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Seasonal Variation of Stored Wheat Environment and Insect Populations

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Environ. Entomol. 16: 77–83 (1987)

ABSTRACT Temperatures of wheat in the top meter in on-farm cylindrical metal bins in Kansas were uniform and within a favorable range of 27–34°C for the first 12 wk and then declined at rates ranging from 1.3 to 2°C/wk. Cooling of grain from the outside and surface inward and downward resulted in temperature gradients. Grain moisture in the top 0.5 m declined during the first 12 wk and then increased to levels well above initial moisture. Elsewhere in the top meter, wheat retained its initial moisture level except for the tendency of grain near the bin wall to be drier. Population growth rate of the dominant species, *Cryptolestes ferrugineus* (Stephens), declined over the wheat storage period in the top meter of grain as a result of first the parasite *Cephalonomia waterstoni* Gahan and then falling temperatures. *C. ferrugineus* adults showed only a slight tendency to move toward the warmer or moister parts of the bin. *Trogoderma glabrum* (Herbst) adults and larvae and *Trogoderma inclusum* LeConte adults, the next most abundant species, were found mainly near the bin wall. *Rhyzopertha dominica* (F.) were first detected after 12 wk and were found only in the center.

KEY WORDS *Rhyzopertha dominica, Cryptolestes ferrugineus*, temperature, grain moisture, parasite, biological control, sampling

INSECT POPULATION trends for a species are determined by its innate life history characteristics within the restraints of the suitability of the environment. Converse et al. (1973) and Muir (1970) have described the seasonality of the stored wheat temperatures and Smith (1978) examined relationships between temperature, moisture, and *Cryptolestes ferrugineus* (Stephens) populations. However, more quantitative studies in a variety of situations are needed before we can generalize about the basic relationships. The present study examines more quantitatively the relationships between the seasonal variation of insect populations and their stored wheat environment.

Materials and Methods

Insect populations, temperatures, and moisture contents for hard red winter wheat stored in two cylindrical metal bins (4.3 m diameter with 27 *t* of wheat and 6.4 m diameter with 82 *t*) on a farm near Enterprise, Kans., were monitored at 2-wk intervals from the time wheat was stored immediately after harvest in early July 1984 until the end of December 1984. On each occasion, 22 samples (0.5 kg) of wheat were taken with a grain trier (Seedburo 1.27-m open-end spiral probe) from each bin. Because the trier was partitioned to keep the wheat from the top 0.5-m layer separate from the next deeper 0.5-m layer, the trier was inserted twice at each of 11 sites to obtain 22 samples (0.5 kg). Samples were taken in the center and at five sites between the center and the wall of each bin in the southern and eastern compass directions. In each compass direction, five sample sites were located 25 cm from the center, midway between the center and the wall of the bin, against the bin wall, and 12, and 38 cm from the bin wall.

The moisture content of the wheat samples was checked in the laboratory with a grain analysis computer (Dickey-John Corp. Model GAC II) after the insects had been removed. The insects were separated from the wheat with an oblong-hole grain sieve (Seedburo, 0.18 mm by 1.27 cm) and removed from the sievings with the aid of a dissecting microscope. Temperatures within the top meter of grain were determined each time a bin was sampled by inserting the probe shown in Fig. 1 at each of the locations where the trier samples were taken, except for those against the bin wall. At 5-min intervals, the temperatures were read at 5, 30, 55, 80, and 105 cm below the surface until readings were within ≤0.2°C of the previous. The Statistical Analysis System (SAS Institute 1982) was used to plot the trends and fit regression equations. The models in Fig. 8 were compared using the model comparison procedures of Draper & Smith (1981).

Results

The temperatures in the top meter of the wheat stored in two bins were quite uniform and were stable between 27 and 34°C for the first 12 wk

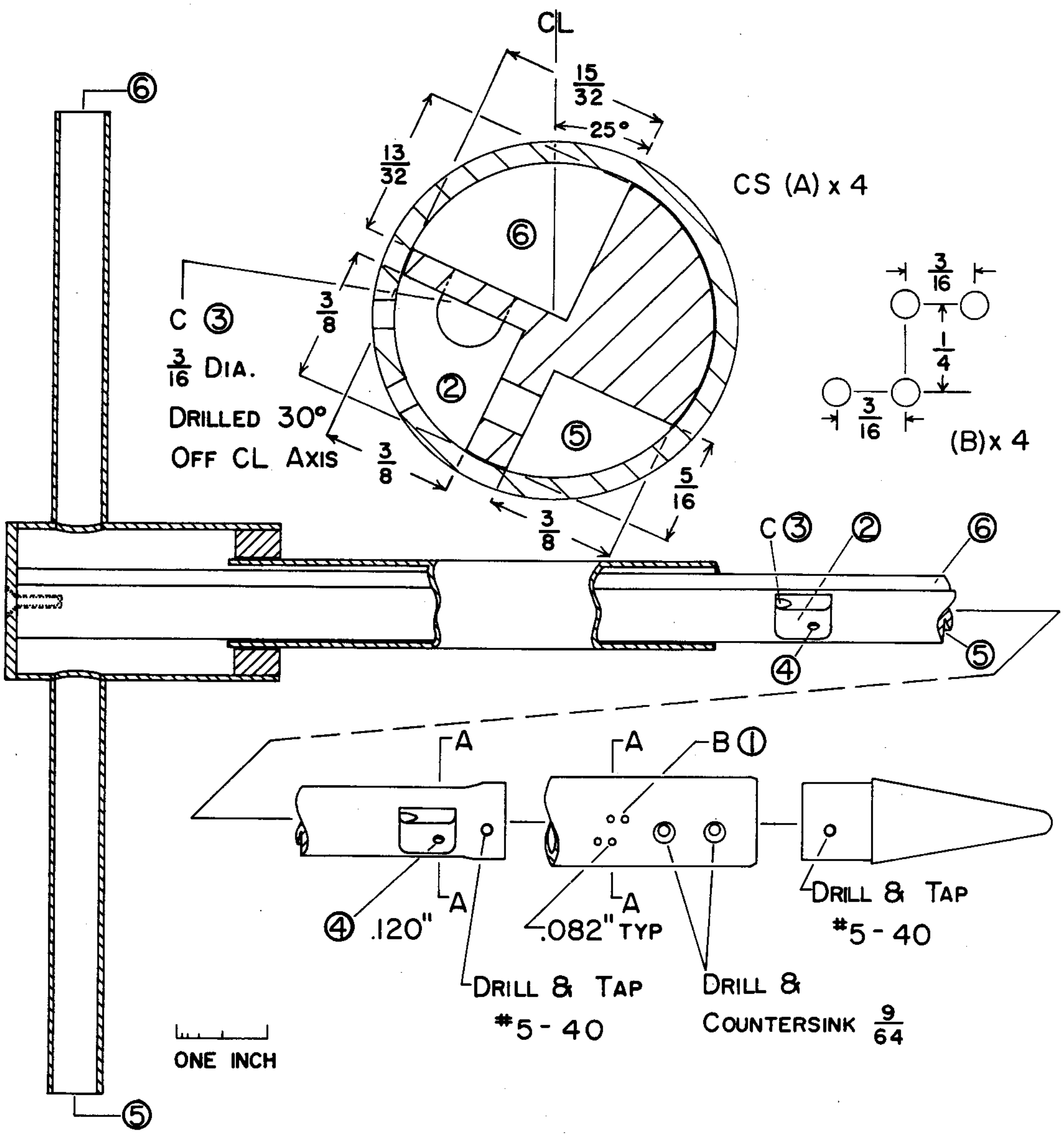


Fig. 1. Diagram of probe for measuring temperatures at five depths 25 cm apart within the top meter of stored wheat. A vacuum pulled air through holes at 1 across thermistor entering chamber 2 through hole 3 and positioned over hole 4. Channel 5 was connected through handle to a vacuum pump and the thermistor cables were connected through the handle to a meter for reading the temperatures via channel 6.

(Fig. 2) and then decreased at rates ranging from 1.3 to 2°C/wk (Fig. 3). The temperatures in the top 0.5 m of wheat fell more rapidly than those deeper in the grain mass, and those near the bin wall fell more rapidly than those in the center of the bin. These rate differences resulted in temperature gradients that increased gradually between the 12th and 22nd wk before finally reaching a difference of 20°C (Fig. 4).

The grain moisture in the top 0.5 m of wheat generally declined during the first 12 wk and then increased in several instances well above the initial moisture content (Fig. 2). These trends occurred in both of the bins, although the initial grain moisture was higher in the bins of 6.4-m diameter than in the 4.3-m bin. The moisture in the layer between 0.5 and 1.0 m deep generally remained unchanged throughout the study, although there was a general tendency for grain nearest the bin wall to be drier than grain nearer the center.

In the 4.3-m bin, the *C. ferrugineus* population level peaked after 4, 10, 17, and 26 wk of storage (Fig. 5). If each of these increases in population level indicates a new generation, *C. ferrugineus*

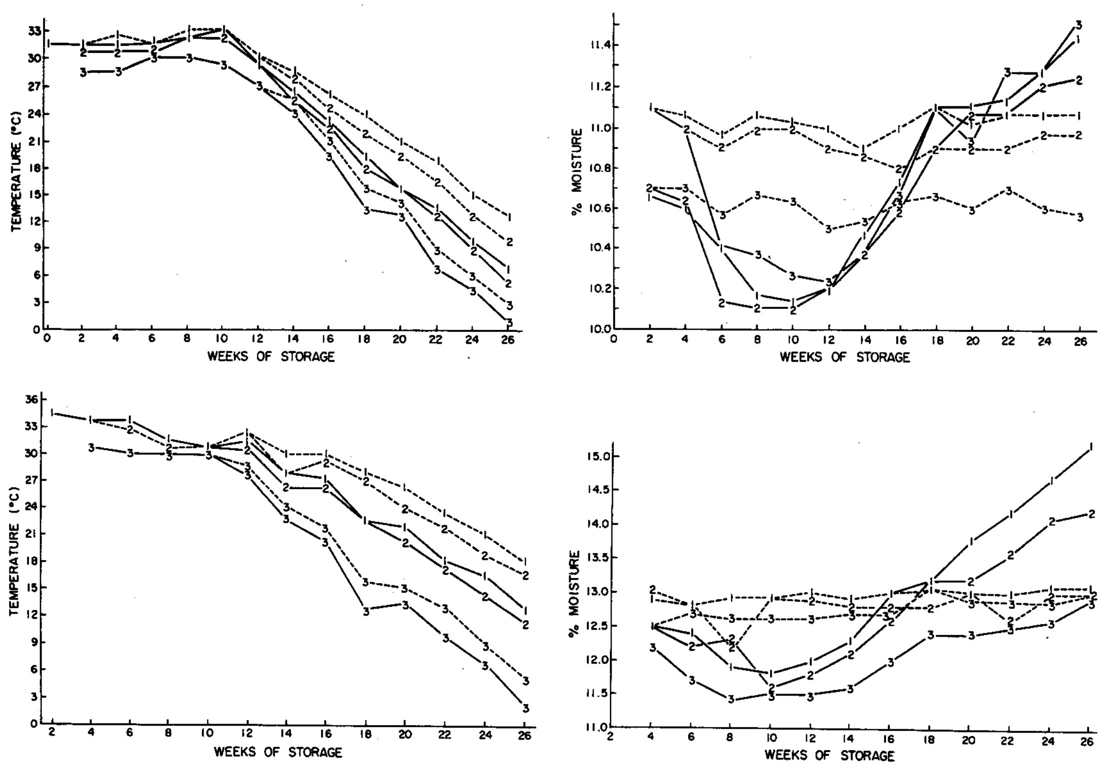


Fig. 2. Seasonal trends in temperature and grain moisture in wheat bins of 4.3-m diameter (top) and 6.4-m diameter (bottom). Data are presented for six zones: center (1), midway (2), and near bin wall (3) in the top 0.5 m (—) and the next deeper 0.5 m (- - -) of wheat.

completed three generations of ca. 6, 7, and 9 wk duration, increasing 6.1-, 1.8-, and 1.0-fold before reaching 1.05 insects per 0.5 kg of wheat. This species was more abundant and generations were less clearly defined in the 6.4-m bin. Assuming

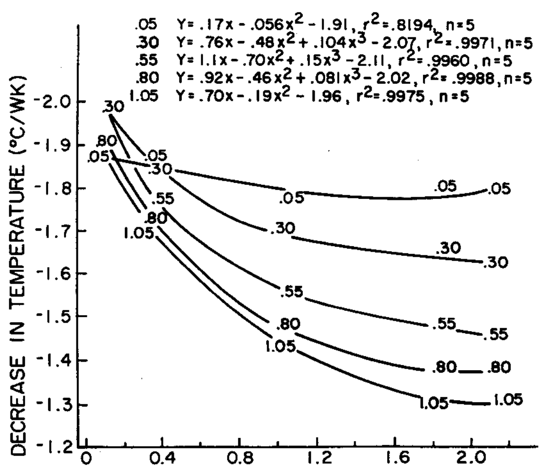
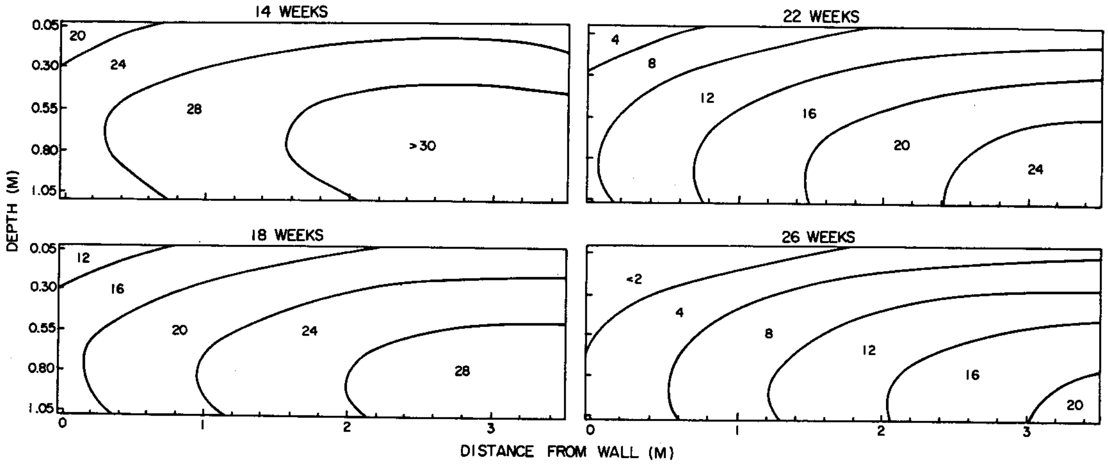


Fig. 3. Rates of decrease in wheat temperature at various locations in the bin between the 14th and 26th wk of storage. Data are given for 0.05, 0.30, 0.55, 0.80, and 1.05 m below the surface.

similar generation times, *C. ferrugineus* reached 4.8 and 8.0 insects per 0.5 kg by the second and fourth generations. In both bins, a peak in the numbers of the parasite *Cephalonomia waterstoni* Gahan followed a peak in the number of third-generation *C. ferrugineus* larvae, which followed the peak in the number of second-generation adult *C. ferrugineus*. By the fourth generation, fewer of the adults in the samples were alive, perhaps as a consequence of falling temperatures and slower population growth rates.

As the wheat cooled from the outside and upper surface inward and down between the 12th and 20th wk of storage, the percentage of *C. ferrugineus* adults in the lower center tended to increase as the percentage elsewhere tended to decrease (Fig. 6). This pattern was most evident in the 6.4-m bin where the higher densities provided better estimates of population levels. During the storage period, 46–83% of the adult beetles in samples were found in the center, but the presence of beetle larvae and parasites at all locations indicated that breeding was not restricted to the center. In both bins, the percentage of adults in the upper central portion of the top meter of wheat first decreased and then increased as the grain moisture there decreased and then increased.

The next most abundant species was *Trogoderma glabrum* (Herbst), followed in decreasing



$$\text{TEMPERATURE} = 57.3 - 4.13x - 0.64x^2 - 11.56y^2 - 3.19z + 0.033z^2 + 1.58yz + 0.76xz - 0.034yz^2 - 0.016xz^2 + 0.078xyz,\ r^2 = 0.9555,\ n = 280$$

Fig. 4. Model and predicted temperature profiles for the depth (y) in the top meter of wheat in two bins and for the lateral distance between the center to edge of bin (x) between the 14th and 26th wk of storage (z).

abundance by *Trogoderma inclusum* LeConte and *Rhyzopertha dominica* (F.) (Fig. 7). The two species of *Trogoderma* were found mainly near the bin wall and probably completed only one generation during the study. The *R. dominica* were first detected after the 12th wk of storage and were found only in the center. They had increased 15.5-fold by the 24th wk of storage. Small numbers of the parasite *Anisopteromalus calandrae* (Howard), and *Tribolium castaneum* (Herbst) were recovered after 4 and 10 wk of storage, respectively. *Typhaea stercorea* (L.) and *Ahasverus advena* (Waltl) were most abundant early in the storage period.

One way of characterizing the seasonal variation in the distribution patterns is the regression of the logarithm of the variance against the logarithm of the mean number of insects per sample. Except for the first 8 wk, these regressions indicated that the distribution of insects among samples did not change during the storage period (Fig. 8). The fraction of samples with insects, representing the probability of detecting an infestation, increased progressively more slowly as the density increased (Fig. 9).

Discussion

Wheat temperatures in the range of 27–34°C favored rapid growth of insect populations during the first 12 wk of storage. Temperatures remained in that range even though outside temperatures began to fall 1.38°C per week after 8 wk of storage (National Oceanic and Atmospheric Administration 1984). This 4-wk delay between the 8th and 12th wk of storage resulted in wheat temperatures falling at rates in excess of the 1.38°C per week for outside temperatures at most of the points sampled (Fig. 3). The time lag between the outside air reaching a particular temperature and the wheat at some point within the bin reaching that temperature can be predicted by the equation y =

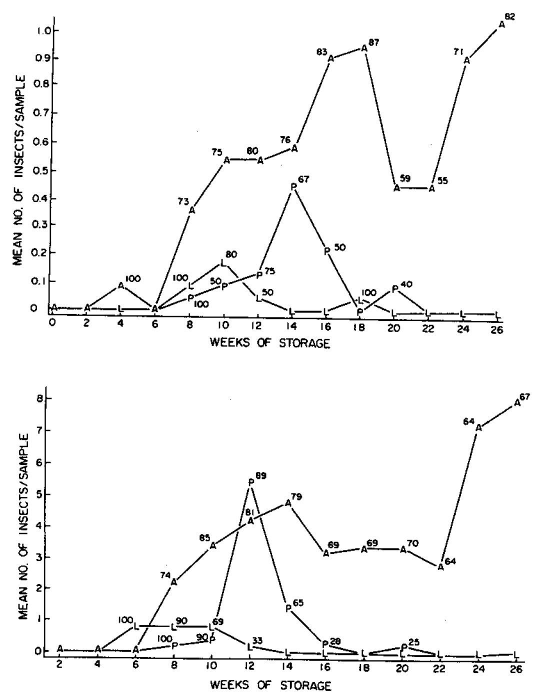


Fig. 5. Population trends for *C. ferrugineus* adults (A) or larvae (L) and the parasite *C. waterstoni* (P) from wheat stored in bins of 4.3-m diameter (top) and 6.4-m diameter (bottom). The numbers above lines are the percentages of insects that were alive in all of the 0.5-kg samples taken on each date.

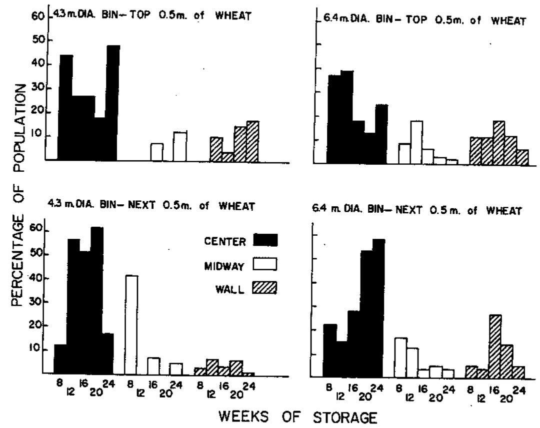


Fig. 6. Distribution of *C. ferrugineus* adults in the samples taken among six zones of bins of 4.3-m and 6.4-m diameter between the 6th and 26th wk of storage. The data were grouped by 4-wk intervals for which midpoint is given.

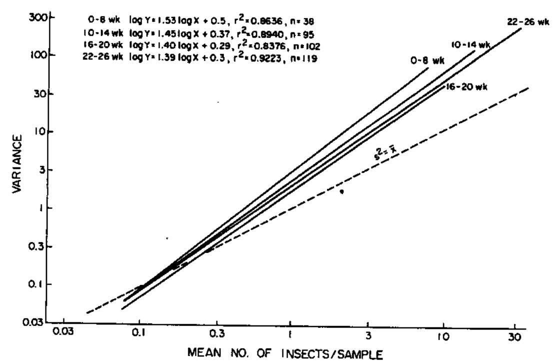


Fig. 8. Changes over the storage period in the regression of logarithm of variance (y) against logarithm of mean (x) numbers of insects of each species in samples from five regions of two bins of bulk-stored wheat. Models for the last three intervals of the storage period were not significantly different ($F = 1.146$; df = 313,317; $P < 0.01$).

$2.4x + 6.5$ ($r^2 = 0.9718$; df = 4; $P = 0.001$), where y = time in weeks and x = distance from wall in meters at a depth of 1 m. This regression equation predicts that temperatures at distances of 1, 2, and 3 m laterally into the wheat would, thus, reach 20°C at 8.9, 11.4, and 13.8 wk after the outside temperatures had reached 20°C. During the first 26 wk of storage, the temperatures below the top meter and above the bottom meter must have been similar to temperatures at 1-m depth. Vertical temperature gradients in the top meter of grain that were as large as those extending over a 3-m radius laterally (Fig. 4) are perhaps a consequence of the insulative properties of the air space above the wheat. Converse et al. (1973) and Muir (1970) conducted similar studies, but the former aerated the wheat to reduce the temperature before study, and neither dealt with the asymmetry near the surface. Clearly, aeration in October can quickly lower wheat temperatures. However, by that time the *C. ferrugineus* populations have completed two generations and attained much of their population growth. Aeration earlier in the storage period, during only the coolest part of the day, might be more effective in reducing the level of insect infestation.

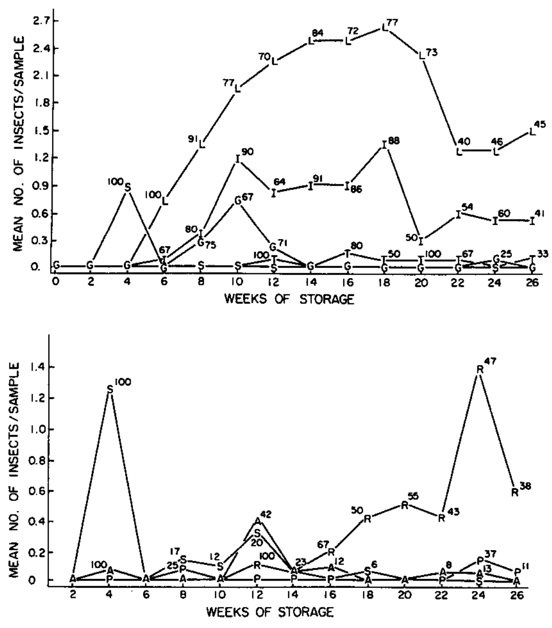


Fig. 7. Population trends for *T. glabrum* adults (G) and larvae (L), *T. inclusum* adults (I), *T. stercorea* adults (S), *T. castaneum* adults (T), *R. dominica* adults (R), *A. advena* adults (A), and adults of the parasite *A. calandrae* (P) from wheat stored in bins of 4.3-m (top) and 6.4-m (bottom) diameter. The numbers above lines are the percentages of insects that were alive in all of the 0.5-kg samples taken on each date.

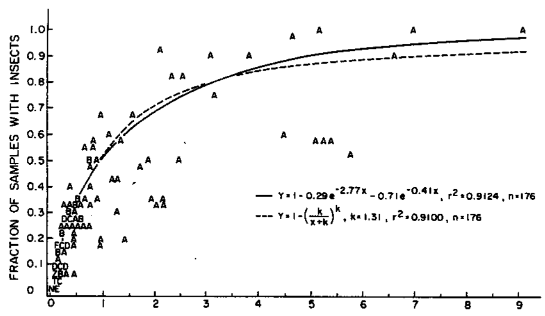


Fig. 9. Increase in the fraction of samples from bulk-stored wheat with insects (y) as a function of the mean number of insects per 0.5-kg wheat sample (x). Each point represents for one species the mean of samples from one of three zones in one of two bins. The number of points at each coordinate is indicated by A to Z for 1 to 26, respectively.

During the first 12 wk of storage, neither the temperature nor the moisture conditions were sufficiently different in the center to explain why insects favor the center of the bin. Chang et al. (1983) measured the gradient of fine materials, which increases from the bin wall to the center, and McGregor (1964) demonstrated in the laboratory that in such a gradient *T. castaneum* tends to choose those areas with the highest level of fine materials. Together these data indicate that the preference for high levels of fine materials might explain the concentration of insects in the center early in the storage period. Although Sinha (1975) found that dockage did not facilitate the growth of *C. ferrugineus* populations in wheat of 14% moisture content, dockage may be important in drier wheat. Later in the present study, a small percentage of the *C. ferrugineus* population did seem to move towards the center and down, perhaps along the temperature gradient. This limited response could have been a result of even the maximum 6°C/m gradient not being steep enough for orientation. If more of the population had moved to the warmer center portion of the grain bulk, population growth and the insect problem could have been much greater than that observed.

As the temperatures reached 20°C near the walls and approached 20°C in the center between the 16th and 24th wk of storage, the finite rate of increase of most species should have approached one (Fig. 10). At that rate, each adult female produces on the average only one female offspring and there is no further population growth. Fig. 10 also shows that population growth at moisture contents of >12% was considerably higher than at moisture contents <12%. The population of *C. ferrugineus* in the 6.4-m bin may have reached a level 7.9-fold higher (1.05 versus 8.0 adults) than that in the 4.3-m bin, at least in part as a result of the higher grain moisture contents. The parasite *C. waterstoni* was apparently more effective at the higher host densities in causing a decline in the *C. ferrugineus* populations in the 6.4-m bin while the populations increased 1.8-fold in the 4.3-m bin between the second and third generations. Nevertheless, the parasites were quite effective in both bins, because the 1.8-fold increase in the 4.3-m bin was considerably less than the 6.1-fold increase in the previous generation. In both bins, the parasite numbers were lower during the next generation, perhaps as a direct result of declining temperatures and indirectly as a result of the declining temperatures reducing the host population.

Ruesink & Kogan (1975) indicated that the number of samples needed to estimate the population levels with a specified level of precision can be calculated as

$$n = \left(\frac{100}{c}\right)^2 t_\alpha^2 a \bar{x}^{b-2}, \qquad (1)$$

where c = accuracy as a percentage of mean, t = value of t distribution for confidence limits α, a = antilogarithm of intercept, and b = slope of the regression of the logarithm of the variance against the logarithm of the mean ($\bar{x}$). If we solve for c in equation 1, we can calculate the expected level of accuracy at 95% confidence limits for each estimate of the insect density based upon the fixed number of 22 samples taken as

$$c = 100 t_\alpha \sqrt{\frac{1.99\bar{x}^{-0.6}}{22}}. \qquad (2)$$

Thus, when the estimated mean insect density equalled 0.1, 0.3, 1.0, 3.0, 10.0, and 30.0, the estimates were within ±118, ±85, ±59, ±42, ±30, and ±21% of actual mean, respectively. The accuracy roughly doubled for each 10-fold increase in density. The probability of detection fits the same models used in a previous study (Hagstrum et al. 1985), and 22 samples should consistently detect a population larger than 0.1 insect per 0.5 kg of wheat.

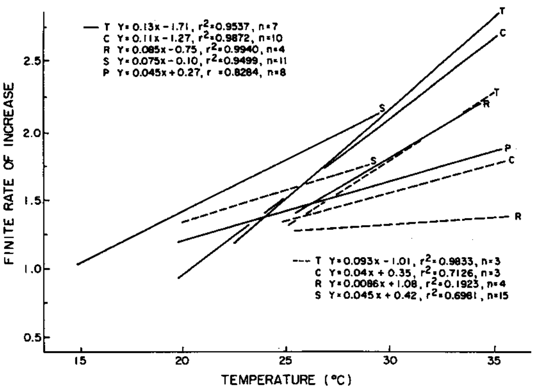


Fig. 10. Changes in finite rate of increase per week (y) for *T. castaneum* (T), *C. ferrugineus* (C), *R. dominica* (R), *Sitophilus oryzae* (L.) (S), and *Cryptolestes pusillus* (Schönherr) (P) with temperature (x) and grain moisture content based upon data from Howe (1962); Smith (1965); Birch (1953); Birch (1953) and Longstaff & Evans (1983); and Currie (1967), respectively. High (—) and low (- - -) moistures were grouped by those above and below 12%, except with *S. oryzae*, for which 13% was used. Data for temperatures >35°C have been omitted.

Acknowledgment

I thank the Sterners for allowing us to do this research on their farm, Sue Waddell for her assistance in collecting the data, Bob Rousser for designing and building the temperature probe, Jeannie Streeter and Marsha Jensen for doing illustrations, and Sandy Mathewson for typing the manuscript. I also acknowledge with appreciation the work of E. E. Grissell and A. S. Menke of the USDA Systematics Entomology Laboratory in identifying the parasitic insects.

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Received for publication 19 February 1986; accepted 29 September 1986.