

# Simulations Comparing Insect Species Differences in Response to Wheat Storage Conditions and Management Practices

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**ABSTRACT** Seasonal changes in the populations of *Cryptolestes ferrugineus* (Stephens), *Oryzaephilus surinamensis* (L.), *Rhyzopertha dominica* (F.), *Sitophilus oryzae* (L.), and *Tribolium castaneum* (Herbst) and differences in their response to pest management programs were compared using validated population-growth-simulation models. The population growth of the five pest species differed in response to temperature and grain moisture conditions during storage, and this partially explains differences among species in their response to management practices. Aerating earlier in the storage season was generally more effective in limiting population growth of *C. ferrugineus* and *O. surinamensis* than the other species. Although fumigation was equally effective against all species, *S. oryzae* was able to grow more rapidly than the others as temperatures decreased in the fall. The internal feeders, *R. dominica* and *S. oryzae*, were much less affected by malathion protectant than the other three external-feeding species. As indicated by these three examples, it would sometimes be advantageous to know which species are present in choosing a management program.

**KEY WORDS** Insecta, temperature, model, population dynamics

IDENTIFICATION OF PEST SPECIES is needed whenever the choice of an insect pest management program depends upon which insect species are present. However, we sometimes are able to select programs that are effective against all of the pest species that might be present. When this is possible, much of the labor required for determining which species are present might be saved. Several insect species usually are found together in stored grain. This generally includes five species of the order Coleoptera: the rusty grain beetle, *Cryptolestes ferrugineus* (Stephens) (Cucujidae); the saw-toothed grain beetle, *Oryzaephilus surinamensis* (L.) (Cucujidae); the lesser grain borer, *Rhyzopertha dominica* (F.) (Bostrichidae); the rice weevil, *Sitophilus oryzae* (L.) (Curculionidae); and the red flour beetle, *Tribolium castaneum* (Herbst) (Tenebrionidae). Thus, a pest management program that is effective against multiple species populations often is desirable.

Several studies have used insect population dynamics models to evaluate the effectiveness of stored-grain pest management on a single species (Thorpe et al. 1982; Sinclair & Alder 1985; Longstaff 1988a,b; Flinn & Hagstrum 1990). However, this paper represents the first reported stored-grain simulation study comparing the effects of pest management programs on multiple pest species. We investigate whether the insect species present should be a factor in the choice of a management program for stored wheat. To make comparisons with all of the major pest species of stored wheat in the United States, we also developed and vali-

dated models for *O. surinamensis* and *S. oryzae*, two species for which models were not available.

## Materials and Methods

**Validating *O. surinamensis* and *S. oryzae* Models.** Validated models for insect population growth are available for three pests of stored wheat (Hagstrum & Throne 1989), and models for two additional species are presented and validated in this paper. The population trends of these two species were observed over several generations, and the changes in population density were compared with those predicted by population dynamics simulation models. For *O. surinamensis*, each of eighteen, 135-kg lots of hard red winter wheat (*Triticum aestivum* L.) in 208-liter (55 gallon) steel drums were infested with 150 recently emerged adults. The tops of drums were covered with fine-mesh cloth for ventilation. Three lots of wheat were maintained at each of the following combinations of temperature and percentage of moisture: 22°C, 14%; 27°C, 10%; 27°C, 12%; 27°C, 14%; 32°C, 12%; and 32°C, 14%. Population estimates were made every wk by taking 350-450-ml wheat samples with a grain trier from full depth of grain at four locations in each drum, two in the center and two halfway between the center and the edge of the drums. On each sampling date, the temperature and moisture were checked at sampling locations. For *S. oryzae*, each of three 680 kg lots of soft red winter wheat in wooden bins (0.9 by 0.9 by 1.2 m high) in a large metal building were infested with

**Table 1.** Equations describing egg production by *O. surinamensis* and offspring production by *S. oryzae* ( $Y$ ) in relation to age of adults ( $A$ ), temperature in °C ( $T$ ), and percentage of grain moisture ( $M$ )

Species	df	Equation <sup>a</sup>	R <sup>2</sup>
<i>O. surinamensis</i>	37	$Y = e^{-1.47 \cdot 0.12A - 0.004A^2 + 0.16M - 0.008AM - 0.00057A^2M - 0.00002A^2M^2}$	0.73
<i>S. oryzae</i> <sup>b</sup>	170	$Y = e^{-17.3 \cdot 3.3 \text{Log}T - 0.12A \text{Log}T + 2.0T - 0.1T^2 + 0.3A - 0.04A^2 \cdot M - 0.16MT + 0.007MT^2 + 0.02MA}$	0.89

<sup>a</sup> Equations for *O. surinamensis* and *S. oryzae* are based upon data published by Arbogast (1976) and Longstaff & Evans (1983), respectively.

<sup>b</sup>  $T = T - 14^\circ\text{C}$ .

900 recently emerged adults. The wheat was initially at 22°C and 12% moisture content, and temperature increased 0.13°C per day during the observation period in response to temperatures increasing in the spring. Insect populations were estimated by taking 90 0.1-kg grain trier samples of wheat at 15-cm-depth intervals from one of the bins every 14 d, from the second bin after 21 and 49 d and from the third bin after 35 and 63 d. Bins were sampled at different times to allow time to process samples. For both species, adult insects were separated from the wheat with an oblong-hole grain sieve (0.18 mm by 1.27 cm; Seedburo, Chicago), counted, and discarded. We used the PROC REG program from the SAS Institute (1982, 39–84) to compare measured and predicted mean population densities for each species.

**The Model.** The distributed delay models of Hagstrum & Throne (1989) and Flinn & Hagstrum (1990) were used to simulate the population dynamics of three species of stored-grain insects. Equations describing the developmental time, fecundity, and toxicity of malathion were added to models to simulate the population dynamics and control of two additional species, *O. surinamensis* and *S. oryzae*. The model consists of four major parts: (1) equations describing the relationship between 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) 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 because adequate data were not available. However, for two of the insect species, *R. dominica* and *S. oryzae*, the offspring production data used in the model include immature mortality because data were available in a form that included natural mortality. These two species develop inside of wheat kernels, and it is easier to count the number of adults emerging than the number of eggs laid. For *S. oryzae* and *O. surinamensis*, developmental times were described by equations from Hagstrum & Milliken (1988), and fecundity was described by equations in Table 1. Because data for *O. surinamensis* egg production was available only for 30°C, a linear interpolation is used to decrease egg production to zero at 20°C. Howe (1965)

gives 21°C as the minimum temperature for population growth of this species.

Adult immigration into the stored grain was simulated using an immigration rate of 1 adult per 35.2 m<sup>3</sup> (1,000 bu) 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 the model predictions 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 that 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 ≈12 d with an airflow rate of 1.3 liters/s per m<sup>3</sup> to cool the grain from 32 to 20°C (120-h cooling time, 10 h of cooling per day). This equation produces greater cooling rates when the grain is stored at higher temperatures. In the model, the moisture content of grain does not change during aeration because several studies showed <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 per wk, starting 1 October. This rate also was based on changes in the overall average temperature of all of the grain in a bin calculated from field data (Hagstrum 1987).

**Protectant.** Malathion is an organophosphorus insecticide that is used as a grain protectant. It is normally applied to the grain at a rate of 10 ppm, as the grain is augered into the bin. We used the equation from Flinn & Hagstrum (1990) to predict the breakdown of malathion in the grain

$$R_t = R_0 e^{\left\{ -(10/7) \ln(2) / 10^{[1.06 - \log(H/50) - 0.05(T - 30)]} \right\}} \quad (2)$$

where  $R_0$  is the ppm of insecticide at the beginning of each 10-d interval,  $H$  is the percentage of relative humidity in the interstitial spaces of the grain,

**Table 2. Logistic equation coefficients for malathion-induced mortality for four insect species**

Species	<i>a</i>	<i>b</i>	Interval <sup>a</sup>	R <sup>2</sup>	<i>n</i>
<i>R. dominica</i> <sup>b</sup>	35.109 ± 8.414	-16.935 ± 3.981	10	0.98	10
<i>C. ferrugineus</i> <sup>c</sup>	28.986 ± 9.080	-23.967 ± 7.410	7	0.80	10
<i>S. oryzae</i> <sup>d</sup>	-0.288 ± 0.145	-1.540 ± 0.107	14	0.98	13
<i>T. castaneum</i> <sup>e</sup>	6.159 ± 0.734	-5.602 ± 0.685	7	0.99	5

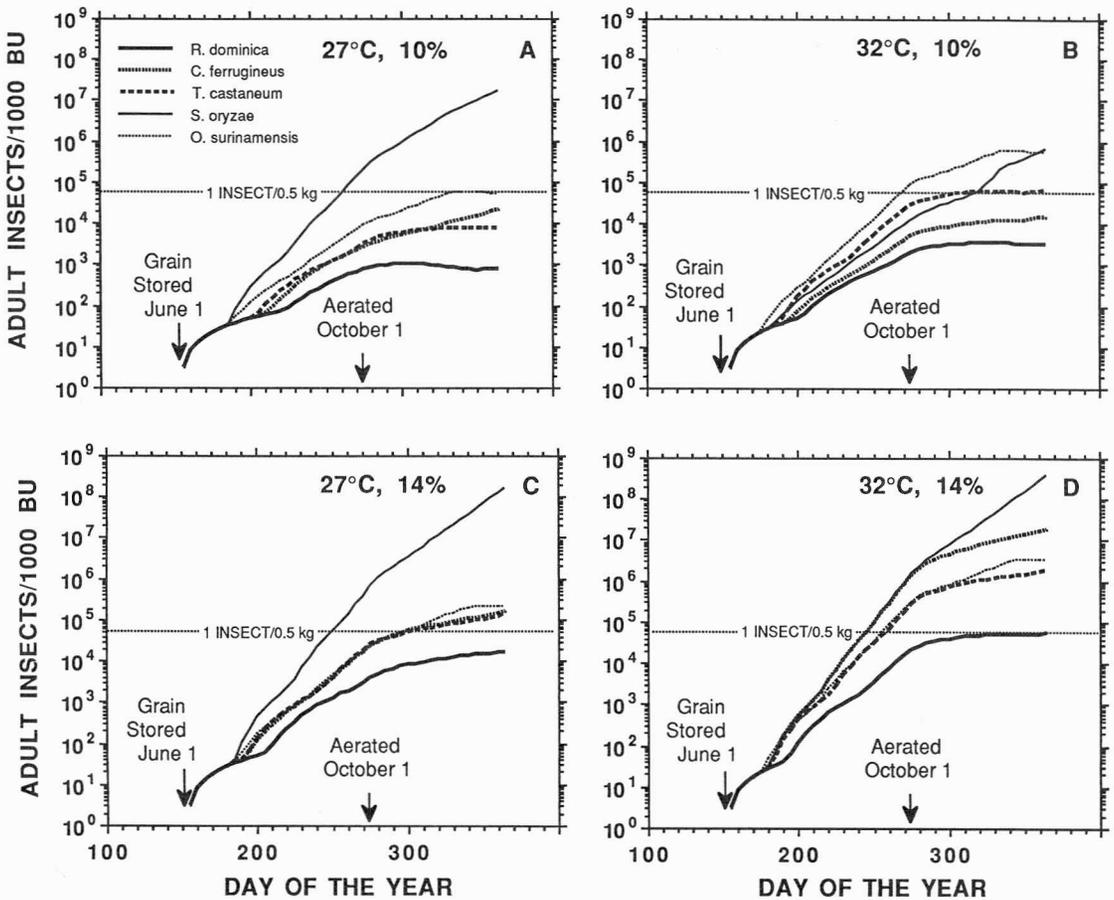
<sup>a</sup> Days over which mortality occurred.  
<sup>b</sup> Data from Champ et al. (1969).  
<sup>c</sup> Data from Watters (1959).  
<sup>d</sup> Data from Strong & Sbur (1960).  
<sup>e</sup> Data from Mensah & Watters (1979).

and *T* is the grain temperature in degrees centigrade.

To predict mortality for each insect species as a function of exposure time and insecticide residue, we fit logistic equations to data for four different species (Table 2) using nonlinear least-squares regression (Wilkinson 1987). Insecticide residue data were not reported except in Mensah & Watters (1979). Therefore, we used equation 2 to estimate the residue. The form of the mortality equation is

$$M = 1 / \{1 + \exp[a + b \log(p)]\} \quad (3)$$

where *M* is the proportion adult mortality occurring either over 7 or 14 d, *p* is the insecticide concentration in ppm, and *a* and *b* are coefficients fit using a nonlinear least squares regression program (Table 2). In these published studies, grain was treated with 10 ppm malathion and stored for different lengths of time (0–100 d) before insects were exposed to the grain for a 7- or 14-d period. Unfortunately, similar studies have not been done for *O. surinamensis*. We decided therefore to use the same coefficients that were used for *T. castaneum* because, of the five species, *T. castaneum*



**Fig. 1.** Predicted effects of initial temperatures and percentage of grain moistures of (A) 27°C and 10%, (B) 32°C and 10%, (C) 27°C and 14%, and (D) 32°C and 14% on the population growth of five species of stored-grain insects with grain aeration starting 1 October.

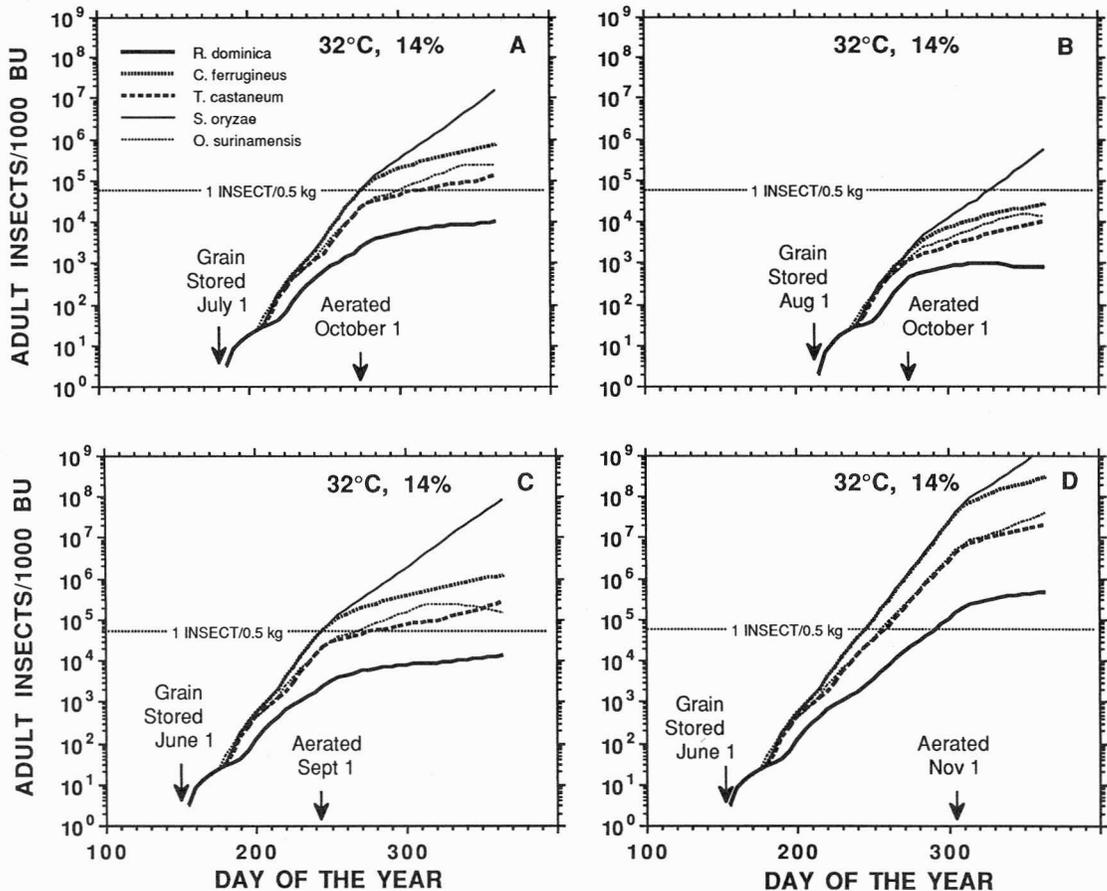
**Table 3. Parameters for regression of measured (y) against predicted (x) population densities for two stored-product insect pests**

Parameters	Species	
	<i>O. surinamensis</i>	<i>S. oryzae</i>
df	53	7
Slope ± SE	1.01 ± 0.048	1.07 ± 0.123
t for HO:slope = 1	0.2803	0.5668
Probability > t	0.7803	0.5885
Intercept ± SE	-0.077 ± 1.79	-12.77 ± 32.23
t for HO:intercept = 0	-0.043	-0.396
Probability > t	0.9661	0.7056
r <sup>2</sup>	0.8967	0.9260

and *O. surinamensis* have the most similar LD<sub>50</sub> (0.06 versus 0.015) for malathion (Haliscak & Beeman 1983).

**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 1988a). Mortality caused by fumigation between 25 and 30°C is similar for the five species considered in our study (Lindgren & Vincent 1966, Hole et al. 1976, Price & Mills 1988).

**Model Simulations.** The model was run using two different grain moistures, 10 and 14%, and two initial grain temperatures, 27 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 stored either on 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. In addition, we 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 reference line of one adult insect per 0.5 kg of wheat is shown on figures to make comparison of treatment effects on different graphs easier. In this study, we were primarily interested in insect densities less than or slightly greater than those at which insects are normally detected (1 insect/0.5 kg). At these densities, interspecific interactions probably do not affect



**Fig. 2.** Predicted effects of (A, B) storage date and (C, D) time of aeration on population growth of five species of stored-grain insects in grain stored at 32°C and 14% moisture content.

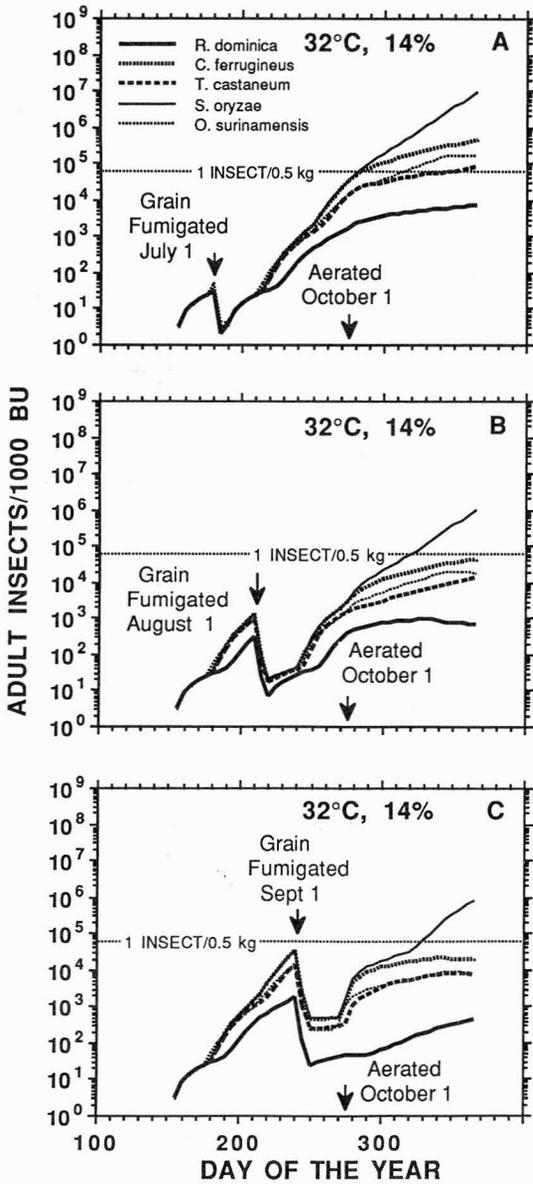


Fig. 3. Predicted effects of time of fumigation on the population growth of five species of stored-grain insects in grain stored at 32°C and 14% moisture content with grain placed in storage 1 June and aeration starting 1 October.

population growth (Solomon 1953). If species interactions were included in the model, the population growth rate would probably decline as populations approached densities of several hundred insects per 0.5 kg.

**Results and Discussion**

**Validation of Models.** Simulation models have been validated for all five species of the insects that we compared. Two of them are validated in this

paper. Models explained 89.7 and 92.6% of the changes in mean estimated population densities of 18 and 3 observed populations of *O. surinamensis* and *S. oryzae*, respectively (Table 3). Slopes >1 indicate that the measured densities of the two species tended to exceed predicted densities. However, neither of the slopes were significantly different from 1. Also, the intercepts of the regression equations were not significantly different from 0, indicating that as densities approach 0, neither measured nor predicted densities were consistently higher or lower than one another. Hagstrum & Throne (1989) have shown that models for *C. ferrugineus*, *R. dominica*, and *T. castaneum* also explain ≈90% of the observed changes in insect population densities. Thus, for all five species, the models provide good representations of their population growth.

**Grain Temperature and Moisture.** The populations of the five pest species grew at different rates in response to temperature and moisture conditions during storage (Fig. 1). It is important to examine differences in population growth among species because they may explain differences in the response of species to management practices. At 14% grain moisture, the difference between population size at 27 and 32°C was much greater for *C. ferrugineus* than for the other species. At 10% grain moisture, the difference between population size at 27 and 32°C was greater for *S. oryzae* than for the other species. In general, grain moisture had a greater effect on *C. ferrugineus* and *S. oryzae* at 32°C than the other three species. Among the other three species, *O. surinamensis* populations were consistently larger than *T. castaneum* populations, and *T. castaneum* populations were consistently larger than *R. dominica* populations. The longer generation time of *R. dominica* was mainly responsible for the slower population growth in comparison to the other species.

**Storage Date.** The amount of time between initial grain storage and fall aeration determines the length of time during which insect pest populations grow under most favorable conditions. Clearly, the time of storage will be an important factor to consider for all species in choosing a management program. Grain is harvested and stored earlier in the southern United States and may be stored longer before cooling than wheat harvested later in the northern wheat-producing regions. A delay of only 1 mo in storage date resulted in an ≈6- to 28-fold reduction in insect pest population densities of the five species by day 365 of the year (Fig. 1D, 2A and B). Differences among species in these reductions were a result of differences in the growth rates of the five species. The largest reduction was for *S. oryzae* and the smallest was for *R. dominica*. The ranked order of the other three species was consistently *C. ferrugineus* > *O. surinamensis* > *T. castaneum*.

**Aeration.** Simulated adult population densities of all five species increased exponentially before

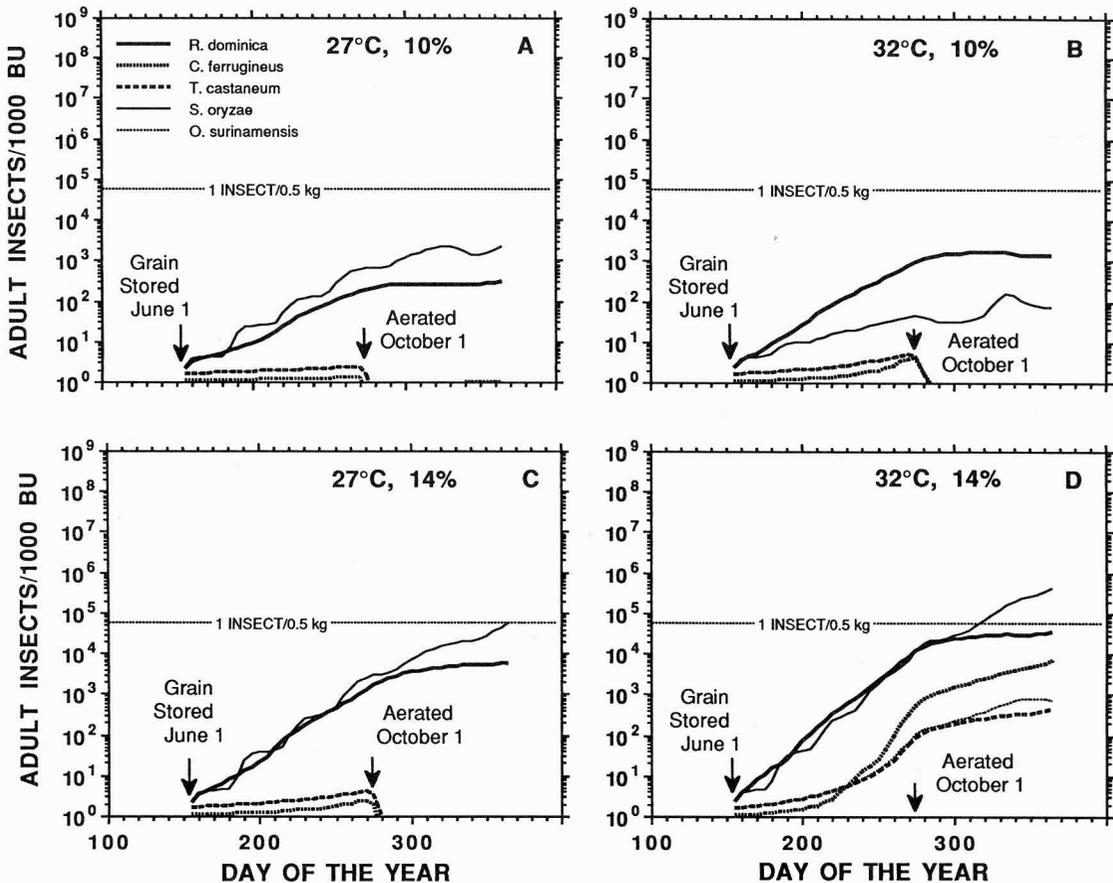


Fig. 4. Predicted population growth of five species of stored-grain insects in grain treated with 10 ppm malathion at grain temperature and percentage moisture conditions of (A) 27°C and 10%, (B) 32°C and 10%, (C), 27°C and 14%, and (D) 32°C and 14% with grain placed in storage 1 June and aeration starting 1 October.

aeration, but their densities generally began to level off soon after the start of aeration (Fig. 1D, 2C and D). Each month aeration was delayed resulted in an  $\approx 4$ - to 24-fold increase in density. Aerating earlier was generally more effective in limiting population growth of *C. ferrugineus* and *O. surinamensis* than population growth of *R. dominica*, *S. oryzae* and *T. castaneum*.

**Fumigation.** Because fumigants have no residual effect, only the insects present in the grain at the time of fumigation are killed. Insects can reinfest the grain almost immediately. Delaying fumigation for 1 or 2 mo generally reduced the numbers of all five insect species that were present on day 365 of the year (Fig. 3). This is because delaying fumigation reduced the time available for population growth after fumigation and before the beginning of cooler fall temperatures. Waiting to fumigate in August or September, instead of fumigating in July, resulted in 6- to 24-fold decreases in population densities of the five species on day 365. Although fumigation was equally effective against all species, the ability of *S. oryzae* populations to grow more rapidly than the other

four species as temperatures decreased in the fall resulted in fumigation being a less effective treatment for this species than for the others.

**Protectant.** The simulations showed that the internal feeding species, *R. dominica* and *S. oryzae*, were much less affected by malathion protectant than the three external feeding species (Fig. 4). Of the two internal feeders, *S. oryzae* was more affected by malathion than *R. dominica*. Treatment of grain with malathion reduced populations of *R. dominica* and *S. oryzae* 2- and 930-fold, respectively, at 32°C and 14% moisture; and 2- and 8,782-fold, respectively, at 32°C and 10% moisture. Populations of the external feeders were eliminated at all conditions except the 32°C and 14% moisture, conditions at which malathion breaks down rapidly. However, even under these conditions, populations of *C. ferrugineus*, *T. castaneum* and *O. surinamensis* were reduced 2,753, 4,272 and 4,493 times, respectively.

**Conclusion.** The simulated growth of insect pest populations in response to wheat storage conditions and insect pest management practices differed among species. These differences generally can be

explained by the way in which population growth rates of the species varied with temperature and moisture conditions and differences in their susceptibility to malathion. Clearly, in some cases, it would be advantageous to know which species are present in choosing a management program and predicting when pest management will be needed. For example, malathion was very effective against the three external-feeding species but was much less effective against *R. dominica*. However, malathion often is applied to grain as it is augered into a storage bin, and the decision to apply protectant is generally made before we know which species will be present. Also, aeration was less effective against *S. oryzae* than the other four species. If we know that *S. oryzae* is present, we might choose to fumigate before aeration, whereas aeration alone might be sufficient to control the other species. Because many of these species of stored-grain insect pests are generally found together, insect control often may require the same combination of several of these management practices regardless of which species actually are present. Unfortunately, species identification generally will be necessary to determine whether there is an optimal management program for the species present or whether the species present is not a factor in choosing a management program.

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