Survival of *Rhyzopertha dominica* (Coleoptera: Bostrichidae) in Stored Wheat Under Fall and Winter Temperature Conditions

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Environ. Entomol. 23(2): 390–395 (1994)

ABSTRACT Cold temperature survivorship of *Rhyzopertha dominica* (F.) populations with a natural age structure in stored wheat was estimated for a natural fall cooling rate of 2°C per week and winter temperatures of 17, 13, 9, and 5°C. Logistic equations were fitted to the data to predict the survivorships of the adults outside kernels and immatures and preemergent adults inside kernels as a function of exposure time over the 5–17°C temperature range. During the acclimation period, many insects died, and roughly 80, 55, and 25% of the insects were alive after temperatures had decreased at a rate of 2°C per week from 17°C to 13, 9, and 5°C, respectively. At the end of cold temperature exposure period, many *R. dominica* survived at 17°C, a few at 13°C, but none at 5 or 9°C. The colder the temperature the more rapidly survivorship decreased. The mostly immature insect population inside kernels was killed less rapidly than the external adult population at 5 and 9°C and more rapidly at 13 and 17°C. Daily survival rates decreased and then increased again indicating that those insects surviving short exposures to cold temperatures had a greater chance of surviving long exposures to cold temperatures. These equations will help extend our population model to predict the survival of *R. dominica* populations in stored wheat through the winter.

KEY WORDS stored product, cold temperature, age structure

COLD TEMPERATURE SURVIVAL of insects in stored grain is a function of cooling rate, exposure times and winter temperature. Winter temperatures in the United States reduce the survival of insects in stored grain but often do not eliminate insect populations. Models have been developed to predict the population growth rates of several species of stored-grain insects during the summer and early fall (Hagstrum & Throne 1989, Hagstrum & Flinn 1990), but equations are needed to predict their survival through the winter. Such predictions are important because much of the wheat is stored through the winter (Hagstrum & Heid 1988). A predictive model for *Rhyzopertha dominica* (F.) will be particularly important because it is one of the most destructive pests of stored wheat.

Adults of *R. dominica* are long lived and lay an average of one to seven eggs per day over several months. Eggs are laid externally on the wheat kernels. After hatching, the larvae bore into and feed inside the kernels. Larvae pupate inside the kernels and adults remain inside for several days after eclosion. The external population thus includes eggs and adults, and the internal population includes larvae, pupae, and preemergent adults. The mean time from egg laying to the emergence of adults from kernels is 45 d at 27°C (D.W.H., unpublished data).

Stored wheat generally remains at the harvest temperature between 27 and 34°C until the end of September (Hagstrum 1987). The grain mass then cools from the outside to the center of the bin and this can result in a 20°C gradient over a 3.2-m radius. Depending on the location in the grain mass, temperatures decrease at a rate of 1.3 to 2°C per week. The seasonal decrease in temperature was similar in Idaho (Halderson 1985), Kansas (Hagstrum 1987), and Oklahoma (Cuperus et al. 1986) and during three different years in Oklahoma. The similarity of the rate of decrease in outside temperatures during the fall throughout the major wheat growing areas of the United States suggests that seasonal decrease in grain temperatures might also be similar throughout this area (Hagstrum & Heid 1988). However, the lowest temperatures to which insects are exposed will vary with the severity of winter. Also, the larger the grain storage bin, the more likely temperatures in the center of the grain mass will be favorable for insect population growth during the winter.

Extensive laboratory data are available for survivorship of several species of stored-product insects at cold temperatures (Fields 1992), and some studies are extensive enough that response

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surface equations for survivorship as a function of exposure time and temperature can be fitted to the data (Brokerhof et al. 1992). David et al. (1977) found that 21- to 24-d-old immature *R. dominica* survived better at 4.4°C than adults, and that adults survived better than younger immatures. Both adults and immatures were generally dead after 42 d at 4.4°C. They also found survival of laboratory and field strains of *R. dominica* to be similar. The survivorship of *R. dominica* immatures (Evans 1987) and adults (Evans 1983) also have been studied at 9 and 13.5°C. These studies found that immatures survived longer than adults. David et al. (1977) and Evans (1983) found that acclimation increased survival.

The current study estimated the survivorship of *R. dominica* populations with a natural age structure under fall and winter temperature conditions as a function of time and temperature. The range of temperatures is greater and insects are acclimated more slowly (2°C per week instead of 4.5 or 5.5°C per week) than in previous studies.

Table 1. Mean ± SEM (n = 12) for densities of *R. dominica* per 0.5 kg of wheat inside wheat kernels and external adult populations during the first 112 d of the test

Sampling day	Inside kernal	External adults	Ratio
56	26.6 ± 5.8	5.0 ± 0.9	5.3
63	79.2 ± 19.7	6.4 ± 1.5	12.3
70	143.7 ± 35.4	7.4 ± 1.7	19.5
77	257.7 ± 58.9	9.5 ± 1.9	27.0
84	282.3 ± 32.5	10.2 ± 1.5	27.6
91	324.1 ± 39.5	8.0 ± 1.2	40.7
98	329.0 ± 45.9	11.0 ± 2.4	29.8
105	326.2 ± 48.1	14.7 ± 3.5	22.1
112	363.5 ± 61.0	28.5 ± 9.5	12.8

Materials and Methods

Five bushel lots of hard red winter wheat in 12 steel drums (0.57-m diameter by 0.85-m depth) were each infested with five male-female pairs of *R. dominica* from a laboratory colony and held at 27°C and 50% RH for 77 d. The temperatures were then dropped at a rate of 2°C per week until the temperatures were 5, 9, 13, or 17°C. The test was replicated in three drums for each of these temperatures. Grain sampling to estimate insect populations was started on the 56th d of the test. This insured that none of the original adults were removed by sampling until adults of the next generation began to emerge from the wheat kernels and reproduce. Four estimates of each insect population were made before the grain temperature was dropped.

Four grain samples were taken weekly from each drum using a grain trier (Model 39-OH Open-End Spiral Grain Probe, Seedburo, Chicago, IL). Two samples were taken within 5 cm of the center of the drum and the other two were taken halfway between the center and the drum wall. Adults were sieved from each sample and counted. Each sample was weighed (Model GT 2100, Ohaus, Florham Park, NJ) and the moisture content of grain was determined (Model GAC II, Dickey-John, Auburn, IL). The average and standard error were 326.8 gm and 1.6 gm, respectively, for the weight of grain per sample and 12.4% and 0.03%, respectively, for the grain moisture content. The sievings and grain samples were then held at 27°C and 70% RH. The numbers of eggs hatching in the sievings were recorded after 14 d and the numbers of live insects within the kernels at the time of sampling were estimated by counting the numbers of adults that emerged during a 42-d period.

Estimates of insect density were standardized for sample size by dividing the number of insects by the sample weight and multiplying by 500 to give the number of insects per half kilogram of wheat. Data were analyzed separately for three time periods: the population growth period between day 56 and day 112 of the test when temperature was above 17°C, the acclimation period from day 112 to days 126, 140, and 154 when temperature declined from 17°C to 13, 9, and 5°C, respectively, and the remaining 210-d cold temperature exposure period when temperature was 17, 13, 9, or 5°C. For the data from the last two time periods, logistic equations were fit to the survivorship of the external adults or insects inside kernels as a function of exposure time or exposure time and temperature (PROC PROBIT, SAS Institute 1985). Daily survival rates were calculated from these equations by differentiating survivorship with respect to exposure time.

Results

Fall and winter survivorship of *R. dominica* populations with a natural age structure were estimated for a natural fall cooling rate of 2°C per week and winter temperatures of 17, 13, 9, and 5°C. Survivorship is the proportion of insects that were alive at the beginning of the acclimation period or the cold temperature exposure period that were still alive on a given day.

During the first 112 d of the test, all 12 populations were exposed to the same temperature conditions and the average insect densities per 0.5 kg of wheat are given in Table 1. The populations of both the insects within kernels and the external adults increased during this period. From day 56 to day 91, the numbers of insects inside the wheat kernels increased faster than the external adult population as indicated by the increasing ratio of internal to external. Subsequently, the internal to external ratio decreased again as the next generation of adults began to emerge from the wheat kernels.

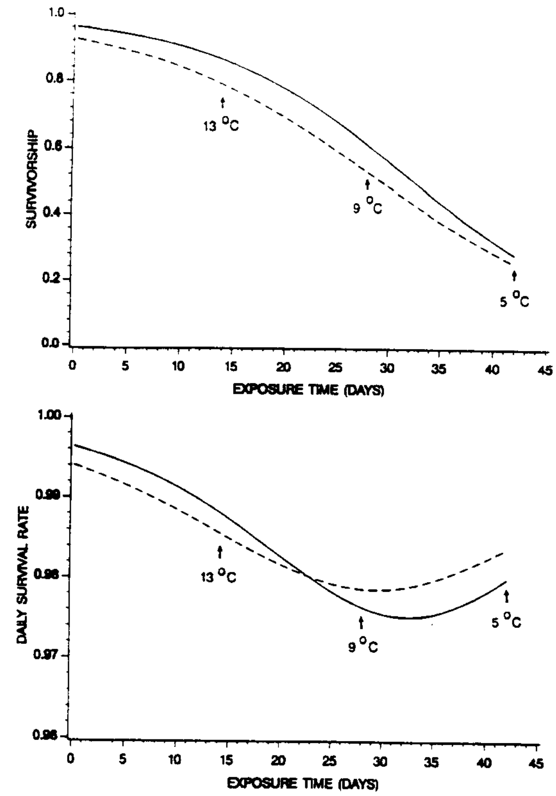

Fig. 1. Survivorships and daily survival rates of the external adult *R. dominica* population (solid line) and the insect population inside kernels (broken line) during the acclimation period as temperature decreased from 17 to 5°C at a rate of 2°C per week. Arrows show the points at which the temperatures reach 13, 9, and 5°C.

As temperature decreased from 17°C to 13, 9, or 5°C during the acclimation period between day 112 of the test and days 126, 140, and 154, respectively, the survivorship of the external adults decreased to 0.86, 0.61, and 0.28, respectively, and that of the insects inside the kernels decreased to 0.79, 0.53, and 0.25, respectively (Fig. 1). Data from 9, 6, and 3 drums were used to fit equation between day 112 and days 126, 140, and 154, respectively. Survivorship during the acclimation period as temperature decreased from 17 to 5°C at a rate of 2°C per week is described by the equation:

$$Survivorship = \frac{1}{1 + e^{-f(ET)}} \quad (1)$$

where for external adults

$$f(ET) = 3.230 - 0.0994 * ET$$

and for insects inside kernels

$$f(ET) = 2.513 - 0.0857 * ET$$

and ET is the exposure time in days. The standard errors of the intercept are 0.94 for external adults and 0.48 for insects inside kernels. The standard errors of the slope are 0.032 for external adults and 0.017 for insects inside kernels. For the regressions of expected against observed, the intercepts were not significantly different from zero (intercept = 0.057, $t = 0.54$, $n = 7$ and $p = 0.61$ for external adults, and intercept = 0.046, $t = 0.48$, $n = 7$ and $p = 0.65$ for insects inside kernels) and the slopes were not significantly different from one (slope = 0.92, $t = 0.57$, $n = 7$ and $p = 0.29$ for external adults, and slope = 0.93, $t = 0.51$, $n = 7$ and $p = 0.31$ for insects inside kernels). The r^2 of 0.89 for both equations indicates that these equations explain 89% of the variation in survivorship.

The daily survival rate of *R. dominica* (Fig. 1) can be calculated by differentiating equation 1 with respect to exposure time to calculate daily mortality rate between time t and $t + 1$ and subtracting this daily mortality rate from one to convert to daily survival rate:

Daily survival rate =

$$1 - \left[-\frac{e^{-f(ET)}}{(1 + e^{-f(ET)})^2} * \frac{d}{dET} f(ET) \right] \quad (2)$$

where for external adults

$$\frac{d}{dET} f(ET) = -0.0994$$

and for insects inside kernels

$$\frac{d}{dET} f(ET) = -0.0857.$$

The daily survival rate of external adults decreased until day 33 and then increased again, and that of insects inside kernels decreased until day 29 and then increased again (Fig. 1).

During the cold temperature exposure period, the survivorship of both the external adults and insects inside kernels are shown in Fig. 2 and can be described by equation 1 where

$$f(ET) = X_0 + X_1 * ET + X_2 * ET^2 + X_3 * ET^3 + X_4 * T + X_5 * T^2 + X_6 * ET * T$$

T is temperature and the parameter estimates are those given in Table 2. For the regressions of expected against observed, the intercepts were not significantly different from zero (intercept = 0.027, $t = 1.70$, $n = 109$ and $p = 0.093$ for external adults, and intercept = 0.018, $t = 0.83$, $n = 87$ and $p = 0.41$ for insects inside kernels) and the slopes were not significantly different from one (slope = 0.97, $t = 0.81$, $n = 109$ and $p = 0.21$ for external adults, and slope = 0.98, $t = 0.41$, $n = 87$ and $p = 0.34$ for insects inside kernels). The r^2 indicates that these equations explain 87 and

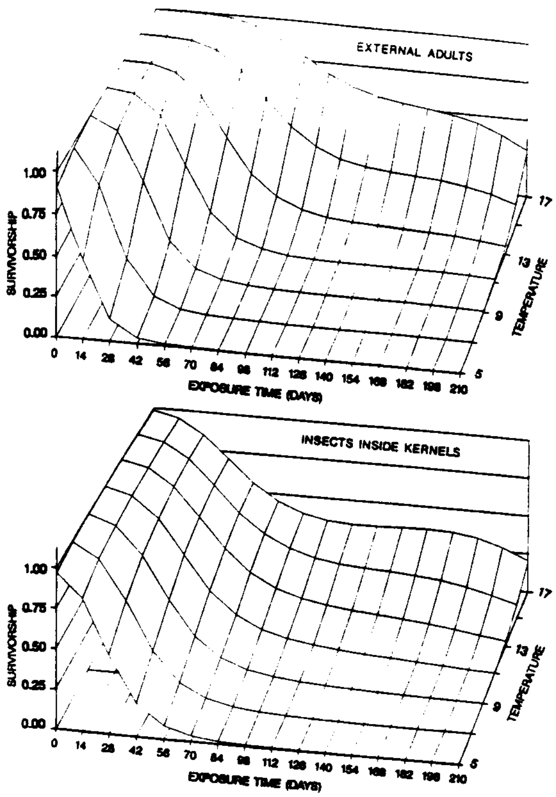

Fig. 2. Survivorship of external adult *R. dominica* population and insect population inside kernels at winter temperatures of 5, 9, 13, and 17°C.

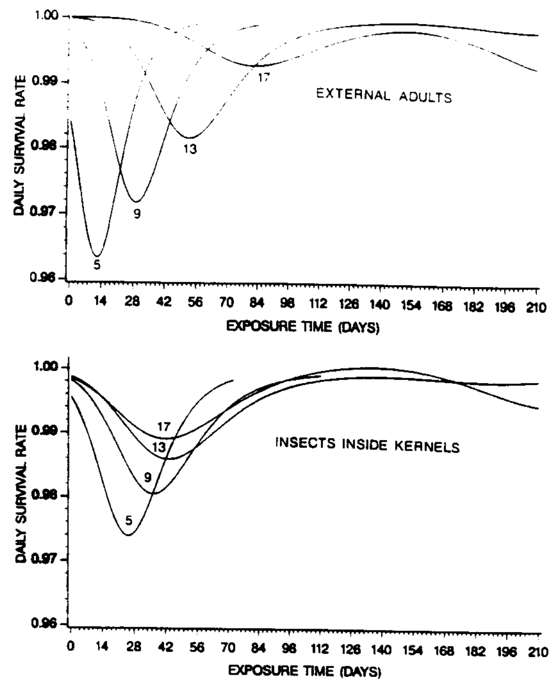

Fig. 3. Daily survival rate of external adult *R. dominica* population and insect population inside kernels at winter temperatures of 5, 9, 13, and 17°C.

90% of the variation in survivorship. The colder the temperature the more rapidly survivorship decreased. No external adults survived an exposure time of 56 d at 5°C and 84 d at 9°C. No insects inside kernels survived an exposure time of 72 d at 5°C and 112 d at 9°C. Insects inside the kernels were killed less rapidly than external adults at 5 and 9°C and more rapidly at 13 and 17°C.

These differences between the survivorship of external adults and insects inside kernels are even more evident in Fig. 3 showing daily survival rate. Daily survival rates are calculated by equation 2 where for external adults

$$\frac{d}{dET} f(ET) = -0.171 + 2 * 0.00119 * ET - 3 * 0.00000262 * ET^2 - 0.000839 * T$$

and for insects inside kernels

$$\frac{d}{dET} f(ET) = -0.159 + 2 * 0.00849 * ET - 3 * 0.00000209 * ET^2 + 0.00268 * T.$$

Daily survival rates of external adults decrease up to the 12th, 30th, 54th, and 84th d at 5, 9, 13, and 17°C, respectively, and then increased again. For insects inside kernels, daily survival rates decreased up to the 26th, 36th, 44th and 42nd d

Table 2. Parameter estimates ± SEM for equations predicting survivorship of *R. dominica* populations inside wheat kernels and external adult populations at winter temperatures

Parameter	Insects inside	External adults
X_0	1.584 ± 1.396	−0.519 ± 1.504
X_1	−0.159 ± 0.0174	−0.171 ± 0.0194
X_2	0.000849 ± 0.000153	0.00119 ± 0.000215
X_3	−0.00000209 ± 0.000000475	−0.00000262 ± 0.000000539
X_4	0.450 ± 0.269	0.580 ± 0.311
X_5	−0.0172 ± 0.0113	0.00649 ± 0.0127
X_6	0.00268 ± 0.000964	−0.000839 ± 0.00119
r^2	0.87	0.90
n	87	109

at 5, 9, 13, and 17°C, respectively, and then increased again.

Discussion

The age structure of the *R. dominica* populations exposed to cold temperatures were typical of those found in stored wheat. Female *R. dominica* lay a few eggs each day over several months. After two generations, the population of *R. dominica* inside kernels is approaching a stable age distribution of 14% egg, 64% larvae, 11% pupae, and 11% preemergent adults. This age structure is based on the number of insects in each developmental stage (when a stable age distribution is reached) being proportional to the percentage of the total developmental time spent in that stage (Hagstrum 1991). Immature *R. dominica* spends 16% of its time in the egg stage, 72% in the larval stage, and 12% in the pupal stage (Hagstrum & Milliken 1988), and the preemergent adult stage is 4.8 d (D.W.H., unpublished data). Adult *R. dominica* live a long time and the external adult population ranges in age from newly emerged (from wheat kernel) to 4 mo old.

Survivorship during the acclimation period and the cold temperature exposure period were analyzed separately. During the acclimation period, many insects died, and roughly 80, 55, and 25% of the insects were alive after temperatures had decreased at a rate of 2°C per week from 17°C to 13, 9 and 5°C, respectively. At the end of cold temperature exposure period, many *R. dominica* survived at 17°C, a few at 13°C, but none at 5 or 9°C. Although this study extends previous studies by looking at a broader range of low temperatures and a slower cooling rate, additional studies may be needed for other cooling rates. The acclimation period will be longer if the cooling rate is less than 2°C per week and survivorship during the acclimation period may be lower. Also, acclimation could be greater with a slower cooling rate, although the similarity of survivorship in the present study with 2°C per week cooling rate to that in studies by David et al. (1977) and Evans (1983) with 4.5 and 5.5°C per week cooling rates suggests that acclimation is not affected by cooling rates in this temperature range.

The mostly immature insect population inside the kernels was more tolerant to 5 and 9°C and less tolerant to 13 and 17°C than the external adult population. Adult survivorship also varied less between temperatures than immature survivorship. The difference in the survivorship of immatures and adults might be explained if partially shutting down immature development at 13 or 17°C is more detrimental than totally shutting down immature development at 5 or 9°C. Daily survival rates decreased and then increased again indicating that those insects surviving short exposures to cold temperatures had a greater chance of surviving long exposures to cold temperatures.

Survivorship may vary between locations in the grain mass. A model predicting grain temperatures at any location in a grain mass has been coupled with our insect population growth model (Flinn et al. 1992). Incorporating the survivorship equations from the present paper into this model will help us to predict survivorship at different locations in the grain mass through the fall and winter. Because the population growth model uses a daily time step, daily survival rates (equation 2) will be more easily incorporated into the population growth model than survivorship (equation 1). By including winter survival in our models we will be able to predict, in addition to the population growth of *R. dominica* in the summer and fall, the fall and winter mortality and the initial *R. dominica* population densities as grain warms up in the spring. This will help us to manage stored-grain insect pests more effectively by predicting the effects of natural cooling and fall aeration on insect population densities.

Acknowledgments

We would like to thank Brian Barnett and Ron Schulze (U. S. Grain Marketing Research Laboratory, Manhattan, KS) for collecting the data, Mike Hopkins (Electrical Engineering Department, Kansas State University, Manhattan) for helping with the mathematics, George Milliken (Department of Statistics, Kansas State University, Manhattan) for helping with the equation fitting and statistical analysis, and Paul Fields (Agriculture Canada, Winnipeg), Richard Lee (Miami University, Oxford, OH) and Steve Naranjo (Western Cotton Research Laboratory, Phoenix, AZ) for reviewing the manuscript.

References Cited

Brokerhof, A. W., H. J. Banks & R. Morton. 1992. A model for time-temperature-mortality relationships for eggs of the webbing clothes moth, *Tineola bisselliella* (Lepidoptera: Tineidae), exposed to cold. J. Stored Prod. Res. 28: 269–277.

Cuperus, G. W., C. K. Prickett, P. D. Bloome & J. T. Pitts. 1986. Insect populations in aerated and unaerated wheat in Oklahoma. J. Kans. Entomol. Soc. 59: 620–627.

David, M. H., R. B. Mills & G. D. White. 1977. Effects of low temperature acclimation on developmental stages of stored-product insects. Environ. Entomol. 6: 181–184.

Evans, D. E. 1983. The influence of relative humidity and thermal acclimation on the survival of adult grain beetles in cooled grain. J. Stored Prod. Res. 19: 173–180.

1987. The survival of immature grain beetles at low temperatures. J. Stored Prod. Res. 23: 79–83.

Fields, P. G. 1992. The control of stored-product insects and mites with extreme temperatures. J. Stored Prod. Res. 28: 89–118.

Flinn, P. W., D. W. Hagstrum, W. E. Muir & K. Sadayappa. 1992. A spatial model for simulating changes in temperatue and insect population dynamics in stored grain. Environ. Entomol. 21: 1351–1356.

Hagstrum, D. W. 1987. Seasonal variation of stored wheat environment and insect populations. Environ. Entomol. 16: 77–83.

1991. Commentary on microbial and invertebrate pest ecology, p. 315–321, *In* J. R. Gorham [ed.], Ecology and management of food-industry pests. Food and Drug Administration Technical Bulletin 4, Association of Official Analytical Chemists, Arlington, VA.

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

Hagstrum, D. W. & W. G. Heid Jr. 1988. U.S. wheat marketing system: an insect ecosystem. Bull. Entomol. Soc. Am. 34: 33–36.

Hagstrum, D. W. & G. A. Milliken. 1988. Quantitative analysis of temperature, moisture and diet as factors affecting insect development. Ann. Entomol. Soc. Am. 81: 539–546.

Hagstrum, D. W. & J. E. Throne. 1989. Predictability of stored-wheat insect population trends from life history traits. Environ. Entomol. 18: 660–664.

Halderson, J. L. 1985. Results of a grain storage study in Idaho. Trans. Am. Soc. Agric. Eng. 28: 246–250, 254.

SAS Institute. 1985. SAS user's guide: statistics. SAS Institute, Cary, N.C.

Received for publication 2 July 1993; accepted 21 December 1993.