Donahaye, E.J., Navarro, S. and Varnava, A. [Eds.] (1997) Proc. Int. Conf. Controlled Atmosphere and Fumigation in Stored Products, 21–26 April 1996, Printco Ltd., Nicosia, Cyprus, pp. 435–442

SIMULATION MODEL OF LOW-OXYGEN ATMOSPHERES ON INSECT POPULATION DYNAMICS IN STORED GRAIN

P.W. FLINN AND D.W. HAGSTRUM
USDA, ARS, Grain Marketing and Production Research Center,
Manhattan, Kansas 66502, USA

ABSTRACT

A spatial model of the relationship between *Sitophilus oryzae* (L.) population dynamics and bin temperature was used to predict the efficacy of low-oxygen (O_2) atmospheres in suppressing insect pests in bins of stored wheat. A two-dimensional spatial model was used to predict population growth of *S. oryzae* as a function of grain temperature and moisture. In the model, a cylindrical 82-t steel bin was divided into 12 compartments, allowing the model to predict different insect growth rates based on each compartment's temperature and moisture. Incorporated into the model were equations to predict the effects of low-O_2 atmospheres, grain temperature and insect stage on insect mortality. This model can predict the duration of fumigation required to produce a given mortality using low O_2 levels. It can also be used to predict insect density in grain 1–2 months post-fumigation. Simulations showed that fumigating grain at 29°C for 15 d resulted in 99.9% mortality to all stages of *S. oryzae*. However, fumigating at 17°C for 15 d only resulted in 95.7% mortality of the pupae. Thus, with cool grain near the bin walls longer fumigation intervals are required to kill all development stages of *S. oryzae*, and the pupal and adult stages take longer to kill than the egg and larval stages.

INTRODUCTION

Previous studies have shown that the pupal stage of *Sitophilus oryzae* (L.) is particularly resistant to low-oxygen (O_2) atmospheres (Storey, 1975; Lindgren and Vincent, 1970). At 27°C it requires only 2–3 d to reach 95% mortality for the egg, larval and adult stages. However, the pupal stage requires almost 10 d to reach 95% mortality. Cool grain requires much longer fumigation duration than warm grain. At 21°C, it requires 4–8 d to reach 95% mortality for the egg, larval and adult stages and 20 d for the pupal stage. Grain managers using low-O_2 atmospheres to fumigate grain need to be aware of the additional time required when the grain is cool. Grain temperature is not homogeneous in the grain mass in unaerated bins. In the fall, the periphery of the grain mass cools more quickly than does the center. Insect populations therefore often continue to increase in the centers of the grain masses during the cold winter months.

Computer simulation models have been used to simulate the effects of various control strategies on stored-grain insects. Models have also been used to investigate the effects of grain temperature, moisture, insecticides, aeration and the timing of fumigation (Flinn and Hagstrum, 1990a; Hagstrum and Flinn, 1990). In addition, models have been used to show how insecticide efficacy is influenced by grain cooling (Longstaff, 1988).

A spatial model that simulates changes in temperature and insect 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 growth in each compartment. A spatial model can simulate the effects of non-homogeneous grain temperatures on insect population growth much better than can a model that uses average grain temperatures for the whole bin.

Stored-grain researchers have known for some time that the duration of fumigation required to kill different insect stages using low-O_2 atmospheres varies with temperature. However, there has not been any method for predicting the effects of non-homogeneous temperatures in a grain mass on insect population dynamics. In this paper, we examine the effects of duration of fumigation, grain temperature and insect stage on the efficacy of low-O_2 fumigation for *S. oryzae*. A simulation model of *S. oryzae* population growth, coupled with a two-dimensional bin-temperature model, is used to compare these effects.

MATERIALS AND METHODS

Model

The spatial model used in this study was previously described in Flinn *et al.* (1992). It uses a 2-dimensional representation of the bin, starting at the bin center and proceeding to the bin wall. A cylindrical steel bin with 82-t capacity was divided into 12 regions (Fig. 1). The model predicts *S. oryzae* population dynamics in each of the regions based on the temperatures and moistures predicted by the bin temperature model (Metzgar and Muir, 1983). The insect model uses a distributed delay using 0.10-d intervals to predict insect growth of all stages of *S. oryzae* and includes density-dependent and cold-temperature mortality. 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. Low-O_2 fumigation mortality equations were estimated using the data from Storey (1975) that predict, based on grain temperature, the number of days required to produce 97% mortality for the egg, larval, pupal and adult stages (Table 1). The composition of the inert atmosphere in Storey's study was <1% O_2 and 8.5–11.5% CO_2, the balance being principally N_2. The regression equations were estimated from data generated by probit equations that were derived from Storey (1975). Regression equations were fitted to data generated by the probit equations for 13 temperatures (15–39°C).

Model simulations

We used 1983 hourly weather data for Topeka, Kansas, and simulations were run from 1 July (harvest) until 1 December. We simulated the effects of fumigation duration, grain

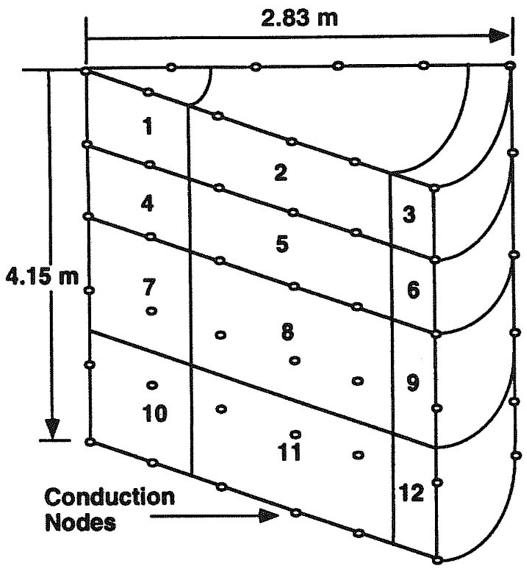

Fig. 1. Diagram showing the 12 bin compartments used in the 2-dimensional model for bin temperature and insect population dynamics in an 82-t cylindrical steel bin.

TABLE 1
Regression parameter estimates for $\log_e$ days until 97% mortality obtained in an atmosphere of <1% O_2 and 10% CO_2 as a function of temperature (°C) for *Sitophilus oryzae*

Life stage	Slope ± SE	Intercept ± SE	R^2	*N*
Egg	0.01990 ± 0.00112	1.16988 ± 0.03138	0.97	13
Larva	−0.00395 ± 0.00109	1.89115 ± 0.03054	0.54	13
Pupa	−0.11088 ± 0.00224	5.26274 ± 0.06276	0.99	13
Adult	−0.15720 ± 0.00632	5.07174 ± 0.17708	0.98	13

Original data from Storey (1975).

temperature and insect density on fumigation efficacy. We started the simulations using a 32°C grain temperature and 12% moisture content. Although the model predicts the effects of aeration, we simulated a no-aeration condition to maximize the effects of non-homogeneous grain temperature on fumigation efficacy. In the simulations, we assumed that the atmosphere in the bin was homogeneous and had the same composition as in Storey's 1975 study.

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

RESULTS AND DISCUSSION

Simulated grain temperatures started at 32°C on 1 July and began decreasing as cooler fall temperatures reduced grain temperature after 1 September (Fig. 2). The model predicted that grain temperatures would fluctuate more in the periphery of the grain mass than in the center. This is because the grain next to the bin wall buffers the grain on the inside of the grain mass from external fluctuations in temperature. Insect population growth rate decreased in the periphery of the grain mass due to the cooler fall temperatures (Fig. 3). In most cases the bin regions that remained warmer longer were predicted to have the highest insect densities. However, the insect density was higher in region 5 than in region 7, even though the temperature remained higher longer in the latter. This was caused by temperatures being higher than optimal in region 7 for part of the storage period.

Insect density at the time of fumigation affected subsequent population recovery (Fig. 4A, B). We simulated the effect of a 10-fold population density by increasing the immigration rate 10-fold. Immigration in the model ceases after 1 October. In Fig. 4B, population density at the time of fumigation was 10 times greater than in Fig. 4A. The resulting population recovery 3 months after fumigation was increased 10-fold in the simulation with the higher immigration rate. These results are similar to those for any insecticide that kills a certain percentage of the population. The larger the population at the time of fumigation, the higher the number of survivors following fumigation. This

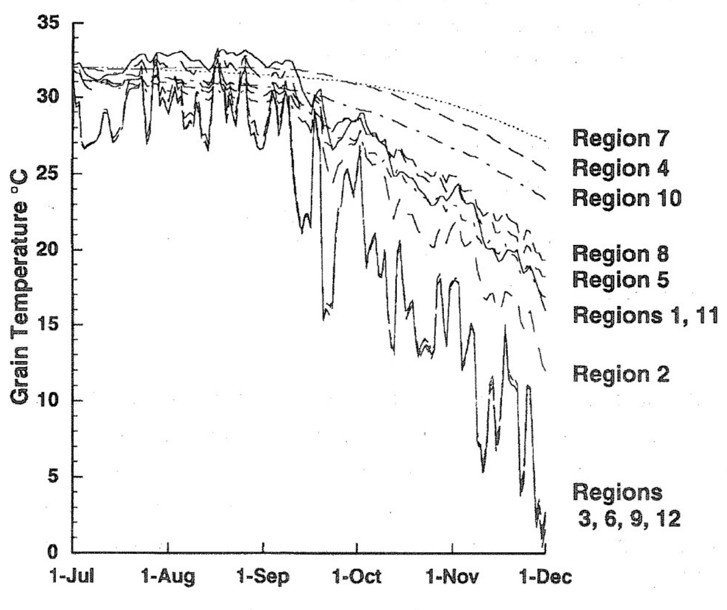

Fig. 2. Simulated grain temperatures in 12 bin compartments for an 82-t capacity cylindrical steel bin located in Topeka, Kansas, using 1983 weather data.

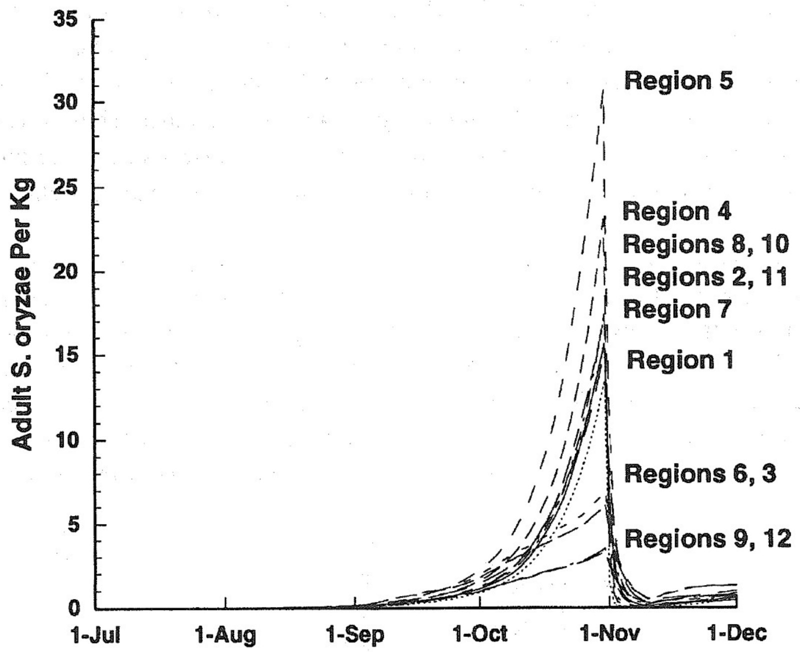

Fig. 3. Simulated *S. oryzae* population density in 12 bin compartments for an 82-t capacity cylindrical steel bin located in Topeka, Kansas, using 1983 weather data. Ten-day fumigation using an exothermic low-O_2 generator was started on 1 November.

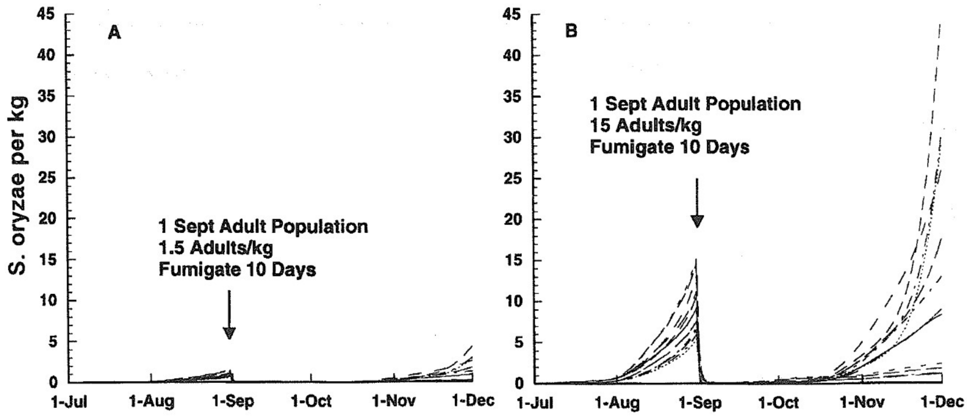

Fig. 4. Simulated population dynamics of *S. oryzae* at a peak density of 1.5 adults/kg (A) and 15 adults/kg (B), fumigated on 1 September.

indicates that population density is an important factor to be considered when making fumigation decisions. A longer fumigation period may be necessary to completely suppress high insect population densities.

The duration of fumigation greatly affected subsequent population recovery (Fig. 5). Our simulated fumigation started 1 September. At this date, the population had reached a density of 16 adult insects per kg. Fumigation for 5, 10, 15 and 20 d resulted in 1,000, 45, 2 and 0 insects per kg, respectively, in bin region 4 by 1 December. Thus, at least a 15-d fumigation period was clearly necessary to kill most of the insect stages and limit recovery. Aeration could of course be used following fumigation to reduce population growth rate.

We examined the effect of temperature on fumigation by simulating the effect of waiting until 1 November to fumigate; by this time, cool autumn temperatures had reduced grain temperatures in the periphery of the grain mass although the center was still warm (Fig. 6). In region 7, at the center of the bin, 15 d of fumigation reduced the egg, larval, pupal and adult stages by over 99.9%. In region 9, at the bin periphery, 15 d of fumigation reduced the egg and larval stages by 99.9% but only reduced the pupal and adult stages by 95.7 and 97.6%, respectively. This is because at low temperatures the pupal and adult stages of

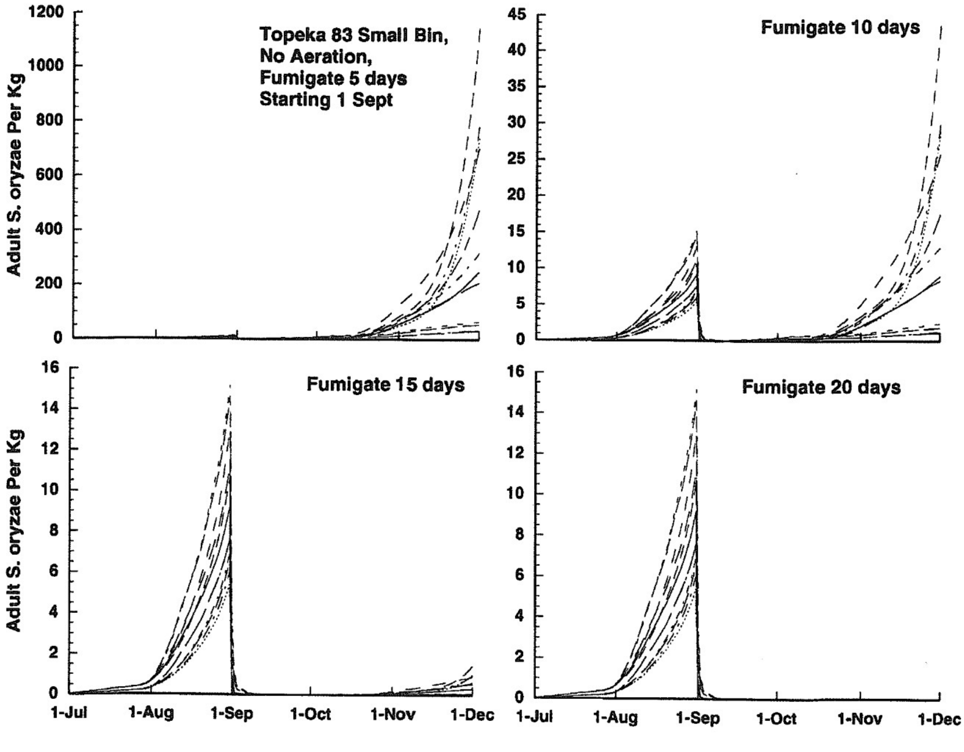

Fig. 5. Simulated population dynamics of *S. oryzae* fumigated for 5, 10, 15 and 20 d starting 1 September. The peak insect density at the time of fumigation was 15 adults/kg.

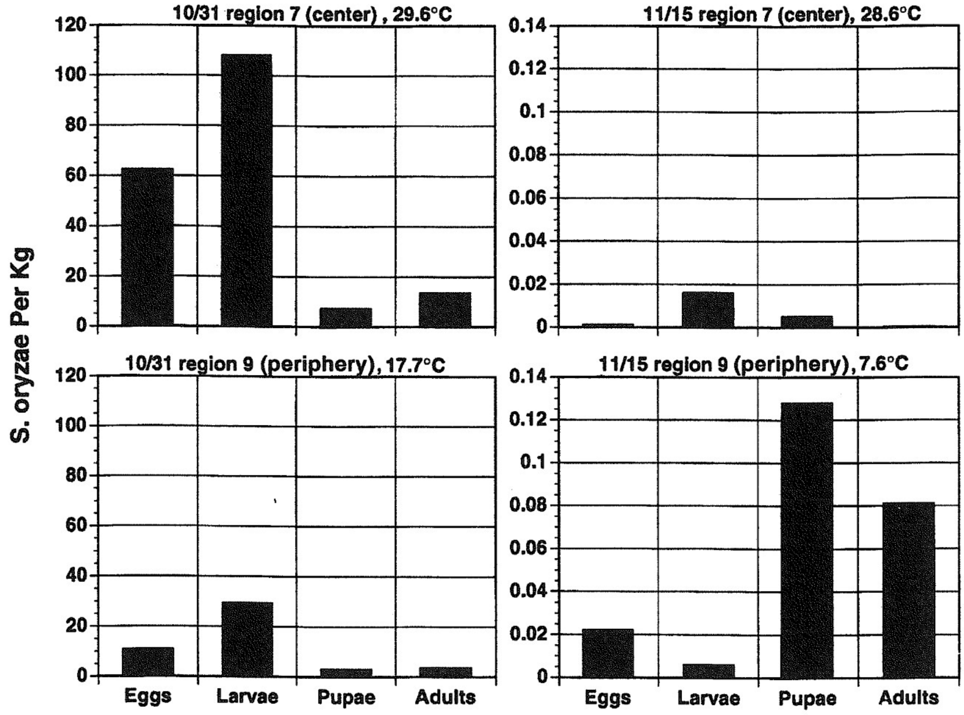

Fig. 6. Effects of grain temperature and low O_2 fumigation on the age structure of *S. oryzae*. The simulated fumigation occurred 1 November and lasted for 15 d.

S. oryzae are more resistant to fumigation than are the other stages. Population density before fumigation was lower in region 9 at the periphery of the grain mass than at region 7 in the center of the grain mass because cooler grain temperature in region 9 suppressed population growth. However, following 15 d of fumigation, the insect density was higher in region 9 than in region 7. It is likely that survivors in region 9 would then migrate into the center of the grain mass. This could cause insect populations to reach high numbers in a few months if the grain center was not cooled by aeration.

We plan to incorporate this model into the Stored Grain Advisor expert system (Flinn and Hagstrum, 1990b) so that it can be used to make low-O_2 fumigation predictions and recommendations for grain managers.

ACKNOWLEDGEMENTS

We wish to thank F. Arthur (USDA, ARS, GMPRC), G. Cuperus (Dept. of Entomology, Oklahoma State Univ.) and E. Soderstrom (USDA, ARS, Hort. Crops Res. Lab.) for reviewing earlier versions of this manuscript.

REFERENCES

Flinn, P.W. and Hagstrum, D.W. (1990a) Simulations comparing the effectiveness of various stored-grain management practices used to control *Rhyzopertha dominica* (Coleoptera: Bostrichidae). *Environ. Entomol.* **19,** 725–729.

Flinn, P.W. and Hagstrum, D.W. (1990b) Stored grain advisor: a knowledge-based system for management of insect pests of stored grain. *Artificial Intelligence Applications in Natural Resource Management* **4,** 44–52.

Flinn, P.W., Hagstrum, D.W., Muir, W.E. and Sudayappa, K. (1992) A spatial model for simulating changes in temperature and insect population dynamics in stored grain. *Environ. Entomol.* **21,**1351–1356.

Hagstrum, D.W. and Flinn, P.W. (1990) Simulations comparing insect species differences in response to wheat storage conditions and management practices. *J. Econ. Entomol.* **83,** 2469–2475.

Lindgren, D.L. and Vincent, L.E. (1970) Effect of atmospheric gases alone or in combination on the mortality of granary and rice weevils. *J. Econ. Entomol.* **63,** 1926–1928.

Longstaff, B.C. (1988) Temperature manipulation and the management of insecticide resistance in stored grain pests: a simulation study for the rice weevil, *Sitophilus oryzae*. *Ecol. Modell.* **43,** 303–313.

Metzgar, J.F. and Muir, W.E. (1983) Computer model of two-dimensional conduction and forced convection in stored grain. *Can. Agric. Eng.* **25,** 119–125.

Storey, C.L. (1975) Mortality of *Sitophilus oryzae* (L.) and *S. granarius* (L.) in atmospheres produced by an exothermic inert atmosphere generator. *J. Stored Prod. Res.* **11,** 217–221.

Wilkinson, L., Hill, M. and Vang, E. (1992) *SYSTAT: Statistics, Version 5.2.* SYSTAT Inc., Evanston, IL, USA.