage, followed by the so-called "bran bugs," and finally there are insects that feed primarily on fungus and do not damage the grain. Criteria for determining whether the insect is included in the identification key were: 1) pest of major importance or 2) commonly found insect in stored grain. This resulted in a list of 20 insect species. We developed our own rules for identification rather than relying on existing keys, because the latter were developed for larger numbers of insect species and rely on subtle characters requiring use of a microscope. The identification is broken down into a series of steps: 1) determining whether the specimen is a moth or not, 2) the size of the insect, 3) whether the head is tucked under, and 4) the color of the insect. This leads to a possible species identification that could include up to three similar species. Pictures of each species are then presented to the user to make the final identification (Fig. 3). The user can page through the pictures using the "next" and "previous" buttons.

**Figure 3.** Example of a picture used in the "identify" submodule to help the user identify insect pests of stored grain. The "Prev" and "Next" buttons are used to browse through the insects that the system has narrowed the possibilities down to.

**Figure 4.** An example of a graph from a simulation run using the "run simulation model" submodule. The population decreases in July because the user selected a July fumigation date.
Sampling. The purpose of this submodule is to tell the manager how, when, and where to sample for insect pests of stored grain. In the past, managers have been asked to sample the grain monthly or bi-monthly. This advice is often not followed because of the amount of labor involved. Results from the simulation studies indicate that sampling once or twice at certain times after storage would be equally reliable. This is because probe traps and grain probes used for detecting grain insects are more accurate at high than at low insect densities. Therefore, depending on the initial storage conditions, the expert system is able to tell the manager how long to wait after storage to sample the grain. This module also graphically displays the proper locations for insertion of probe traps within the grain mass or where grain samples should be taken. Managers can use it to calculate the accuracy of the estimate based upon the number of traps used and the insect density or the number of traps necessary to achieve a certain level of accuracy.

Fumigation. The purpose of this submodule is to describe for the manager the proper use of fumigation equipment and the necessary safety precautions. Fumigation with phosphene gas is relatively dangerous and requires that self-contained breathing apparatus be available. Many managers choose to fumigate their grain themselves, rather than contract with a fumigation company. Thus, it is important that the managers take proper safety precautions. Bins must be properly sealed so that gas leakage is minimized, and the correct amount of fumigant needs to be used. This module will calculate the amount of fumigant necessary based on volume of grain and grain temperature and will specify where the fumigant pellets should be placed within the grain mass and how long the bin should be left sealed.

Run Insect Model. This submodule is used for examining different

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**Figure 5.** Menu headings available in the main startup screen and headings within the "management" submodule. Selections are made by clicking on the top heading with the mouse and then "pulling down" and releasing the mouse on the desired selection.

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**Grain Probe Trap**

Grain probe traps are efficient at catching most of the major insect pests of stored grain. The advantage of using traps is that samples don't have to be sieved to separate insects from grain. The traps are plastic and about 14 inches long. Insects fall through the small holes in the side of the trap as they move through the grain. It is not necessary to use pheromones with these traps.

3 to 5 traps should be used per bin. Put one in the center, the others 1/3 the distance from the side of the bin to the center. The top of the trap should be about 3 inches from the surface of the grain. Check the traps in one week and identify the insects and the numbers caught.

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**Figure 6.** An example of a help screen. When asking if the user has sampled the grain yet, three buttons are available "yes," "no," and "?". This is one of the screens that appears when the user clicks on the "?" button.
management scenarios and as an educational tool. It contains simulation models for five of the primary insect pests of stored grain. The user can select different starting conditions, such as storage date, sell date, initial grain temperature, moisture, different management options for protectants, and time of aeration and fumigation. Simulation results are then graphed as insect numbers over time (Fig. 4). The purpose of this submodule is to let managers and extension agents play with the models so that they will learn more about the stored-grain ecosystem.

System Structure and Operations

For simplicity, only the Macintosh version of the expert system will be discussed in this section. The MS-DOS version works similarly, except for the lack of mouse control. The expert system has the typical Macintosh pull-down menus (Fig. 5). The main menus are file, edit, and insect. Under the “file” menu, the user can load or save a bin profile, change the current date and time, or quit the program. The bin profile contains stored information about the management facility and individual bins (one profile is used for each bin). Information stored in the profile is relatively static. Some examples are: location of facility within the U.S., bin size, storage date, and protectant applied. Upon starting the expert system, the manager is greeted with the startup screen and a dialog box asking whether he or she wishes to open a bin profile. If the manager selects yes, then he or she is asked to select from previously stored profiles. Ideally, a grain manager would have one profile for each bin. Upon exiting the expert system, the manager is asked if he or she wants to save the current bin profile. If yes is selected, then the profile is saved under the same file name, or it can be renamed.

Under the edit menu are the typical Macintosh editing functions: undo, cut, copy, paste, and clear. Also under the edit menu are selections for “resetting all variables,” “resetting all except the profile,” and “editing grain profile.” Submodules under the insect menu are: “management,” “identify,” “sampling,” “fumigation,” and “run insect model.” When one of these submodules is selected, the main menus change to “file,” “edit,” and the name of the submodule which the user has selected. All of the options are dimmed under the submodule except for quit. (A dimmed menu item indicates to the user that the option is not available at this time.) An example of how the user would interact with the system after selecting the management submodule is as follows: 1) the user is asked if the grain was sampled for insects; 2) the user answers questions by clicking on the buttons with the mouse (clicking on the “?” button brings up a help screen, Fig. 6); 3) the user is then asked to enter the storage date and the expected date of sale (Fig. 7) (the calendar has mouse-sensitive regions, so clicking on a day selects it; the arrow regions are used to change the month); 4) the user is then prompted for the initial storage temperature and moisture of the grain and asked if the grain will be aerated in the fall. After answering these questions, the user is presented with a recommendation. At this time, the subcategories under management cease to be dimmed. If the user selects “explain,” a detailed explanation of the reasoning behind the recommendation is presented. Selecting “about” shows additional information relative to the submodule that the user has selected (Fig. 8). A printout can be obtained for information in “about,” “explain,” or “recommendation.”

An important facility of the system is the ability to investigate different management scenarios. This is accomplished by selecting “reset all variables” or “reset all except profile” and then selecting “recommendation.” This erases any previous investigations from memory and begins the consultation again. The difference between “resetting all variables” and “resetting all except profile” is that, in the latter, only the frames which are not stored in the profile are reset. For example, questions regarding the expected date of sale or aeration date would be reset, but storage date and whether a protectant was used would not be reset, because they are stored in the profile. If the user wishes only to change the answers to questions that are stored in the bin profile, then he or she would select “edit the bin profile.” By editing “change date and time” under the “file” menu, the user can investigate how recommendations are affected by the current date. Recommendations specific to fumigation or selling the grain are affected by the current date.

Discussion

The SGA will primarily be used by growers and grain managers. The ability of this expert system to store information on individual bins, forecast, and provide advice should make it a valuable tool for managers of stored grain. It should also prove to be a useful educational tool for extension specialists and county agents. The frequency of use of the expert system will depend upon the size of the grain storage facility. With small facilities, it is more likely that it will be used at key times of the year when decisions in stored grain management are made, for example, at the time the grain is stored (June to September) or when insects usually begin to be found in grain (October to December). The expert system is used both at the time of storage to forecast problems and suggest alternative management schemes, and later for diagnosis and treatment recommendations for insect infesta-
Figure 7. Dates are entered by using the mouse to click on the appropriate day, month, and year.

Figure 8. An example of the type of information that is provided to the user when “about” is selected within the management submodule. This information can be requested after a recommendation is given.

Aerating the grain earlier cools the grain sooner and thus inhibits insect growth. Grain temperatures below 60°F will prevent insect growth and reproduction. The length of time that the grain is stored before it is cooled in the fall determines how high the population will reach before insect growth is inhibited.

This expert system has several advantages over current extension manuals for stored grain management. Perhaps the most important is its ability to customize recommendations specifically to the user’s situation and to accurately predict population growth of stored-grain insect pests for specific storage conditions. This ability is critical to making rational pest management decisions. Use of this expert system should not only result in better quality grain, but also less frequent sampling of the grain for insects and reduced chemical control. For example, extension manuals recommend sampling the grain at monthly intervals. The expert system recommends that the manager wait 60 days after storage to sample the grain for insects. This is because results from the simulation studies show that it takes that long for grain insects to reach levels where they can be detected. The expert system advises that sampling is not necessary in cases where the storage durations are short and conditions are unfavorable for insect development. Because insecticides are applied at binning without knowing whether insects will become a problem, in many cases unnecessary protectants are used. If the time from storage until fall aeration is less than three months and the grain moisture is less than 10 percent, then the manager would not need to use a protectant. This expert system also predicts the likelihood for the grain becoming heavily infested and gives advice for ways to avoid catastrophic economic losses. Extension manuals do not provide these types of information.

Currently, there is little variation in treatment recommendations for stored grain insect problems. This expert system should allow recommendations to be customized based on geographic region and storage conditions. The quality of the recommendations should be higher than
current extension manuals, because the rules in this expert system are based on simulation models that are able to forecast population trends and the effects of management practices.

References


David W. Hagstrum is a research entomologist at the USDA-ARS Grain Marketing Laboratory in Manhattan, Kansas, and an adjunct assistant professor at Kansas State University. He received a Ph.D. in entomology from the University of California at Riverside in 1970. From 1971 to 1983 he was at the USDA-ARS Insect Attractants, Behavior, and Basic Biology Laboratory in Gainesville, Florida. There he studied the field ecology of stored-product insects infesting citrus pulp, peanuts, and cowpeas. His current research is aimed at understanding the ecology of stored-product insects in the wheat marketing system as a means of developing new pest management options, improving capabilities for early detection and subsequent monitoring, and improving insect control.

Paul W. Flinn is a research biologist at the USDA-ARS Grain Marketing Research Laboratory in Manhattan, Kansas, and an adjunct assistant professor at Kansas State University. Flinn received his B.S. from the University of Michigan and a Ph.D. in entomology from Pennsylvania State University in 1984. He did postdoctoral work at Penn State on GYPSSEX, an expert system for aerial application of B.t. for gypsy moth suppression. His previous experience also includes the development of a simulation model for the potato leafhopper and the coupling of this model with an alfalfa growth model. His current research involves the population dynamics and ecology of stored-grain insects. His interests center on the development and analysis of IPM systems through computer simulation of crop-pest agroecosystems and knowledge-based systems.