Spatial Model for Simulating Changes in Temperature and Insect Population Dynamics in Stored Grain

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ABSTRACT A spatial model describing insect population dynamics in a grain bin was developed by coupling a model of *Cryptolestes ferrugineus* (Stephens) with a two-dimensional bin temperature model. In the model, the bin is divided into 16 compartments. The insect model is run separately for each compartment. This allows the insect model to simulate different population growth rates based on each compartment's average daily temperature. Field data for a 351-m^3 (10,000 bu) bin located in Cloud County, KS, was used to validate the model. The model predicted grain temperatures accurately for each of the nine compartments, except the center top portion of the grain mass. In this region, observed grain temperatures were 8°C higher than predicted during December. This may have been caused by convective air movement. In general, the model accurately predicted insect density for most of the bin compartments. However, the model tended to overestimate insect density in the center of the grain mass during the end of the storage period in December. During this period, actual grain temperatures were still optimal for *C. ferrugineus* growth. *Cephalonomia waterstoni* (Gahan), a common host-specific parasitoid of *C. ferrugineus*, may have been responsible for the pest population decrease.

KEY WORDS *Cryptolestes ferrugineus*, spatial model, stored products

THE COMPUTER SIMULATION APPROACH has been used to investigate the influence of various management practices on the control of stored grain insects. Thorpe et al. (1982) showed that air flow rate and the percentage of the coolest part of the day that fans were run influenced the effectiveness of aeration in suppressing insect populations in a grain bin. Longstaff (1988b) reported that insecticide efficacy was affected by the type of insecticide used and grain cooling. Cooling reduced the rate of degradation of both pyrethroids and organophosphorus insecticides; however, pyrethroids were more effective at cooler temperatures. Longstaff (1988a) also stated that cooling grain increased the generation time of grain insects and, therefore, slowed the rate of spread of an insecticide-resistant gene. Sinclair & Alder (1985) developed a model that simulated management of insect populations on farm-stored grain. The importance of bin sanitation in reducing pest numbers was particularly evident on farms that did not use bin sprays.

Models have also been used to investigate timing of aeration, timing of fumigation, protectants, and initial grain moisture or temperature on insect population growth in stored grain (Flinn & Hagstrum 1990a, Hagstrum & Flinn 1990). The results of these studies have been used to develop an expert system for stored grain management (Flinn & Hagstrum 1990b). However, none of these models has considered the effects of nonhomogeneous temperatures within the grain mass on insect population growth at different locations in the bin. During the fall in unaerated grain, the outer layers of the grain mass cool more rapidly than the center layers. Because grain insects increase more rapidly at warmer than at cooler temperatures, we hypothesize that grain insects should reach higher densities in the center than in the outer layers of the grain mass. A spatial model that can simulate the effects of nonhomogeneous grain temperature and moisture content on insect population growth should be more accurate than previous stored grain insect models.

The primary goal of this research was to provide stored grain managers with a more accurate method of predicting insect population dynamics in stored grain. In this paper, we describe the coupling of an insect population dynamics model with a two-dimensional bin-temperature model (Metzger & Muir 1983).

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Materials and Methods

A distributed-delay model was used to predict population growth of the rusty grain beetle, *Cryptolestes ferrugineus* (Stephens) (Coleoptera: Cucujidae) as a function of grain temperature and moisture. The details of the model are described by Flinn & Hagstrum (1990a) and Hagstrum & Flinn (1990). This insect was selected for model validation because it is one of the most common insect pests of stored wheat and because it is found throughout the bin (Hagstrum & Flinn 1991); thus, it would be more susceptible to nonhomogeneous grain temperatures. The insect model consists of four major parts: (1) an equation describing the relationship between the daily rate of insect development and grain temperature and moisture, (2) a delay process for moving the immature insects through the stages and simulating variation in developmental rate, (3) a 70-element array for keeping track of adult age, and (4) an equation describing the relationship between temperature, female age, and daily egg production. We developed a regression equation for predicting low temperature mortality for the immature stages using data from Smith (1965): $\ln Y = 10.6465 - 0.3384X$ (n = 4, r^2 = 0.97, P = 0.01), where Y is the daily percentage mortality and X is the grain temperature in degrees Celsius. The SEs of the slope and intercept were 0.8416 and 0.0393, respectively. We constrained the equation to $0 \leq Y \leq 100$ because it predicts that temperatures <17.85°C and >31.46°C result in mortalities of <0 and >100, respectively.

The insect model was coupled with a two-dimensional bin temperature model developed by Metzger & Muir (1983). The bin model predicts temperatures in a grain bin using a finite difference method to solve the heat transfer equations and uses an hourly time step (Metzger & Muir 1983). The bin model requires initial values for bin diameter, depth of grain, type of grain (wheat, corn, etc.), bin wall material, latitude, hourly data for dry-bulb temperature, dew point temperature, barometric pressure, wind speed, and cloud opacity (or solar radiation). This model assumes that temperatures throughout the bin were symmetrical about the vertical axis, and free convection was not included. Of course, in practice, the amount of radiation received by the bin wall is highest on the south side in temperate regions of the Northern Hemisphere. However, a three-dimensional model that accounts for this difference greatly increases computation time. This model compromises by using the average solar radiation for a cylindrical bin.

In the simulation studies, a 351-m^3 (10,000 bu) bin was divided into 16 compartments (Fig. 1). Because the bin model predicts temperatures for 77 nodes within a bin, nodes within a compartment were averaged to predict the temperature for a given compartment. The two models were coupled by allowing the bin model to provide daily information for the insect model on grain temperature and moisture for 16 compartments within a bin. An important concept used to couple the two models was the idea of running the insect model separately for each compartment. This allows the insect model to simulate different population growth rates based on each compartment's average daily temperature. For the initial version of the model, there is no movement of insects between compartments. This was done for two reasons: (1) we wanted to look at the simplest model first to see if temperature alone was sufficient to explain population density differences, and (2) currently, we do not have information on how insect density and temperature gradients affect *C. ferrugineus* movement.

In the simulation, adult *C. ferrugineus* immigration into the grain bin was based on data from Hagstrum (1987). We used a daily immigration rate of seven adult females per 351 m^3 in the top two horizontal layers and an immigration rate of four adult females per 351 m^3 in the bottom two horizontal layers for both bins. These immigration rates are obviously not applicable under all conditions; however, the purpose of the simulation studies was to show general trends.

Model Validation. We purposely chose to validate the model using unaerated bins because this case is the more interesting one. Under aerated conditions, bin temperature is much more homogeneous. Thus, we would expect insect growth rates within the bin also to be more homogeneous. Field data for a 351-m^3 cylindrical bin was used to validate the model (C. Reed, unpublished data). The bin was located on a farm in Cloud County, KS. It was sampled monthly from July to December 1987 for grain temperature, grain moisture, and insect density. Twenty-seven 800-g samples were taken at predetermined locations (Fig. 2) with a pneumatic grain sampler (Cargill Probe-A-Vac, Minneapolis, MN). Adult insects were separated from the grain samples with a grain sieve with oblong holes (Seedburo, Chicago, IL; 0.18 by 1.27 cm), identified to species, and counted. Three estimates of insect density per horizontal layer were obtained from (1) the single sample in the center region, (2) average of the four inner samples, and (3) average of the four outer samples. We could not compare predicted versus observed insect densities for all 16 bin compartments because the validation data set did not have samples taken at seven of the compartments predicted by the model. Grain moisture was estimated using the whole-kernel oven-drying method (19 h at 130°C). Grain temperatures were estimated using thermocouples that remained in the grain during the experiment. They were located close to the locations where grain samples were taken.

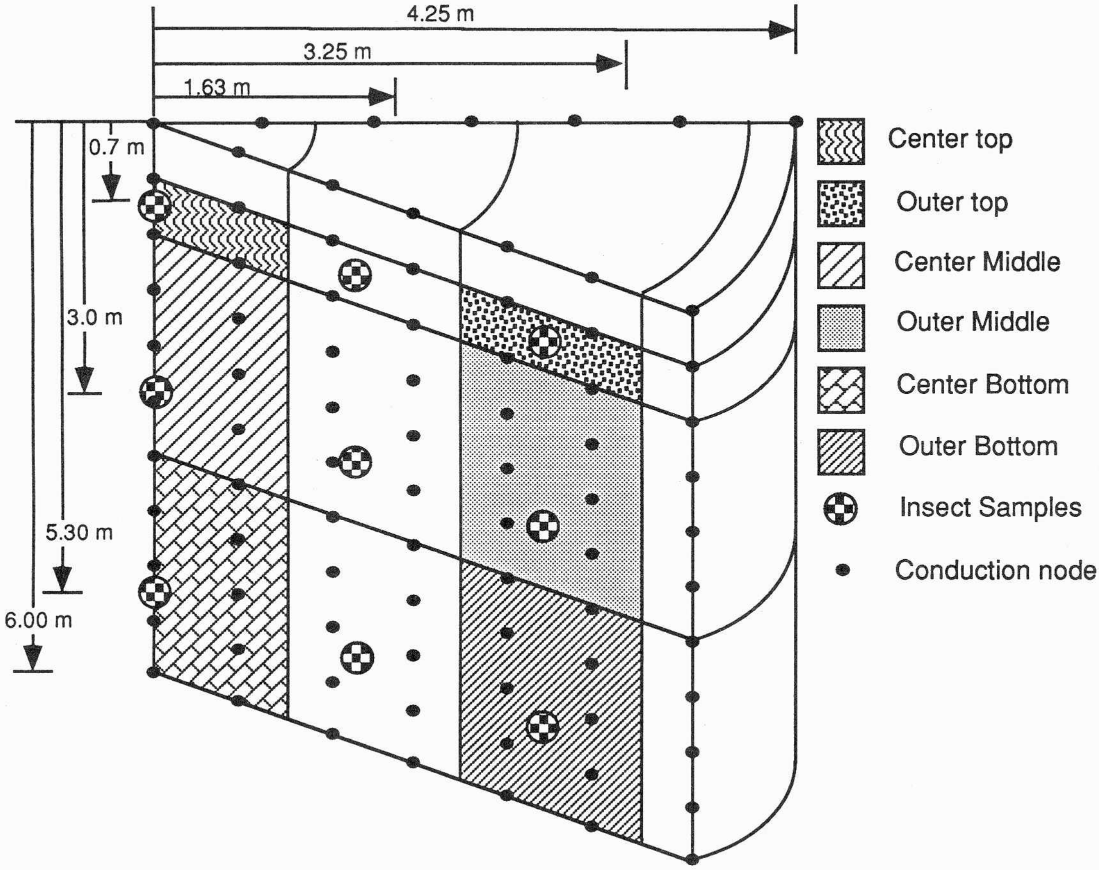

Fig. 1. Diagram showing the 16 bin compartments and temperature nodes used in the combined model for bin temperature and insect population dynamics. The checker-patterned circles indicate where grain samples were taken.

We used 1987 and 1988 Topeka, KS, weather data to run the model. This data set was obtained from the National Climatic Data Center and contained hourly data for dry-bulb temperature, dew point temperature, barometric pressure, wind speed, and cloud opacity.

Predicted versus measured insect densities and grain temperatures were compared using the regression analysis procedure of SYSTAT version 5.1 (Wilkinson 1989).

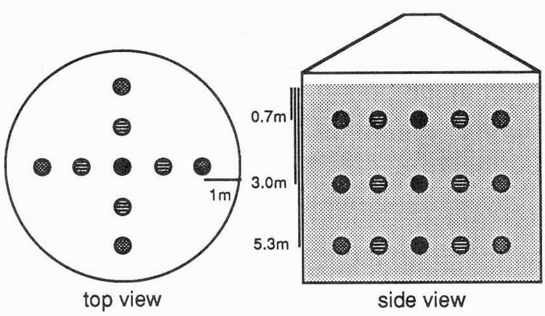

Fig. 2. Diagram showing the 27 locations in a 351-m^3 (10,000 bu) grain bin where grain samples were taken (Reed, unpublished data).

Results

Temperature Predictions. The bin model predicted grain temperatures fairly accurately for each of the nine compartments, with the exception of the center top and inner top compartments (Fig. 3). In these two compartments, observed grain temperatures were ≈8°C higher than predicted grain temperatures during the last two sampling periods. Regressions of observed versus predicted temperatures resulted in r^2 ranging from 0.55 to 0.99 (Table 1). The intercepts were not significantly different from 0 (t = 2.776; df = 4, $P < 0.05$) in the inner middle, outer middle, and all three bottom compartments, and the slopes were not significantly different from 1 (t = 2.776, df = 4, $P < 0.05$) for the outer top, the three middle, and the three bottom compartments. This indicates that the model predictions of grain temperature were accurate for these compartments.

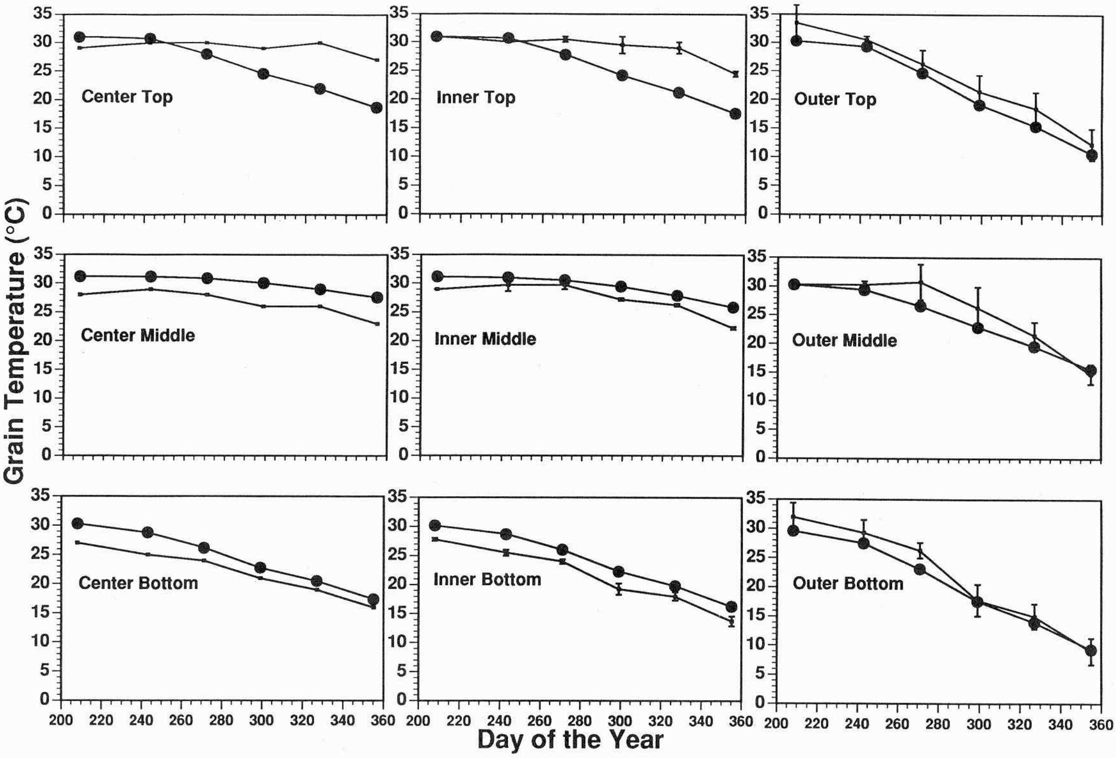

Fig. 3. Predicted ● and observed ▪ grain temperatures for a 351-m^3 (10,000 bu) bin of wheat located in Cloud County, KS. Vertical lines indicate SE of the mean. SEs could not be calculated for the center compartments because there was only one estimate.

Grain-moisture predictions were not compared because the model predicts changes in grain moisture only when aeration is used, and the bin in this study was not aerated. Actual grain moisture in the bin changed very little. It increased from 12.0 to 12.5% moisture in the middle top compartment and decreased a similar amount in the middle bottom compartment during the last two sample periods. This small change in moisture would have a minimal effect on insect population growth.

Insect Predictions. In general, the model predicted insect density accurately enough to make management decisions. A visual comparison of observed versus predicted densities showed that the model predictions were fairly accurate for most compartments, except for the center middle and inner middle (Fig. 4). The model tended to overestimate insect density in these compartments. We expected densities in the center middle and inner middle compartments to continue to increase from days 300 to 326 because temperatures were still optimal for insect growth. However, observed insect density decreased in these compartments during this period. Most of the predictions were within the 95% confidence intervals of the observed insect density. Regression of observed versus predicted densities resulted in r^2 values ranging from 0.02 to 0.98 (Table 2). Intercepts and slopes were not significantly different from 0 or 1 (t = 2.776; df = 4, P < 0.05) in the center top, inner top, and all three bottom compartments. This indicates that the model predictions of insect density were accurate for these compartments r^2 values were low for the inner bottom, outer bottom, and outer middle regions, even though the model accurately predicted low insect densities for these regions. This was primarily because of overprediction of insect density at the last sampling pe-

Table 1. Regressions of observed versus predicted grain temperatures for nine compartments in a 351-m^3 bin of wheat located in Cloud County, KS

Bin region	n	Intercept ± SE	Slope ± SE	r^2	P
Center top	6	25.90 ± 3.73	0.29 ± 0.13	0.55	0.09
Inner top	6	24.89 ± 3.38	0.33 ± 0.12	0.65	0.05
Outer top	6	10.20 ± 2.12	0.79 ± 0.09	0.95	0.00
Center middle	6	−31.23 ± 9.46	1.92 ± 0.28	0.92	0.00
Inner middle	6	−11.38 ± 6.51	1.38 ± 0.20	0.93	0.00
Outer middle	6	−0.76 ± 2.48	1.09 ± 0.09	0.97	0.00
Center bottom	6	−3.06 ± 1.53	1.08 ± 0.06	0.99	0.00
Inner bottom	6	0.14 ± 1.45	0.99 ± 0.05	0.99	0.00
Outer bottom	6	0.44 ± 1.25	1.03 ± 0.05	0.99	0.00

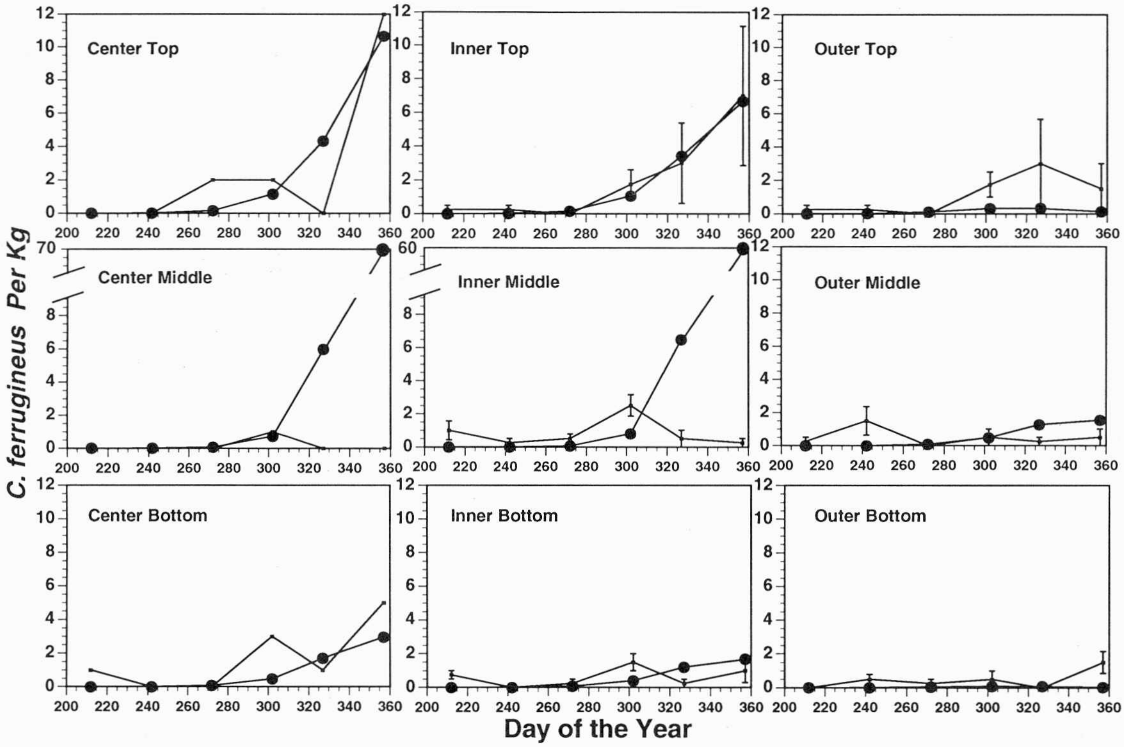

Fig. 4. Predicted ● and observed ▪ *C. ferrugineus* densities in a 351-m³ (10,000 bu) bin of wheat located in Cloud County, KS. Vertical lines indicate SE of the mean. SEs could not be calculated for the center compartments because there was only one estimate.

riod, which has the effect of making the slope of observed versus predicted densities equal to zero, resulting in a low r^2 value.

Discussion

Differences in predicted and observed grain temperatures for the center top and inner top compartments may have been caused by convective air movement. The bin model assumes no convective air movement, except for aeration. Even a small amount of convective air movement within the grain mass could explain these differences. However, in most cases, the difference in predicted versus observed temperatures would have very little effect on predictions by the insect model because they occurred at the end of the storage period. This can be seen in Tables 1 and 2, in which insect predictions were the most accurate for the center and inner top compartments, even though temperature predictions were the least accurate for these compartments.

The model predicted that during the fall and winter, insect density would be greater in the center of the bin than in the outer layers. This trend also occurred in the validation data set. Temperature is the driving factor for this phenomena. Insects continue to develop in the center core because temperatures remain warmer longer in this region. This is an important concept that previous stored grain insect models did not have.

Incorporating a spatial element into our stored grain insect population dynamics model should result in a more realistic model. Bins do not cool down homogeneously in the fall. The outer layers cool or warm up faster than the inner core. Temperature is one of the most important factors affecting insect population growth in grain (Flinn & Hagstrum 1990a). This model should be

Table 2. Regressions of observed versus predicted insect densities for nine compartments for a 351-m³ bin of wheat located in Cloud County, KS

Bin region	N	Intercept ± SE	Slope ± SE	r^2	P
Center top	6	0.02 ± 1.24	0.97 ± 0.26	0.78	0.02
Inner top	6	0.17 ± 0.23	0.99 ± 0.07	0.98	0.00
Outer top	6	0.05 ± 0.41	7.09 ± 2.06	0.75	0.03
Center middle	6	0.21 ± 0.20	−0.01 ± 0.01	0.04	0.69
Inner middle	6	0.97 ± 0.41	−0.01 ± 0.02	0.12	0.50
Outer middle	6	0.59 ± 0.32	−0.15 ± 0.38	0.04	0.71
Center bottom	6	0.57 ± 0.72	1.26 ± 0.52	0.60	0.07
Inner bottom	6	0.51 ± 0.33	0.20 ± 0.38	0.06	0.63
Outer bottom	6	0.55 ± 0.40	−2.10 ± 7.24	0.02	0.79

more accurate than previous stored-grain insect models because it adjusts population growth rate based on differences in grain temperature within a bin. This model is also more flexible because it can be used to predict changes in population growth rate for different bin sizes and cooling regimes. In unaerated grain, the size of the bin becomes a critical factor in determining how long the inner core remains favorable for insect growth. The inner core in larger bins will remain warmer much longer than in smaller bins. Thus, insects can continue to develop in this area, even through the winter months.

There is an important inconsistency that occurred in the validation data set that may suggest directions for further research. In both bins, observed densities in the center middle and inner middle compartment, on the last two sampling dates, were lower than predicted. Cooler grain temperature was not a reason for lower insect density, because actual grain temperatures remained favorable for insect growth in these compartments (31.4 and 27.6°C during the last two sample dates, respectively). A possible reason for the decrease in observed *C. ferrugineus* density may be due to parasitism by *Cephalonomia waterstoni* (Gahan) (Hymenoptera: Pteromalidae), a host-specific parasitoid of *C. ferrugineus* that is commonly found in stored grain. Hagstrum (1987) reported that natural populations of this parasitoid dramatically reduced populations of *C. ferrugineus* under field conditions. Hymenopteran parasitoids were found in the center and inner compartments during the fourth and fifth sampling periods. Unfortunately, these parasitoids were not identified in the study by Reed (unpublished data), so it is difficult to determine if *C. waterstoni* was responsible for this reduction. We are currently working on a model for this parasitoid which will be coupled with the *C. ferrugineus* model. Grain temperature will be a very important component of the model because it affects both the numerical and functional response of *C. waterstoni* (Flinn 1991). The addition of the parasitoid model should make model predictions of *C. ferrugineus* more realistic when this parasitoid is present in the grain.

This model will be incorporated into an existing expert system for stored grain management (Flinn & Hagstrum 1990b). This will allow the system to make more accurate recommendations for a particular storage situation. The expert system will use the model to determine optimum grain management techniques for various climatic regions of the United States, based on predicted insect density, bin size, aeration capacity, and power costs.

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