

Simulations Comparing the Effectiveness of Various Stored-Grain Management Practices Used to Control *Rhyzopertha dominica* (Coleoptera: Bostrichidae)

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ABSTRACT A simulation model for the population dynamics of *Rhyzopertha dominica* (F.) was used to compare the effectiveness of various stored-wheat management programs in controlling this insect in the United States. Infestations on day 365 were reduced 88 times when wheat was harvested and stored in August instead of June, 34 times by aerating the grain in September instead of November, 20 times by storing grain at 10% instead of 14% moisture content, 18 times by fumigating in August or September instead of July, four times when wheat was stored at 27°C instead of 32°C, and approximately three times when malathion was used as a protectant. The model simulations provide an overview of the relative advantages of various approaches to managing stored-grain insects in various geographic localities.

KEY WORDS Insecta, *Rhyzopertha dominica*, stored products, simulation models

INSECT INFESTATIONS of stored wheat and the need for pest control probably differ seasonally and among wheat growing regions in the United States. With such diversity, it is not possible to make empirical comparisons of the effectiveness of various management programs at different times of the year and at different locations. Computer simulation models provide a cost-effective method of determining the importance of time of year and location in choosing a pest management program.

The computer simulation approach has been used to investigate the influence of various factors on the cultural and chemical control of rice weevils, *Sitophilus oryzae* L., in stored wheat in Australia. 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 (1988) showed that the effects of grain cooling used together with insecticide treatment depended upon the type of insecticide employed. Cooling reduced the rate of degradation of both pyrethroids and organophosphorus insecticides. Moreover, pyrethroids benefit doubly by cooling because of the negative temperature-toxicity relationship. However, the situation with organophosphorus compounds is less clear. Sinclair & Alder (1985) developed a model which they used to simulate management of insect populations on grain farms. On unsprayed farms, the importance of cleanup in reducing pest numbers was confirmed. The use of some chemical sprays was shown to induce resistance more rapidly under certain management practices, particularly spraying major permanent grain residues on farm and irregular spraying.

The lesser grain borer, *Rhyzopertha dominica* (F.), is an insect pest that causes as much damage to stored wheat as the rice weevil. Adults generally infest grain soon after it is stored on the farm (Hagstrum & Throne 1989), which is between June and August in the United States. Adults may live more than 100 d, but most of the oviposition occurs during the first 70 d, during which time they may lay several hundred eggs (Birch 1945). After larvae emerge from the egg, they bore into the wheat kernels where they complete four larval stadia and pupate (Howe 1950). The average time from oviposition to adult eclosion is 37 d at 32°C and 51 d at 27°C (Hagstrum & Milliken 1988). This species can complete several generations before low grain temperatures limit population growth in the fall (Hagstrum 1987). In the United States, common management practices include protectants, fumigation, and aeration.

In our study, we use a simulation model to compare the effectiveness of various management programs in the United States against the lesser grain borer. This simulation study emphasizes the importance of time of year and location in choosing a pest management program.

Methods

The Model. A distributed delay model, described by Hagstrum & Throne (1989), in conjunction with several new subroutines was used to investigate the effects of aeration, fumigation, and insecticides on lesser grain borer population growth in a 35.2-m³ (1,000 bu) bin of wheat. The model consists of four major parts: (1) an equation describing the relationship between rate of insect de-

velopment 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) equations describing the relationship between temperature and insect egg production. Except for mortality caused by insecticide or fumigation, survivorship was not explicitly included in the model. However, offspring production was estimated using data from Birch (1945) on rate of increase per generation, and thus, included natural mortality.

Adult immigration into the stored grain was modeled using an immigration rate of 1 adult/35.2 m³ per day. These insects entered the adult array as reproducing 8-d-old adults. This average immigration rate was calculated by adjusting immigration rate in the model until predictions of adult density fit actual field data (Hagstrum & Throne 1989). This immigration rate is obviously not applicable under all conditions; however, the purpose of the simulation studies is to show general trends and to make comparisons between management strategies.

Aeration. The aeration subroutine simulated daily decreases in grain bin temperature by using a linear equation which was derived from field data (Noyes et al. 1988):

$$r = (t - 20.0)/12 \quad (1)$$

where r is the daily decrease in temperature of grain in the bin and t is the temperature of the grain at the time aeration begins. The divisor was based on the assumption that it takes approximately 12 d to cool the grain from 32 to 20°C (120-h cooling time, 10 h of cooling/d). This equation produces greater cooling rates when the grain is stored at higher temperatures. In the model, the moisture content of the grain does not change during aeration, because several studies showed less than 0.25–1.0% decrease in grain moisture during aeration (Johnson 1957, Holman 1960, Foster 1967, Converse et al. 1977). In the case where the grain is unaerated, natural cooling was simulated by decreasing the average grain temperature in the bin by 0.5°C/wk starting October 1. This rate also was based on field data (Hagstrum 1987).

Protectant. Malathion is the most commonly used stored-wheat protectant in the United States. We selected an application rate of 10 ppm because this is the rate normally applied to grain as it is put into storage. We used an exponential decay equation to describe the breakdown of insecticide with time:

$$R_t = R_0 e^{-kt} \quad (2)$$

where R_t is the amount of insecticide (ppm) at time t in the future, R_0 is the present amount of insecticide (ppm), and k is the rate per unit t of insecticide degradation. The half-life can be solved for by substituting 1/2 for R_t/R_0 and rearranging Equation 2:

$$1/2 = e^{-kt_{50}} \quad (3)$$

and

$$\frac{\ln(2)}{k} = t_{50} \quad (4)$$

We used an equation from Desmarchelier & Bengston (1979) to predict the half-life of malathion as a function of temperature and relative humidity:

$$t_{50} = 10^{[1.08 - \log(H/50) - 0.05(T-30)]} \quad (5)$$

where t_{50} is the half-life (weeks) of malathion, H is the percentage relative humidity, T is the temperature (°C) of the grain, and \log is base 10. Substituting the left side of Equation 4 for t_{50} :

$$\frac{\ln(2)}{k} = 10^{[1.08 - \log(H/50) - 0.05(T-30)]} \quad (6)$$

The rate of decay, k , is then:

$$k = \frac{\ln(2)}{10^{[1.08 - \log(H/50) - 0.05(T-30)]}} \quad (7)$$

Because grain moisture is more commonly used than relative humidity, we developed an equation to predict relative humidity from grain moisture and temperature based on data from Pixton (1982). The following equation best fit the data ($r^2 = 0.99$, $P = 0.0001$, $n = 24$):

$$H = -110.302 + 0.309T + 44.662\sqrt{W} \quad (8)$$

where H is the percentage relative humidity, T is the temperature (°C), and W is the percentage grain moisture. The standard errors of the intercept and two slopes are 0.52, 0.01, and 0.26, respectively.

In the model, the amount of insecticide in the grain (ppm) is recalculated every 10 d. This interval was used because the insecticide mortality data from Champ et al. (1969) are based on a 10-d interval. Because the half-life is in weekly time units (Desmarchelier & Bengston 1979), 10 d was converted into weekly units by dividing by 7. The final equation used to determine the amount of malathion in the grain is

$$R_t = R_0 e^{\left\{-\frac{(10/7)\ln(2)}{10^{[1.08 - \log(H/50) - 0.05(T-30)]}}\right\}t} \quad (9)$$

The next step was to predict mortality as a function of exposure time and insecticide residue. We used data from Champ et al. (1969), in which they present the 10-d mortality for the lesser grain borer when exposed to grain that was treated with 10 ppm malathion and stored for different lengths of time (0–100 d) before exposing the insects to the grain. Since Champ et al. (1969) do not present insecticide residues for all treatments, we used Equation 9 to estimate them. This was possible because Champ et al. (1969) specify the initial dose applied to the grain, the temperature, and percentage moisture of the grain during the storage period. Nonlinear least-squares (Wilkinson 1987)

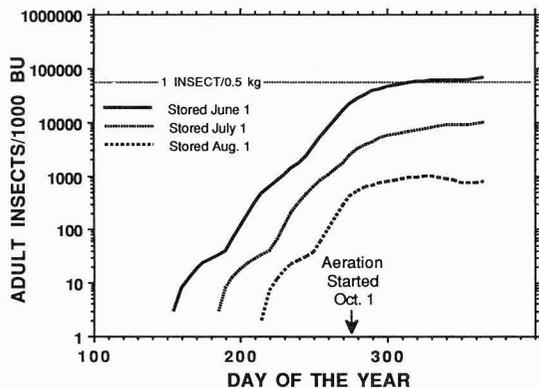


Fig. 1. Predicted effects of storage date on the growth of adult lesser grain borer populations in grain stored at 32°C and 14% moisture content with aeration starting 1 October.

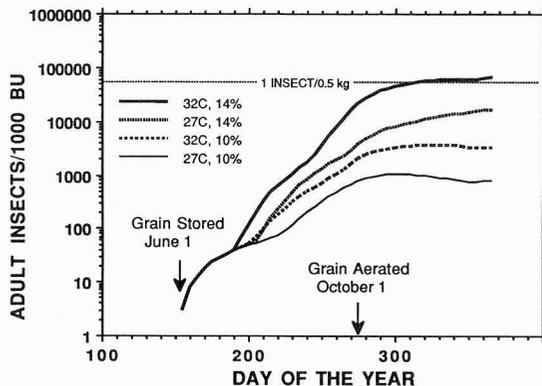


Fig. 2. Predicted effects of initial temperature and grain moisture on the growth of adult lesser grain borer populations with grain aeration starting 1 October.

was used to fit a logistic equation to the data. The form of the equation was

$$M = 1 / \{1 + \exp[a + b \log(p)]\} \quad (10)$$

where M is the proportion adult mortality occurring over 10 d, p is the insecticide concentration in parts per million, and a and b are constants ($r^2 = 0.98$; $P > 0.01$; $n = 10$). The estimates (and standard errors) for a and b were 35.109 (8.414) and -16.935 (3.981), respectively.

Fumigation. Unlike protectants, fumigation has no residual effects. Fumigation was simulated in the model by causing 90 and 99% mortality to pupal and adult stages, respectively, and 100% mortality to eggs and larvae over a 5-d period (Longstaff 1988).

Model Simulations. Temperatures and grain moistures that were within the range of those observed under bin storage conditions were used to simulate lesser grain borer population growth. The model was run using two different grain moistures, 10 and 14% water weight, and two grain temperatures, 27°C and 32°C, at the time grain was put into storage. In the model, grain conditions were constant during the first 3 mo of storage, because temperature and moisture normally change very little before 1 October (Hagstrum 1987). We also investigated the effects that storage in different growing regions of the United States might have on insect population growth. In the simulations, grain was harvested and stored on one of three dates, 1 June, 1 July, or 1 August to duplicate the storage dates that would occur in the southern, middle, and northern growing regions of the United States, respectively (Burkhead et al. 1972). We also examined the effects of aerating or fumigating at different times during the year. Only reasonable combinations of control methods were used because of the large number of possible combinations. A threshold of 1 adult insect/0.5 kg of wheat was used as a reference line because this is a density that is likely to be detected with current marketing

practices (larvae are not counted because they live inside the kernels).

Results and Discussion

Storage Date. Wheat is usually harvested and stored earlier in the southern United States than in the northern wheat producing regions. When wheat was stored at 32°C and 14% moisture, a difference of only 1 mo in storage date resulted in approximately one order of magnitude difference in lesser grain borer density by day 365 of the simulation (Fig. 1). The amount of time between initial grain storage and fall aeration determined the length of time during which the insect population grew under optimal conditions. With aeration in October, grain stored in the northern wheat producing regions had 2 mo less time at optimal conditions for insect population growth than grain stored in the southern regions. These differences between the wheat producing regions thus have important implications in management programs. For example, grain protectants may not be needed in the northern wheat producing regions if proper bin sanitation and aeration procedures are followed. In contrast, in the middle and southern wheat producing regions, fumigation or protectants are more likely to be needed, depending on the length of the storage period.

Initial Grain Temperature and Moisture. Lesser grain borer population growth was simulated using four different combinations of initial grain temperature and moisture. Moisture content had a greater effect on insect population growth than did temperature (Fig. 2). Increasing moisture at 32°C from 10 to 14% resulted in a population density 20 times higher by day 365. However, a 5°C change in grain temperature at 14% moisture resulted in a population density only four times higher by day 365. Effects of moisture on population growth were greater at 32°C than at 27°C.

Aeration. The timing of fall aeration had a very strong effect on lesser grain borer population

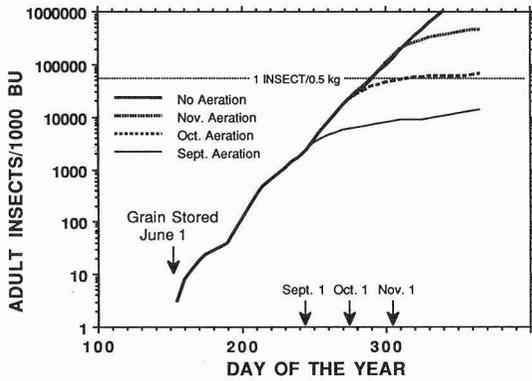


Fig. 3. Predicted effects of time of aeration on growth of adult lesser grain borer populations in grain stored at 32°C and 14% moisture content.

growth. In the model, natural cooling started 1 October, and mechanical aeration could start on the first day of September, October, or November. Adult population density in unaerated grain increased exponentially up to day 365, whereas the density of insects in aerated grain began to level off soon after initiation of aeration (Fig. 3). Each month that aeration was delayed resulted in approximately 6 times increase in insect density. A 2-mo delay in aeration increased adult insect density 34 times. Thus, the earlier aeration can begin, the less chance insects have of reaching damaging levels. The reductions in insect density when aerating earlier are similar to those when harvesting and storing wheat later, in that both reduce the amount of time the grain is stored under conditions that are favorable for insect development.

Fumigation. Unlike insecticides, fumigation has no residual effect. After the grain is fumigated, insects are able to reinfest the grain almost immediately. Immigration into the grain was set at the rate of 1 insect/35.2 m³/d from the time grain is put into storage until 1 October. In the simula-

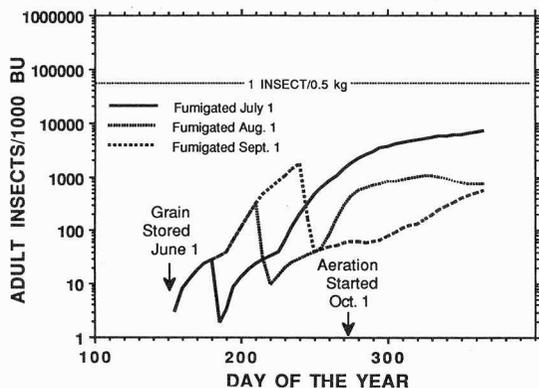


Fig. 4. Predicted effects of time of fumigation on the growth of adult lesser grain borer populations in grain stored at 32°C and 14% moisture content with aeration starting 1 October.

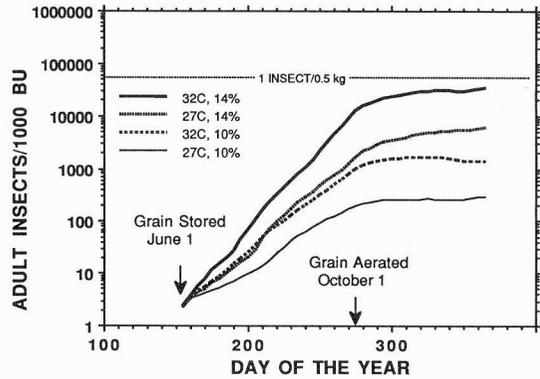


Fig. 5. Predicted growth of adult lesser grain borer populations in grain treated with 10 ppm malathion at four different grain temperatures and moistures with aeration starting on 1 October.

tion, fumigation of the grain occurred on 1 July, 1 August, and 1 September (Fig. 4). Waiting to fumigate in August or September instead of in July resulted in an approximately 20-fold decrease in population density on day 365. This is because insect populations in grain that is fumigated in August or September have less time to grow again before it is cooled, either by aeration or naturally. Therefore, even though grain that was fumigated in August or September had a higher initial insect density before it was fumigated than grain fumigated in July, the insect density from the middle of September until the end of the year was much lower. Thus, delaying fumigation until August may result in better population control, provided, of course, that insects do not exceed economic levels before August.

Protectants. We simulated the effects of malathion and aeration under four initial grain temperatures and moistures on insect populations.

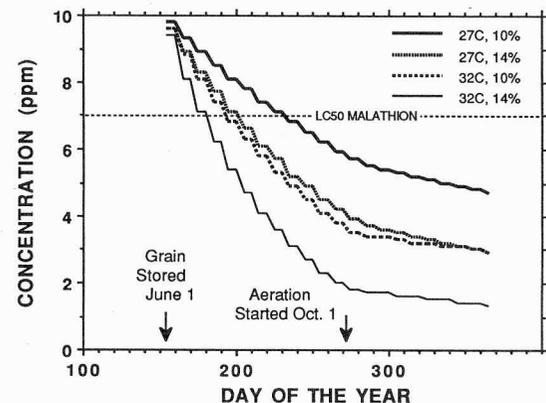


Fig. 6. Predicted concentrations of malathion in grain stored at four different temperatures and moistures with aeration starting 1 October. Horizontal dashed lines indicate LC₅₀'s for the lesser grain borer exposed to malathion for 10 d.

Treatment of grain with malathion (Fig. 5) reduced populations 2.0 times at 32°C, 14% moisture and 2.8 times at 27°C, 10% moisture, compared with populations on untreated grain (Fig. 2). The predicted residual concentrations of malathion over time are shown in Fig. 6. The higher the grain moisture and temperature, the faster malathion degraded. At 32°C and 14% moisture, malathion degraded to an LC₅₀ of 7 ppm (Champ et al. 1969) in only 22 d. At 27°C and 10% moisture, it took 72 d for malathion to degrade to this concentration. Thus, it appears that malathion is most effective when applied to grain being stored at less than 27°C and 10% moisture.

With further development, this model will enable farmers and commercial elevator operators to anticipate pest outbreaks and to select control measures that will be most cost effective. The model simulations provide an overview of the relative advantages of various approaches to managing stored-grain insects in various geographic localities. We are currently using results from the simulations reported in this paper to develop rules for a stored-grain insect management expert system.

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