

## Effects of Time of Aeration, Bin Size, and Latitude on Insect Populations in Stored Wheat: A Simulation Study

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**ABSTRACT** A spatial model of *Cryptolestes ferrugineus* (Stephens) population dynamics and bin temperature was used to simulate effects of time of aeration, bin size, and latitude on *C. ferrugineus* density in stored wheat. In unaerated grain, densities of *C. ferrugineus* were predicted to be much greater in wheat stored in Oklahoma than in Kansas or South Dakota and reach greater densities in 272.2-T (10,000 bu) than in 81.6-T (3,000 bu) bins. Automatic aeration controllers (fans turned on when outside air was 10°C lower than grain temperature) suppressed *C. ferrugineus* population growth better than manual aeration starting in November. Automatic aeration also worked better when started at grain harvest rather than waiting until 1 September. In Oklahoma, automatic aeration starting at harvest was the only aeration strategy that prevented *C. ferrugineus* from exceeding 2/kg. Average fan hours to cool the grain to 10°C using automatic control starting at harvest was 270 h for 272.2-T bins and 220 h for 81.6-T bins. Starting automatic aeration at harvest added an additional 30 h. This small increase in fan hours resulted in much greater *C. ferrugineus* suppression, especially in latitudes similar to those of Oklahoma and Kansas. In temperate climates, automatic aeration controllers should greatly reduce the need for chemical control.

**KEY WORDS** *Cryptolestes ferrugineus*, stored grain, model, aeration, integrated pest management

THE STORED GRAIN system is complex, and many factors affect insect population growth in storage bins. Grain temperature and moisture are 2 of the factors that have the greatest effect on insect population growth. In the fall, the periphery of the grain mass cools more quickly than the center. Insect populations continue to increase in the center of grain bins during the cold winter months. We also know that bin size affects the rate that unaerated grain cools in the fall. The centers of large bins cool more slowly than those in smaller bins. Latitude also has an important effect on insect population growth in stored grain. Grain that is harvested in Oklahoma is usually stored 3-4 wk earlier than grain harvested in Kansas. This is caused by earlier warm temperatures in the spring. Because grain is stored earlier in Oklahoma, it remains warmer longer before it cools in the fall. Thus, the grain environment remains favorable for insect population growth longer in Oklahoma than in Kansas. Aeration, using small electric powered fans, can be used to cool the grain earlier; thus it suppresses insect population growth sooner in the storage period. Several state extension programs (Kansas and Indiana) recently have begun advocating early aeration (starting at harvest) as the best nonchemical insect suppression method for

stored grain. Several studies conducted in these states have shown that early aeration alone allows safe storage of grain for many months (Mason et al. 1994, Reed and Harner 1997).

Computer simulation models have been used to simulate the effects of various control strategies on insects of stored grain. Models have been used to investigate the effects of grain temperature, moisture, insecticides, and timing of fumigation (Flinn and Hagstrum 1990a, Hagstrum and Flinn 1990). Models also have been used to show how insecticide efficacy is influenced by grain cooling (Longstaff 1988a) and that resistance develops more slowly in grain that is cooled because of longer generation times (Longstaff 1988b). In addition, aeration air flow rate and the time of day the fan is run influence grain cooling, and the effectiveness of aeration to suppress insect population growth (Thorpe et al. 1982).

A spatial model that simulates changes in temperature and *C. ferrugineus* population dynamics in a grain bin has been developed and validated (Flinn et al. 1992). By dividing the grain bin into many compartments, the model can simulate different rates of insect population growth for each compartment. A spatial model can simulate the effects of non-homogeneous grain temperatures on insect population growth much better than a model that uses average grain temperatures for the whole bin.

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Stored grain researchers have questioned the most economical method to cool grain using aeration. Fans can be controlled manually, or automatically using sensors for air and grain temperature. In this paper we examine the effects of bin size, latitude, and aeration strategy on *C. ferrugineus* population dynamics in stored wheat. A validated model (Flinn et al. 1992) is used to compare these effects using 5 yr of historical weather data.

### Materials and Methods

**Model.** The spatial model used in this study was previously described by Flinn et al. (1992). It uses a 2-dimensional representation of the bin, starting from the bin center and proceeding to the bin wall. The bin is divided into 16 or 12 regions in the large (272.2-T) and small bin (81.6-T) sizes, respectively. The model predicts *Cryptolestes ferrugineus* (Stephens) population dynamics in each of the regions based on temperatures and moistures predicted by the bin temperature model (Metzger and Muir 1983). The insect model uses a distributed delay using 0.1-d intervals to predict insect population growth of all stages of *C. ferrugineus*, and includes density-dependent and cold temperature mortality. Insect immigration rate into the large and small bins was 40 *C. ferrugineus* per 27.2 T per day in the top 2 layers and 20 *C. ferrugineus* per 27.2 T per day in the bottom 2 layers (Flinn et al. 1992). We assumed that immigration into the bins stopped after 1 October because of cooler temperatures. Although immigration may continue slightly longer in Oklahoma, this would have only a minor effect compared with population growth rate in the bin. The bin temperature model uses hourly weather data for wet- and dry-bulb temperature, wind speed, and cloud opacity to predict changes in grain temperature and moisture. The model includes both conduction and convective modes of heat exchange. Thus, cooling or warming of the grain using aeration fans can be simulated as well as no aeration. It also simulates changes in grain moisture caused by aeration. In the simulations, we used push aeration at an airflow rate of 1.3 liters/s/m<sup>3</sup> and assumed a 1.3°C temperature rise caused by heat of compression. The model also assumes that the bins have a fully perforated bin floor to obtain uniform airflow through the grain.

**Model Simulations.** We simulated 4 separate storage seasons, using hourly weather data for Oklahoma City, OK; Topeka, KS; and Sioux City, SD, from 1983 to 1987. These locations were selected to represent the major wheat-growing areas of the United States. We simulated harvest on 1 June, 1 July, and 1 August for Oklahoma City, Topeka, and Sioux City, respectively. Simulations were run from harvest until 30 May the next year. In the simulations, new grain is put into the bins in each of the 4 simulation years. The initial grain temperature and moisture for all of the simulations was 36°C and 12% moisture. The 272.2- and

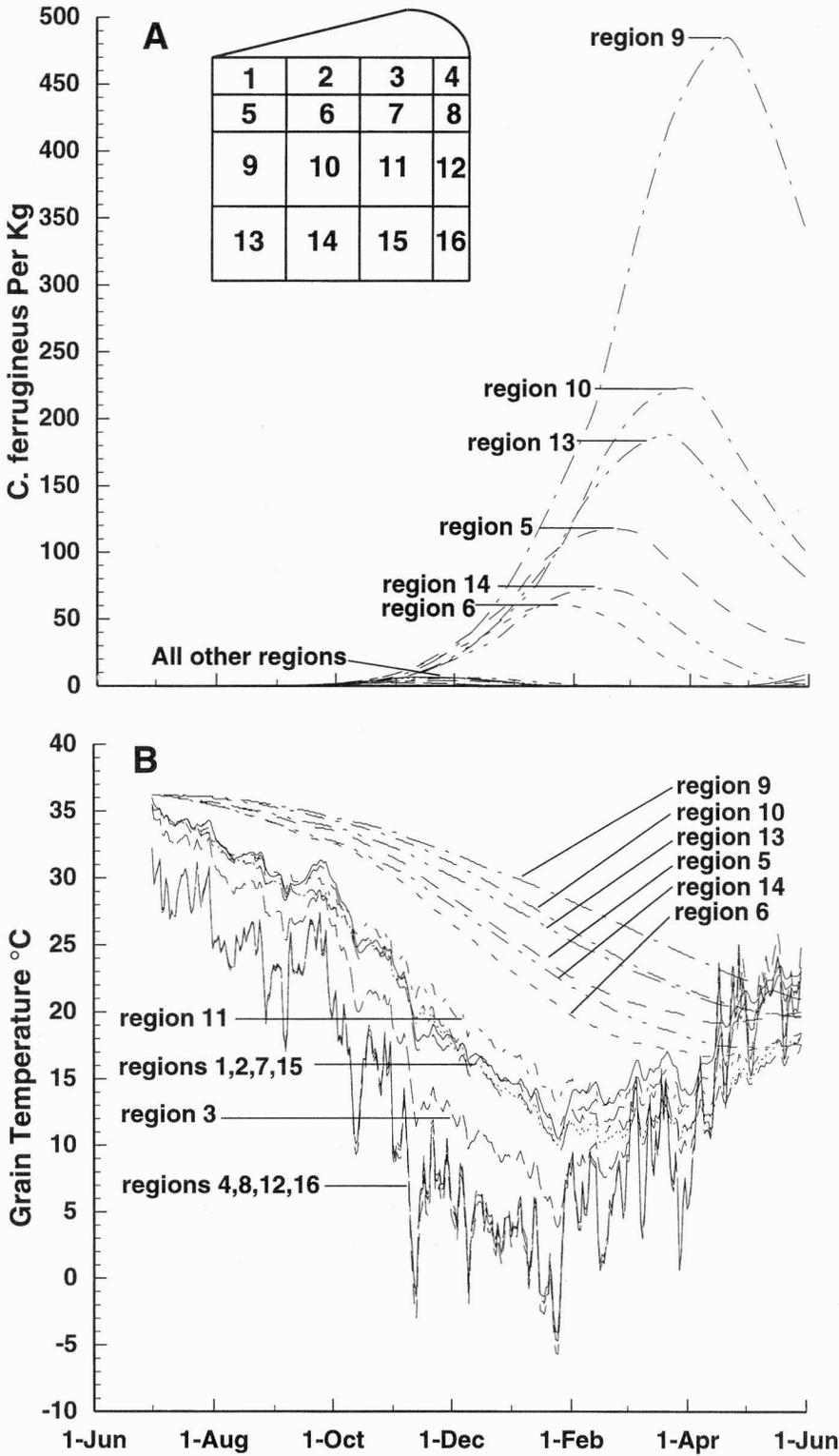
81.6-T bins had diameters of 7.54 and 5.66 m, respectively. Four different aeration strategies were used—no aeration, manual aeration, automatic aeration starting at harvest, and automatic aeration starting 1 September. For manual aeration starting 1 November, we used the recommended 120 h at an airflow rate of 1.3 liters/s/m<sup>3</sup> (Holman 1960). We selected 1 November as the manual aeration start date because farmers often wait for cold temperatures in November to aerate. Automatic aeration was modeled using a simulated temperature sensor located 0.95 m and 1.17 m down from the grain surface in the center of the 81.6- and 272.2-T bins, respectively. Operation of the fan and forced aeration of the grain was simulated when the outside air temperature was at least 10°C below the simulated grain temperature at the sensing point. The fan was operated intermittently rather than continuously. When the fan was on, the model simulated the exchange of heat and moisture between the grain layers and the aeration air. When the fan was off, heat conduction through the grain bulk in the vertical and radial directions was simulated. Because we are simulating push aeration, cool air starts at the bottom of the grain mass and gradually moves to the top of the grain mass. The simulated temperature sensor was placed 0.95 or 1.17 m down in the grain, because the sensor needed to be placed as close as possible to the grain surface to ensure that the controller would continue to cool the grain all of the way to the grain surface, while also minimizing the influence of day and night fluctuations in surface grain temperature on the controller. Automatic aeration stopped for the rest of the storage period after the temperature sensor in the bin reached 10°C.

Simulation results were compared graphically and means and standard errors were computed using Systat 5.2 (Wilkinson et al. 1992).

### Results and Discussion

In unaerated bins, *C. ferrugineus* density was always greatest in the center of the grain mass (Fig. 1A). *C. ferrugineus* population growth rate decreases in the periphery of the grain mass because of cooler temperatures in the fall. However, in the center of the grain mass, temperatures remained warm and the population growth rate continued to be high. These results are similar to what Reed et al. (1991) found in actual field studies. Grain temperature fluctuated greatly on the periphery of the grain mass and little in the center (Fig. 1B). This is because grain near the periphery of the bin tends to buffer grain near the center of the grain mass from external fluctuations in temperature. The bin regions that remained warmer longer were predicted to have the greatest *C. ferrugineus* densities.

Because of space limitations, we cannot graphically show each of the 96 simulations conducted in this study. However, we can show the seasonal



**Fig. 1.** Predicted *C. ferrugineus* density (A) and grain temperatures (B) in 16 regions of an unaerated, 272.2-T (10,000 bu), 7.54-m-diameter steel bin filled with wheat in Topeka, KS. The inset diagram (A) refers to the 16 bin regions simulated by the model (regions 1, 5, 9, and 13 are in the center of the bin).

changes in average *C. ferrugineus* density in a bin, averaged over 4 yr (Fig. 2). Peak *C. ferrugineus* density was always greater at southern latitudes.

In unaerated bins, *C. ferrugineus* density was greater in large (272.2-T) bins compared with small (81.6-T) bins. *C. ferrugineus* densities were  $\approx 5$ , 10, and 25 times greater in large bins compared with small bins in Oklahoma, Kansas, and South Dakota, respectively. Most stored grain insects stop developing and ovipositing when the temperature falls below 17°C (Fields and Muir 1996). No aeration always resulted in much greater *C. ferrugineus* densities compared with other aeration methods.

Manual aeration started on 1 November suppressed *C. ferrugineus* density, but not as much as automatic aeration started at harvest or on 1 September. Farmers often wait until November to cool the grain because of the increased certainty of a sufficiently long period of cold weather to cool the grain completely. However, the sooner the grain is cooled, the more rapidly insect population growth rate is reduced.

Automatic aeration starting at harvest suppressed *C. ferrugineus* population growth more than automatic aeration starting 1 September. In the Oklahoma and Kansas simulations, peak *C. ferrugineus* densities in bins using automatic controllers starting at harvest were  $\approx 1/2$  that of bins with automatic controllers starting 1 September. In Oklahoma, grain temperature was decreased from 36°C at harvest to 25°C 10 d later by using the automatic aeration controller starting at harvest. The rate of population increase of *C. ferrugineus* is  $\approx$ two times as great at 36°C compared with 25°C. Peak population densities in the large Oklahoma bins were  $0.9 \pm 0.3$  (mean  $\pm$  SE) and  $3.1 \pm 0.3$  *C. ferrugineus* per kilogram in bins aerated at harvest, and those aerated 1 September, respectively. The controller usually ran the fan intermittently for 6–13 d after storage and then did not turn on the fans again until September because of warm air temperatures. The aeration fan ran intermittently and accumulated  $\approx 90$  h from 1 June to 12 June.

In South Dakota, there was very little difference in peak population density between the 2 automatic aeration strategies. This is probably because there was only 1 mo from harvest until the 1 September automatic aeration date; this is only enough time for 1 *C. ferrugineus* generation. In contrast, in Kansas and Oklahoma, there were 2 or 3 mo from harvest until 1 September, allowing for 2 or 3 generations.

Grain moisture loss is an important consideration because wheat is sold on a weight basis. Moisture loss should be less with automatic control because the fan operates during the coolest hours only (usually associated with the highest relative humidities). With the automatic controller starting at harvest in Oklahoma, Kansas, or South Dakota, grain moisture decreased from 12.0% at harvest to

$\approx 11.3\%$  when the fan was turned off after the grain reached 10°C. When the controller was started 1 September, grain moisture decreased from 12.0% to 11.5%. With manual aeration starting 1 November, grain moisture decreased from 12.0% to  $\approx 11.5\%$ . Moisture losses using manual aeration can be much higher than automatic aeration because the fan operates continuously.

Variability in *C. ferrugineus* density caused by yearly variation in weather data is indicated by the standard error bars (Fig. 2). The largest variation in *C. ferrugineus* density occurred in small, unaerated bins and was more variable in northern than in southern latitudes. Variation in predicted *C. ferrugineus* density over the 4 yr was least in the bins with automatic controllers. The fact that *C. ferrugineus* density predictions were not that variable over the 4 yr suggests that variability in weather may be somewhat reduced because of the ability of grain in the periphery of the grain mass to act as a buffer. Even though air temperatures may rise and fall rapidly during a day, the grain in the bin center is relatively isolated from these oscillations, as are the insects that live in these areas of the grain.

In most cases, automatic aeration starting at harvest required only an additional 30 h compared with automatic aeration starting 1 September (Fig. 3). Large bins (272.2-T) with automatic aeration at harvest required about 290–320 h to cool to 10°C. Large bins with automatic controllers starting on 1 September required  $\approx 270$ –290 h to cool to 10°C. Small bins (81.6-T) with automatic controllers starting at harvest required  $\approx 230$ –260 h to cool to 10°C. Small bins with automatic controllers starting on 1 September required  $\approx 200$ –230 h to cool to 10°C. The fan hours for the larger bin were greater than for the smaller bin because the fans ran intermittently during the fall, and when the fans were off, the smaller bin was cooled more rapidly than the larger bin by natural cooling.

In most cases, *C. ferrugineus* density was  $1/2$  as great in bins with automatic controllers starting at harvest compared with automatic controllers starting 1 September. The additional 30 h of time would cost approximately \$0.78 at \$0.07/kwh for a 0.5-hp fan. The cost to aerate a 272.2-T bin for 300 h is approximately \$7.88. A controller would cost approximately \$500 to \$700. In contrast, chemical control using chorpyrifos methyl costs approximately \$0.02/27 kg (\$0.02/bu) or \$200 for 272.2 T.

If we use the Federal Grain Inspection Service threshold of 2 live adult insects per kilogram of grain, the simulations showed that in Oklahoma, automatic aeration starting at harvest was the only way to remain less than this threshold using aeration alone. In Kansas and South Dakota, aeration starting 1 September or at harvest prevented average *C. ferrugineus* densities in the bins from becoming greater than 2 insects per kilogram. Field studies in Kansas showed that cooling grain start-

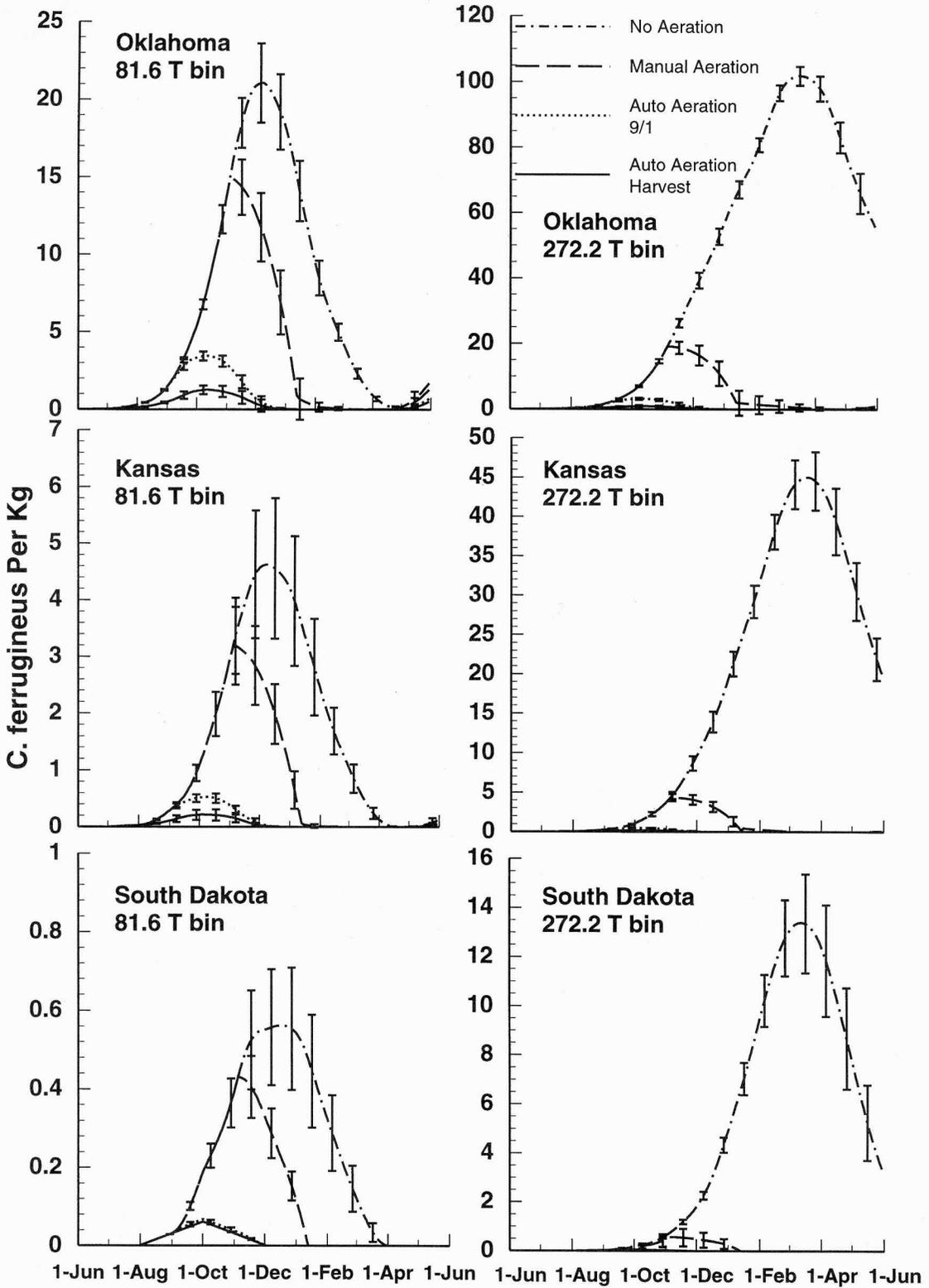


Fig. 2. Predicted average densities of *C. ferrugineus* in Oklahoma, Kansas, and South Dakota. Simulations were conducted using 1983-1987 weather data and 4 aeration strategies in 81.6-T (3,000 bu) and 272.2-T (10,000 bu) bins of wheat. Vertical bars indicate standard errors of the mean.

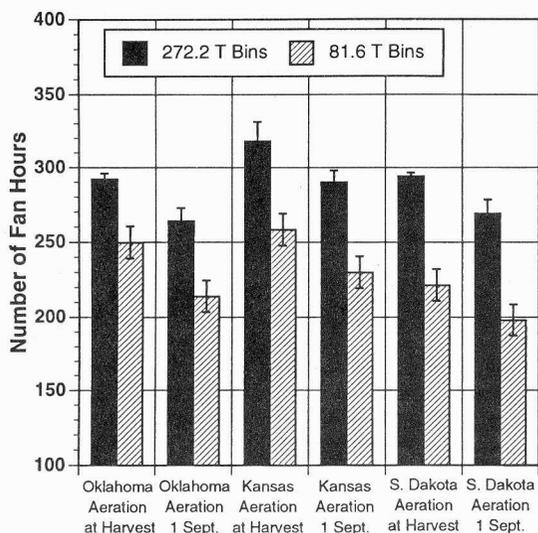


Fig. 3. Average number of fan hours accumulated during 4 storage seasons (1983–1987) using automatic aeration controllers turned on at harvest, or 1 September for wheat stored in Oklahoma, Kansas, and South Dakota, in large (272.2-T) and small (81.6-T) bins of wheat. Vertical bars indicate standard errors of the mean.

ing at harvest in July resulted in well-controlled insect populations; significantly more insects were found in bins that were not cooled until October (Reed and Harner 1997). In South Dakota, both manual aeration or automatic aeration resulted in average *C. ferrugineus* densities of < 2/kg. When manual aeration starting 1 November was used in Kansas and Oklahoma, *C. ferrugineus* densities were greater than the FGIS threshold.

In temperate climates, automatic aeration controllers should greatly reduce the need for chemical control, and they should be the primary choice for suppressing insects in stored grain. This study showed that the best strategy was to allow the automatic aeration controllers to reduce grain temperature as soon as the grain is stored rather than waiting for cooler fall temperatures.

We plan to incorporate this model into the Stored Grain Advisor expert system (Flinn and Hagstrum 1990b) to improve the accuracy of its predictions. This expert system is currently available through the Kansas State University Extension Service.

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