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Simulation model of *Rhyzopertha dominica* population dynamics in concrete grain bins

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Abstract

Rhyzopertha dominica is one of the most damaging insect pests in grain elevators and causes millions of dollars worth of stored grain losses annually in the USA. A simulation model was developed for predicting *R. dominica* population dynamics in concrete grain bins. The model used a two-dimensional representation of a cylindrical concrete bin (33 m tall × 6.4 m wide), and used hourly weather data to predict changes in grain temperature. Output from the grain bin temperature and moisture module was used by the insect module to predict changes in insect density in 32 different bin regions. When compared to validation data from nine grain bins, the model accurately predicted insect vertical distribution and insect density. In December, the highest insect density was in the top center of the grain mass, and decreased steadily with increasing depth and towards the periphery of the grain mass. *R. dominica* attains this spatial distribution because immigration is primarily through the top of the bin, and higher populations occur in the interior of the grain mass because of warmer temperatures there. Initially, the model underestimated actual insect density in the grain bins. We increased the immigration rate by 50% and this resulted in a much better prediction of *R. dominica* density by the model. From 20 September to 14 December, populations of *R. dominica* increased from 0.1 to 3.5 insects per kg of wheat.
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Keywords: *Rhyzopertha dominica*; Population dynamics; Stored wheat; Spatial model; Concrete bin

1. Introduction

Stored grain insects cause millions of dollars worth of losses annually in the US. Most of the wheat is stored in concrete bins in elevator facilities. Wheat is often infested by several species of

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insect soon after harvest in June or July in Oklahoma and Kansas (Hagstrum, 1987, 1989). *Rhyzopertha dominica* (F.), the lesser grain borer, is one of the most damaging insect pests in elevators. The adults and larvae tunnel into the kernels while feeding and result in insect fragments in flour following milling. Two or more live "grain-damaging" insects per kg of wheat result in an infested designation on the grain inspection certificate (FGIS, 1997). The infested designation can be removed by killing the insects, usually by fumigating the grain. Penalties are charged when insect-infested wheat is sold (Reed et al., 1989). Insects that develop and feed inside wheat kernels can produce "insect-damaged kernels" or IDK (FGIS, 1997). The lesser grain borer produces IDK when adults emerge from the kernels. If wheat contains more than 32 IDK per 100 g, it is designated as sample grade (FGIS, 1997). Sample grade wheat cannot be sold for human consumption and the market value drops dramatically.

Computer models have been developed for predicting changes in grain temperature and moisture in grain bins (Metzger and Muir, 1983). Models have also been developed for insect population growth in farm-stored wheat (Flinn and Hagstrum, 1990; Flinn et al., 1997). Because wheat is often stored longer and in larger quantities at elevators than on farm, insect ecology could be different in concrete grain bins compared to grain stored in steel bins on farms. Typical elevators consist of double rows of concrete bins, 33 m tall × 6.4 m wide. Each bin holds approximately 680 t of wheat. However, no models have been developed that predict insect population dynamics in concrete elevators. In this paper, we develop and validate a model that predicts *R. dominica* population dynamics in wheat stored in concrete elevator bins.

2. Materials and methods

2.1. Model

The spatial model used in this study was modified from a previously described farm bin simulation model (Flinn et al., 1992, 1997). For the insect component, a distributed-delay model (Manetsch, 1976) was used to predict population growth of *R. dominica* as a function of grain temperature and moisture (Flinn and Hagstrum, 1990). This insect was selected because it is one of the most numerous and damaging pests of stored grain in central and southern USA. 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 grain 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.

The insect model was coupled with a two-dimensional bin temperature model developed by Metzger and 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. The bin model requires initial values for bin diameter, depth of grain, type of grain (wheat, maize, 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. The bin model is a two-dimensional representation of a cylindrical concrete bin, starting from the bin center and proceeding to the bin wall; the bin width was assumed to be 6.4 m. We modified the farm bin model by increasing the height of the bin from 6 to 33 m. This required that we increase the number of vertical temperature conduction nodes from 11 to 21 (a node is a spatial location in the bin model that predicts temperatures). We assumed that the bin wall was 15 cm-thick concrete, the bin floor was solid concrete, and that the headspace temperature was the same as ambient air temperature. These dimensions are averages of the dimensions of the validation bins.

For the insect component of the model, we divided the bin into 32 regions (four regions wide by eight regions tall). The model predicts *R. dominica* population dynamics in each of the regions based on grain temperatures predicted by the bin temperature model. The insect model uses a distributed delay using 0.1-d intervals to predict insect population growth of all stages of *R. dominica*, and includes mortality during the immature stages and low temperature mortality. We first evaluated the model with the same insect immigration rate that we used in a previous model for farm-stored grain (Flinn et al., 1997). However, we changed the immigration rate into the top eight layers of grain to: 0.015, 0.0074, 0.0037, 0.0018, 0.00092, 0.00046, 0.00023, and 0.00011 insects/t/d, respectively. This was done to simulate the exponential decrease of insects immigrating into the grain from the top of the grain bin (Hagstrum, 1989). We assumed that immigration into the bin stopped after 1 October because of cooler temperatures.

2.2. *Model validation*

We simulated one storage season, using hourly weather data for Topeka, Kansas, USA. We assumed that the bin was filled on 1 July. Simulations were run from 1 July until 14 December. The initial grain temperature and grain moisture for the simulation were set at 27°C and 12% moisture content (wet weight).

Validation data were obtained by sampling insect populations in concrete bins filled with wheat using a vacuum-probe sampler. The elevator was located in central Kansas. Approximately nine bins were sampled every 2 months starting in September. The bins were approximately 33 m tall × 6.4 m wide. The wheat was sampled for insects using a vacuum pump powered by a 5.3-kW gasoline engine, connected by flexible plastic tubing to sections of rigid aluminum tubes 1.2 m long × 3.5-cm wide. To minimize insect mortality during grain probing, we used the lowest vacuum setting possible. A 3.91 (about 3-kg) sample of grain was taken during every 1.2 m transect of grain, to a depth of 12 m. Grain samples were processed twice over an inclined sieve ($89 \times 43\,\mathrm{cm}^2$, 1.6 mm aperture) (Hagstrum, 1989) to separate insects from the grain; only live adult insects were counted. Validation data were selected from bins that were sampled at least three times, starting in autumn, in which the grain was not moved or fumigated.

Simulation results were compared graphically and means and standard errors were computed using SAS (SAS, 1997).

3. Results and discussion

The model tended to underestimate the average density of *R. dominica* in the grain bin when we used the same immigration rate that was used in the farm-storage model (0.35 insects/27.2 t/d) (Fig. 1). We increased the immigration rate by 50% and the new model predicted the population trends much better (dashed line). Immigration rates may be higher in elevators than in farm bins because there may be higher numbers of resident insect populations in elevators. Grain bins are much larger in concrete elevators and these bins often do not have aeration fans; thus, unaerated grain remains warmer longer at the elevator compared to farm storage. Because the grain remains warmer longer, insects have the potential to reach a higher density before natural cooling occurs in the winter. In the USA, grain is stored year-round in elevators, whereas it is usually present on farms for not more than half a year. In addition, there are more insect refugia in elevators located in tunnels, boot pits, legs, and dust storage bins.

Figure 2 shows the predicted insect density and spatial distribution of *R. dominica* populations over a 3-month period. Population density was predicted to be highest in the top center of the bin. The reasons for this are: (1) immigration rates are highest in the top layers of the grain and decrease exponentially in subsequent layers (Hagstrum, 1989); (2) the periphery of the grain mass cools faster than the center, so population growth is slower in the periphery. *Rhyzopertha dominica* populations increase two times faster at 32°C than they do at 25°C, and *R. dominica* population growth ceases at temperatures below 20°C (Hagstrum and Milliken, 1988).

The model tended to slightly overestimate cooling of the top layer of grain. On 7 September predicted and actual average grain temperatures in the top layer (0–1.2 m) were 28.6° and 27.8 ± 0.5°C, respectively. On the same date, predicted and actual average temperatures in the lower layers (1.2–11 m) of the grain bins were 29.0° and 27.8 ± 0.5°C, respectively. On 2 November in the top layer, predicted and actual grain temperatures were 19.4° and 23.5 ± 1.7°C, respectively. Predicted and actual average temperatures in the lower layers were 28.9° and 28.9 ± 0.6°C, respectively.

The model predicts a hypothetical situation in which no insects are present in the bottom of the bin. If the bin bottom is not cleaned before filling, or if infested grain is not properly fumigated

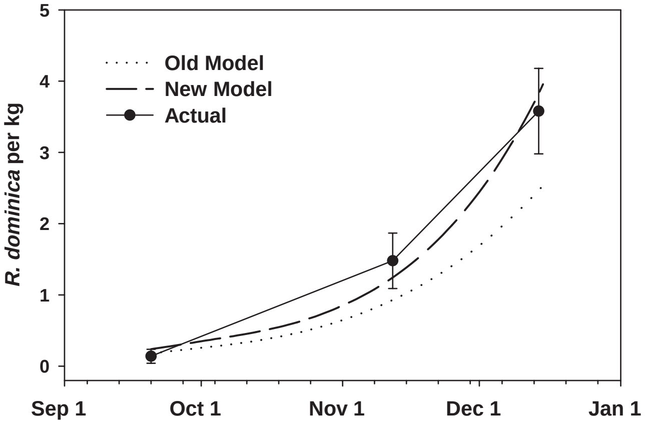

Fig. 1. Average *R. dominica* density in concrete bins, and model predictions (error bars indicate SE of the mean).

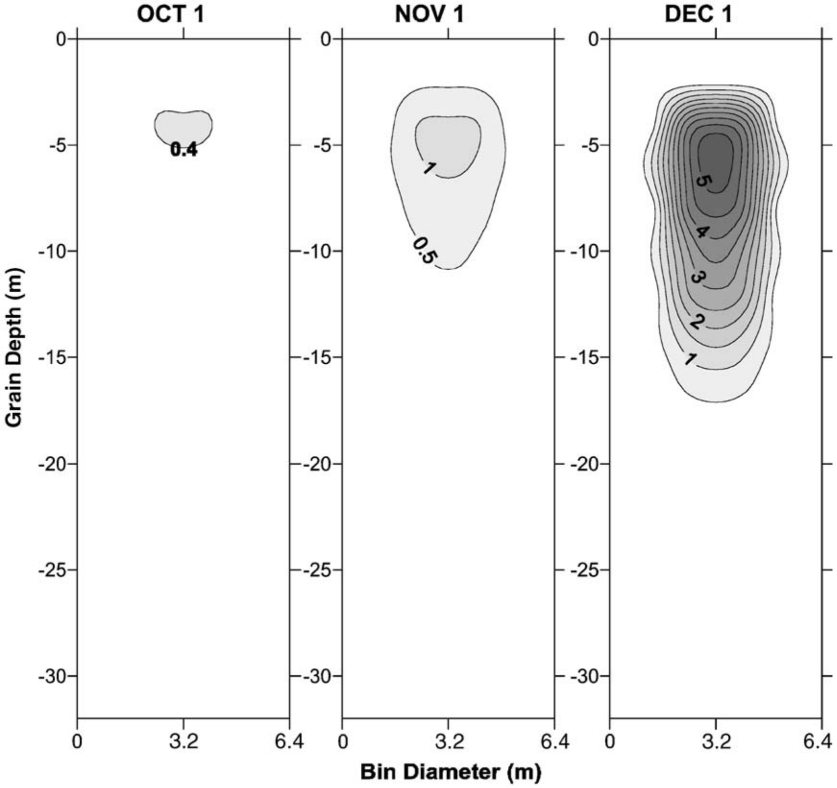

Fig. 2. Predicted *R. dominica* population density (insects/kg) and spatial distribution over a 4-month period (September, October, November, and December). The cylindrical concrete bin was 6.4 m wide × 33 m tall.

during bin filling, then the insect distribution in the bin can be different from what is predicted by the model.

The vertical distribution predicted by the model was compared to the average actual distributions for nine grain bins sampled on 14 December (Fig. 3). Insect density was highest in the 1.2–3.7-m layer of the grain, and decreased exponentially with depth. The distributions were similar, although the model predicted lower densities in layers below 2.4 m than were observed in bins. This could be caused by insect movement into lower, warmer, grain layers as the sides and top of the grain mass cool in the fall. A model has been developed for farm-stored wheat that predicts insect movement for *Cryptolestes ferrugineus* (Stephens) in response to temperature gradients (Mani et al., 2001).The current model does not include insect movement; we will incorporate this component in a future version of the model.

This model will be used in a decision support system we are developing for elevators, as part of the area-wide integrated pest management (IPM) program for insect pests in stored wheat. Predictions of insect growth by the model can reduce the cost of sampling by reducing its frequency. An additional advantage of using the model in an IPM program is that the time required for insects to reach an economic injury level can be predicted. This allows fumigations to

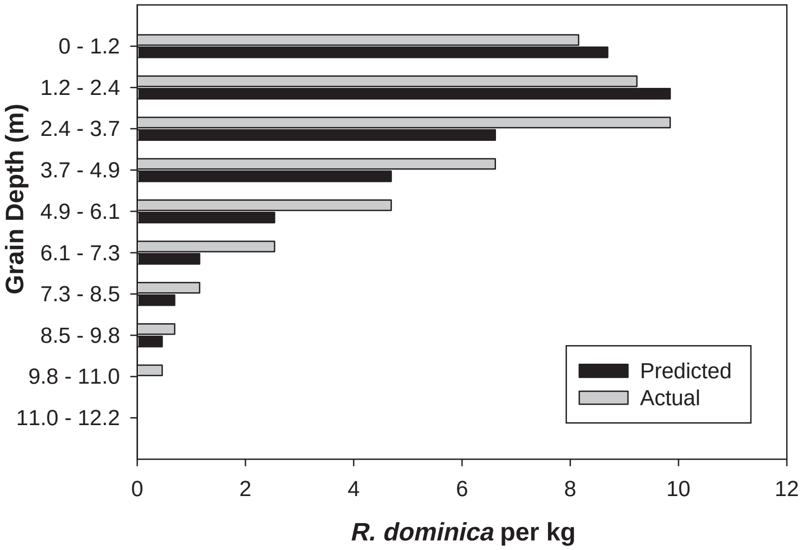

Fig. 3. Average actual and predicted vertical distributions of *R. dominica* density in nine concrete bins (6.4 m wide × 33 m tall) on 14 December 1999.

be timed more accurately, and reduces the frequency of fumigation. Finally, the number of IDK can be predicted with the model. When a new adult *R. dominica* or other internal feeding insect emerges from inside a wheat kernel, one IDK is produced. Grain managers and flour mills use IDK as an index to judge internal insect infestation when buying or selling grain. The number of IDK found in a grain sample influences grain price, and can result in rejection of the grain shipment (Reed et al., 1989).

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References

Federal Grain Inspection Service (FGIS), 1997. Grain Inspection Handbook, Book II Grain Grading Procedures. Fed. Grain Insp. Serv., US Department of Agriculture, Washington, DC.

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

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

Flinn, P.W., Hagstrum, D.W., Muir, W.E., 1997. Effects of time of aeration, bin size, and latitude on insect populations in stored wheat: a simulation study. Journal of Economic Entomology 90, 646–651.

Hagstrum, D.W., 1987. Seasonal variation of stored wheat environment and insect populations. Environmental Entomology 16, 77–83.

Hagstrum, D.W., 1989. Infestation by *Cryptolestes ferrugineus* (Coleoptera: Cucujidae) of newly harvested wheat stored on three Kansas farms. Journal of Economic Entomology 82, 655–659.

Hagstrum, D.W., Milliken, G.A., 1988. Quantitative analysis of temperature, moisture, and diet factors affecting insect development. Annals of the Entomological Society of America 81, 539–546.

Mani, W., Muir, W.E., Jayas, D.S., White, N.D.G., 2001. Computer modeling of insect-induced hot spots in stored wheat. Canadian Biosystems Engineering 43, 47–414.

Manetsch, T.J., 1976. Time-varying distributed delays and their use in aggregative models of large systems. IEEE Transactions on Systems, Man, and Cybernetics 6, 547–551.

Metzger, J.F., Muir, W.E., 1983. Computer model of two-dimensional conduction and forced convection in stored grain. Canadian Journal of Agricultural Engineering 25, 119–125.

Reed, C., Wright, V.F., Pedersen, J.R., Anderson, K., 1989. Effects of insect infestation of farm-stored wheat on its sale price at country and terminal elevators. Journal of Economic Entomology 82, 1254–1261.

SAS Institute, 1997. SAS/STAT software changes and enhancements through release 6.12. SAS Institute, Cary, NC.