MODELING THE EFFECTS OF INSECT STAGE AND GRAIN TEMPERATURE ON PHOSPHINE-INDUCED MORTALITY FOR *RHYZOPERTHA DOMINICA*

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ABSTRACT

Experiments were conducted to determine the effects of insect stage and temperature on phosphine-induced mortality for *Rhyzopertha dominica*. Insects were exposed to 180 ppm (0.25 g/L) of phosphine. The temperatures used were 10, 15, 20, 25, 30, and 35 C. Egg, larval, pupal and adult *R. dominica* were exposed to phosphine for 12, 24, 36, 48, 72, or 96 h. The egg and pupal stages were the most resistant. At 15 C, it took 1.5 days exposure to phosphine to kill 95% of the eggs. At 35 C, it took only 0.7 days to kill 95% of the eggs. A stage-specific model was developed for predicting phosphine-induced mortality for *R. dominica*. The model predicts *R. dominica* population growth as a function of grain temperature. Equations were incorporated into the model that predicts the effects of grain temperature and insect stage on phosphine mortality. The model can be used to predict the length of fumigation required to produce a given mortality at a given grain temperature, and to predict insect population recovery following fumigation. Simulations showed that fumigating grain at 31°C for 2 d resulted in 99.9% mortality to all stages of *R. dominica*. However, fumigating 18°C grain for 2 d only resulted in 99% mortality of *R. dominica* eggs and pupae. Increasing the fumigation duration to 3 d killed 99.9% of eggs and pupae even when the grain was 18 C. These estimates do not include the time necessary for gas to reach 180 ppm in a bin, so an additional day should be added for this. Population recovery following fumigation was rapid in un-aerated grain if the grain was fumigated for two d. If the bin was aerated following fumigation, populations remained very low for 4 months until the grain began to warm in the spring.

INTRODUCTION

Many factors can affect whether an insect population will survive phosphine (PH_3) fumigation. Some of the more important factors include gas concentration, duration of fumigation, grain temperature, and stages of the insects that are present. Researchers have known for a long time that some insect stages are more resistant to PH_3 than others, and that tests should investigate all insect stages (Lindgren and Vincent 1966; Winks and Hyne 1997). Both temperature and insect stage can affect fumigation efficacy. Previous studies have shown that the egg and pupal stages of *Rhyzopertha dominica* (F.) are particularly resistant to PH_3 fumigation (Hole *et al.* 1976). Lindgren and Vincent (1970) showed that it took much longer exposure

periods to kill adult *Tribolium confusum* Duv., and *Sitophilus oryzae* (L.) at lower temperatures than at higher temperatures. For example, at 26.7°C it took only 4 h to kill 99%, and at 15.6 C it required 16 h to kill 99% of the *T. confusum* adults. Stored grain researchers have known that the duration of fumigation required to kill different insect stages using PH_3 varies with grain temperature. Computer models have been developed (Annis and Banks, 1993) that predict the changes in PH_3 concentration in grain bins. However, only rudimentary attempts have been made to predict PH_3 induced mortality in population dynamics models (Flinn and Hagstrum 1990) and, this model does not include the effects of temperature on insect mortality. A complete data set is not available for *R. dominica* that describes PH_3 induced mortality over a full range of grain temperature and for all insect stages.

A spatial model that simulates changes in grain temperature and insect population dynamics in a grain bin has been developed and validated (Flinn *et al.* 1992). This model could be made more useful if it could accurately predict the effects of PH_3 fumigation on insect population dynamics in stored grain.

The objective of this study was to develop equations that predict the effects of temperature and insect stage of *R. dominica* on PH_3-induced mortality, and to use these equations in a population dynamics model to examine the effects of duration of fumigation, grain temperature, and insect stage on the efficacy of PH_3 fumigation for *R. dominica*.

MATERIALS AND METHODS

Model

The spatial model used in this study was previously described in Flinn *et al.* 1992. It uses a two-dimensional representation of the bin, starting from the bin center and proceeding to the bin wall. A cylindrical steel bin with 82-ton capacity was divided into 12 regions. The model predicts *R. dominica* population dynamics in each of the regions based on temperatures and moistures predicted by the bin temperature model (Metzgar and Muir 1983). The insect model uses a distributed delay, using 1/10 of a day intervals to predict insect growth of all stages of *R. dominica*. 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.

In a study that will be published separately, all stages of *R. dominica* were exposed to 180 ppm (0.25 g/L) of phosphine gas. Eggs, larva, pupa, and adults were placed into small vials (20 per), and the vials were put into a fumigation chamber, a 3.8 L glass jar. The jar was fitted with a metal lid with a rubber septum. Standardized PH_3 gas was injected into the jar. The PH_3 concentration inside the jar was about 180 ppm (0.25 g/L). The jars were kept in chambers maintained at 10, 15, 20, 25, 30, and 35 C. After the fumigation period was over (0, 12, 24, 36, 48, 72, or 96 h) the jars were opened, and the vials were moved into a growth chamber. The vials were kept in the chamber long enough so that the insects would progress into the next stage (1-2 week); at this point, the percentage mortality was determined.

A nonlinear logistic dose response equation was used to fit the survivorship as a function of exposure time for each life stage and temperature:

$$y = a + \cfrac{b}{\left\{ 1 + \left(\cfrac{x}{c} \right)^{d} \right\}}$$

Where y is survivorship, x is time, and a, b, c, and d are fitted parameters. TableCurve 2D (Anon. 1996) was used to fit the data to this equation. The survivorship graphs were used to estimate the time in days to reach 95 % mortality for each insect stage and temperature. Linear equations were fit to this data to predict the number of days to reach 95% mortality based on temperature, for each life stage.

Model simulations

We used 1983 hourly weather data for Topeka, Kansas, and simulations were run from harvest (1st July) until 1st December. We simulated the effects of grain temperature, insect stage, and fumigation duration on fumigation efficacy. We started the simulations using a grain temperature of 35°C and 12% moisture content. We simulated the effects of un-aerated and aerated grain to investigate the effects of grain temperature on fumigation efficacy. In the simulations, we assumed that the PH_3 gas concentration in the bin was homogeneous, and that it reached a concentration of 180 ppm (0.25 g/L) immediately, and remained at that concentration until fumigation ended. We realize that gas concentrations are not homogeneous, and that the concentration changes over time. These refinements will be included in future versions of the model. Our assumptions, while simplistic, should still demonstrate how grain temperature affects PH_3 efficacy, and insect population dynamics in stored grain.

RESULTS AND DISCUSSION

The nonlinear logistic dose response equation fit the data well (r^2 ranged from 0.98 – 0.99) for all four insect stages and six temperatures. Figure 1 shows one of the fits for survivorship of *R. dominica* eggs at 35 C. Because a probit analysis will be presented in another paper, the rest of the graphs are not shown. The graphs were used to determine the number of days it took to reach 95 % mortality, for each stage and temperature. The longest survival occurred at 15 C for all insect stages (Table 1). The egg and pupal stages were the most resistant. At 15 C, the egg stage reached 95% mortality after 1.5 d exposure to 180 ppm of PH_3. The pupal stage reached 95% mortality after 1.7 d of exposure. At 35 C, the egg and pupal stages reached 95% mortality after 0.7 and 0.3 d, respectively. In contrast, the larval and adult stages took 0.8 and 1.2 d to reach 95% mortality at 15 C.

A linear model was fit to data in Table 1 to predict the number of days to reach 95% mortality as a function of temperature, for each insect stage (Table 2). The model fit the data well for most insect stages. The r^2 values for the egg, larval, pupal and adult stages were 0.97, 0.54, 0.99, and 0.98. These equations were used to develop a PH_3 gas mortality algorithm for the *R. dominica* population dynamics model.

Simulated grain temperatures started at 35°C on 1st July, and began decreasing as cooler temperatures in autumn reduced grain temperature after 1st September, and decreased rapidly when aeration was applied on 20th October (Fig. 2). The model predicted that grain temperatures would fluctuate more in the periphery of the grain
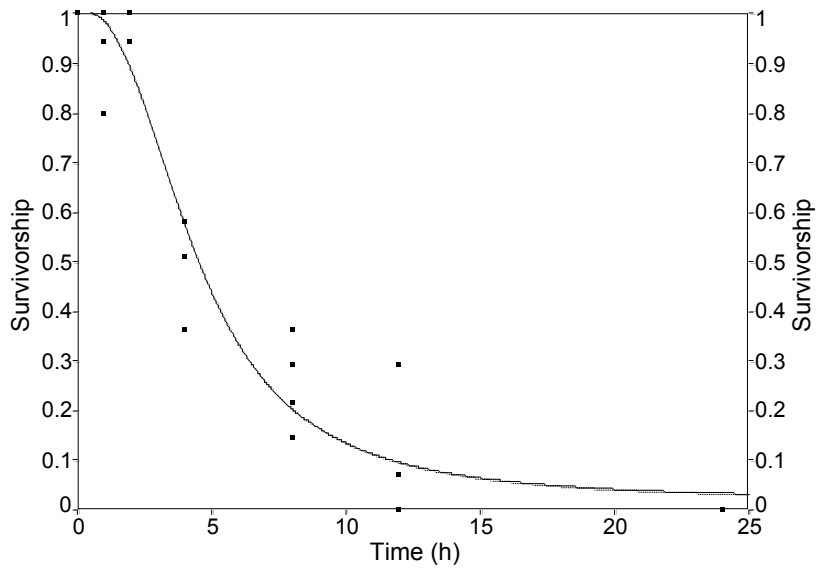
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Fig. 1. Effects of exposure time on survivorship of *Rhyzopertha dominica* eggs exposed to 180 ppm phosphine at a temperature of 35 C.

mass than in the center. This is because grain next to the bin wall buffers the grain on the inside of the grain mass from external fluctuations in temperature. We used the center region (region 7) of the bin for comparisons because this region of the bin remained warmer longer, and remained cool when aerated (Fig. 3). The simulation model predicted that when the bin were fumigated on 1st November for 2 d, egg and pupal stages would survive the fumigation better than the adult stages would (Fig. 4). When the bin was fumigated on 1st November, and either aerated on 20th October or not aerated, fumigation killed 99.9% of the immature stages in un-aerated grain and 99% of the immature stages in aerated grain (Fig. 5). Grain temperatures in region 7 on 1st November were 31.4 C if not aerated and 17.9 C when the bin was aerated.

TABLE 1
Effects of temperature and insect stage for *Rhyzopertha dominica* exposed to 180 ppm phosphine

Temperature	Days Until 95 % Mortality			
	Eggs	Larvae	Pupae	Adults
10	1.0	1.0	0.9	0.6
15	1.5	0.8	1.7	1.2
20	1.5	0.8	0.9	0.7
25	1.0	0.4	0.5	0.3
30	0.8	0.6	0.8	na
35	0.7	0.3	0.3	0.3

The duration of fumigation had a big effect on population mortality (Fig. 6). Even if the grain was cooled by aeration in October, the model predicted 99.9% mortality to the immature stages if the duration of fumigation was increased to 3 d. Thus, it is evident that at least a 3-day fumigation period was necessary to kill most of the eggs and pupae when the grain was cool. For the model we assumed that gas concentrations reached 180 ppm immediately; in the real world, it may take more than 24 h for gas concentrations to reach this level. Thus, the actual total fumigation time may be closer to 4-5 d.
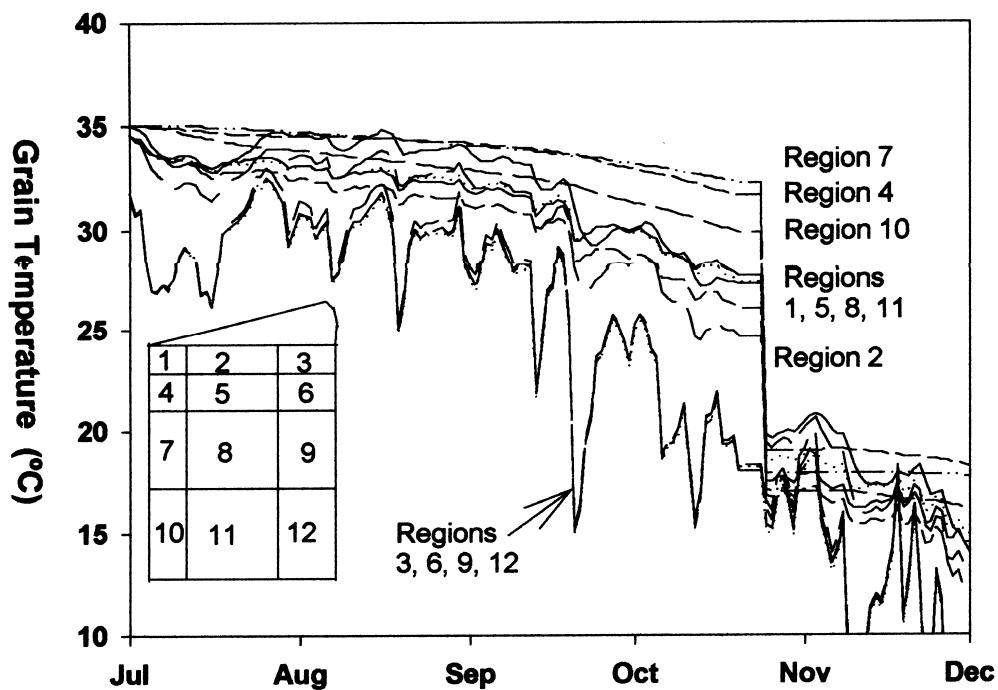
Fig. 2. Simulated grain temperatures in 12 bin compartments for a 82 ton capacity cylindrical steel bin located in Topeka Kansas, using 1983 weather data The bin was aerated for 120 h on 20th October.

The model showed that aerating the grain after fumigation was very effective in suppressing population recovery (Fig. 7). Fumigating un-aerated grain caused a 99.9% reduction, however, the density of immature *R. dominica* reached damaging levels 40 d later. If the grain was aerated following fumigation, the density of immature insects remained very low until spring. If possible, it is important to cool the grain with aeration following fumigation. This can greatly decrease population recovery, because in un-aerated grain, the center of the grain mass can remain warm through the winter, so that even if the grain is fumigated, a few survivors can lead to high insect densities several months later.
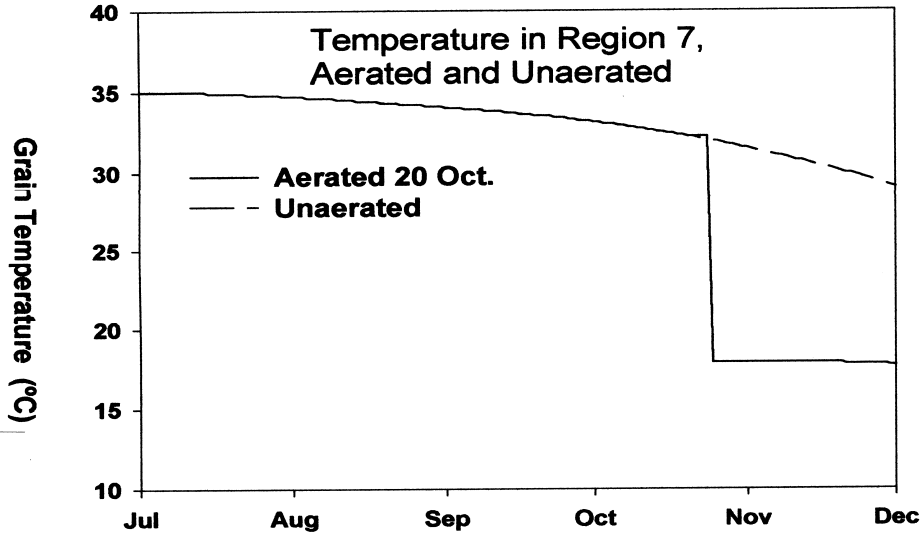
Fig. 3. Simulated grain temperatures in the middle bin region for a 82 ton capacity cylindrical steel bin located in Topeka Kansas, using 1983 weather data; either un-aerated or aerated for 120 h on 20th October.
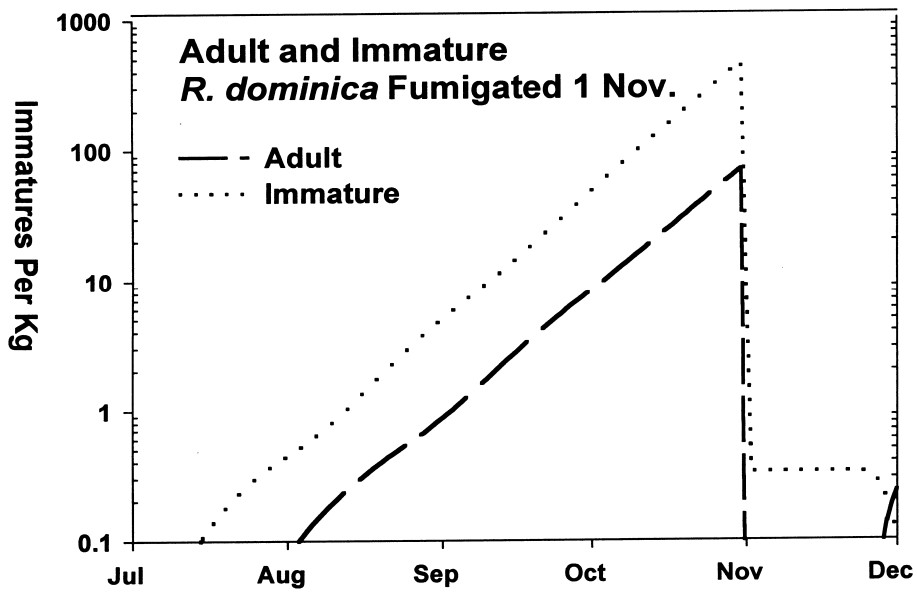

Fig. 4 Effects of phosphine fumigation (180 ppm for 2 d) on adult and immature stages of *Rhyzopertha dominica*
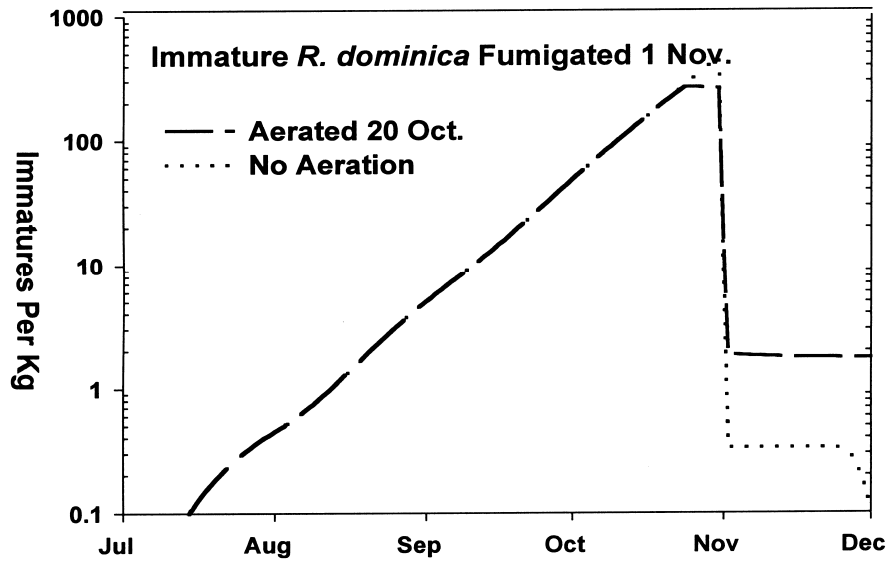
Fig. 5. Effects of grain temperature on fumigation efficacy for immature *R. dominica*. Grain temperatures in region 7 (center of the bin) were 17.9 C if aerated, and 31.4 C if unaerated.
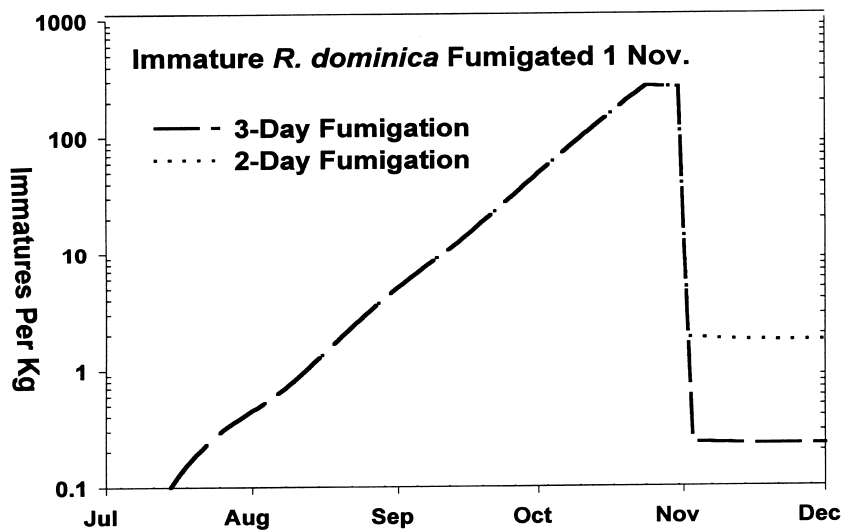

Figure 6. Effects of duration of fumigation on density of immature *R. dominica*.
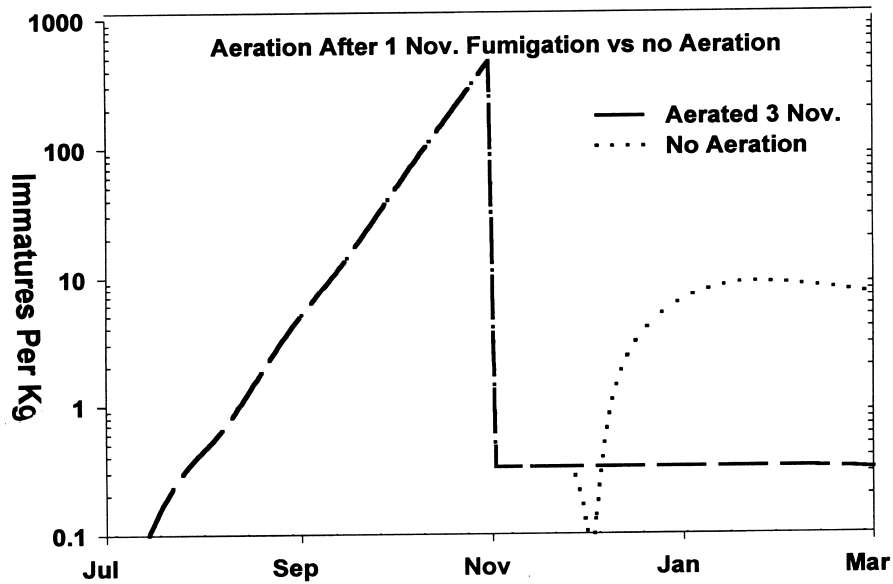
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Fig. 7. Effects of aeration following fumigation versus no aeration.

TABLE 2
Regression parameter estimates for days until 95% mortality as a function of temperature
(°C) for *Rhyzopertha dominica* exposed to 180 ppm phosphine

Life stage	Slope ± SE[a]	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

We plan to incorporate this model into the Stored Grain Advisor Pro expert system, so that it can be used to make fumigation recommendations for grain managers.

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