BIOLOGICAL CONTROL

Suppression of Beetles in Stored Wheat by Augmentative Releases of Parasitic Wasps

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ABSTRACT Field studies were conducted to assess the effectiveness of the parasitoid wasps, *Cephalonomia waterstoni* (Gahan), and *Choetospila elegans* (Westwood), for controlling *Cryptolestes ferrugineus* (Stephens), rusty grain beetle and *Rhizopertha dominica* (F.), lesser grain borer. On 6 July 1993 and 7 July 1994, adults of both *C. ferrugineus* and *R. dominica* were released at monthly intervals into 6 steel grain bins each containing 27.2 t of hard red winter wheat, *Triticum aestivum* L. Adults of both parasitoid species were released into 3 of the bins 21 d after the 1st beetle release. The amount of suppression of *C. ferrugineus* by *C. waterstoni* could not be measured in either year of this study because *C. waterstoni* infested the control bins. However, *C. elegans* was effective in suppressing *R. dominica* populations. In 1993 and 1994, *R. dominica* populations were suppressed by 98 and 91% compared with the control bins. After 198 d from initial beetle release in 1993, the treatment bins averaged 0.05 *R. dominica* per kilogram and the control bins averaged 2.06 *R. dominica* per kilogram. After 131 d from initial beetle release in 1994, the treatment bins averaged 6.94 *R. dominica* per kilogram and the control bins averaged 81.03 *R. dominica* per kilogram.

KEY WORDS *Rhizopertha dominica, Cryptolestes ferrugineus, Choetospila elegans, Cephalonomia waterstoni*, biological control, stored-products

BIOLOGICAL CONTROL is an overlooked component of integrated pest management of stored grain. Most of the parasitoids that attack the primary beetle pests are in the families Pteromalidae and Bethylidae (Hagstrum and Flinn 1992). These hymenopterous parasitoids are typically small (1–2 mm), and do not feed on the grain. They will normally die within 5–10 d if no beetles are present in the grain. These parasitoids are found naturally in stored grain, which suggests that once released they may continue to suppress pests for many years (Sinha et al. 1979). Because the adult wasps are external to the grain, they can easily be removed from it using normal cleaning processes.

The rusty grain beetle, *Cryptolestes ferrugineus* (Stephens), and the lesser grain borer, *Rhizopertha dominica* (F.), are 2 of the most common and damaging insect pests of farm-stored wheat in the United States (Storey et al. 1984). Adults and larvae of *C. ferrugineus* feed primarily on the wheat germ and can cause considerable damage. *R. dominica* larvae develop within the grain kernel and cause major damage to grain stores.

*Cephalonomia waterstoni* (Gahan) is a small beetlidal wasp that is frequently found with *C. ferrugineus* in stored wheat (Hagstrum and Flinn 1992). *C. waterstoni* is host-specific (Finlayson 1950). Although this wasp will parasitize larvae of other *Cryptolestes* species, when given a choice, it invariably prefers *C. ferrugineus*. This wasp usually parasitizes 4th instars; however, it will paralyze and feed on 1st through 3rd instars (Rilett 1949). Fourth-instar *C. ferrugineus* normally wander through the grain interstices looking for pupation sites. After a wasp finds and stings the host, paralysis occurs within 1 min. This wasp can paralyze up to 15 larvae per day (Flinn 1991); however, it normally lays only 2 eggs per day (Finlayson 1950). Wasp larvae feed externally on the host and mature rapidly. The generation time of the wasp is ≈14 d at 30°C, which is half as long as *C. ferrugineus*. If hosts are available, female wasps live for 15–20 d at 30°C.

*Choetospila elegans* (Westwood) is a small pteromalid wasp that attacks *R. dominica, Sitophilus* spp., *Stegobium panicum* (L.), *Callosobruchus* spp., and *Sitotroga cerealella* (Oliver) (Burks 1979). This wasp also parasitizes beetle larvae that are feeding inside the grain kernel. Eggs will successfully develop when laid on 4th-instar *R. dominica* (P.W.F., unpublished data). They normally lay 1 egg externally on each host (Sharifi 1972). If >1 egg is present, only 1 larva completes development. At 30°C, it takes ≈15 d to complete development on *R. dominica* (P.W.F., unpublished data). The generation time of this wasp is ≈1/2 that of *R. dominica*. If hosts are available, female wasps live for 10–20 d at 30°C. *C. elegans* can parasitize up to 6 *R. dominica* per day (P.W.F., unpublished data).
Only a few large-scale field studies have been conducted on the use of beneficial insects to suppress insect pests in stored grain (Parker and Nilański 1990), and the results were not conclusive. The objective of this study was to assess the effectiveness of *C. waterstoni* and *C. elegans* to suppress population growth of *C. ferrugineus* and *R. dominica*, respectively, in stored wheat.

**Materials and Methods**

**1993 Field Study.** Six cylindrical bins (4.72 m diameter by 3.35 m tall at the eaves) were constructed so that they were air-tight, except for 2 roof ventilation ports that were covered with 80-mesh screen. Because of the uncertainty of obtaining new-crop wheat directly from farmers, we used 1992 crop hard red winter wheat that was acquired 1 yr before the start of the 1993 experiment (6 July 1993). Ten, 1-kg grain samples were taken per truckload, and no insects were found in any of the samples. The grain was tested for insecticides using rice weevil, *Sitophilus oryzae* (L.), as a bioassay, and none was found or expected because it was obtained directly from farmers as new-crop wheat. This wheat was stored in the U.S. Grain Marketing Research Laboratory (USGMRL) elevator during the summer. It was fumigated twice with phosphine during the summer of 1992 to ensure that no insects would be present. Each of the 6 bins was filled with 27.2 t of wheat in September 1992. The depth of the grain was ~2 m in each bin. The grain was cooled to 10°C with aeration during September. The grain was warmed starting 15 June 1993, using ambient aeration. The fans were screened with 80-mesh screen to prevent insects from entering. The 1st experiment was started 6 July 1993. At this time, the grain had warmed to 26.66 ± 0.12°C (±SEM) and the average grain moisture was 13.18 ± 0.03%. We did not attempt to control grain temperature in the bins during the experiment because we wanted to simulate normal storage procedures for grain that is not aerated in the fall.

On 6 July 1993, 270 *R. dominica* (1 wk old) and 270 *C. ferrugineus* (1 wk old) adults were released on the grain surface of each of the 6 bins. The sex ratio of these beetles was 1:1.1. The same number of beetles were released at monthly intervals up to 6 October to simulate beetle immigration, for a total of 4 releases. These insects were obtained from a USGMRL culture which had wild strains added to it in October 1992 to maintain genetic diversity. Beetles were released by inverting 9 jars (0.53 liter, 1 pint), each containing 30 insects, on top of the grain surface and letting the beetles crawl down into the grain.

Adult parasitoids were released into 3 of the 6 bins 21 d after initial beetle infestation. Based on simulations with a model (Flinn and Hagstrum 1995), 21 d from storage was found to be the best time to start parasitoid releases. The parasitoids were obtained from a USGMRL culture that had wild strains added in October 1992 to maintain genetic diversity. Five-hundred forty *C. waterstoni* adults and 540 *C. elegans* adults (all <3 d old) were added to 3 of the 6 bins on 27 July. The sex ratio of both species of wasps was ~2:1 female to male. Two additional parasitoid releases were made in the same bins at weekly intervals. Parasitoids were released by inverting 9 jars (0.53 liter, 1 pint), each containing 60 parasitoids, on top of the grain surface at evenly spaced intervals. This was done in the morning to avoid high temperatures. Because grain samples taken on 22 August indicated that *C. waterstoni* density was relatively low in the treatment bins, we released 900 *C. waterstoni* on 9 September into each of the 3 treatment bins.

**1994 Field Study.** Grain used in the 1994 study was also obtained directly from farmers 1 yr before the start of the experiment. The grain was checked for insects and insecticides using the methods described in the 1993 study. It was also fumigated twice during the summer of 1993 to eliminate insect infestation. The 6 bins were each filled with 27.2 t of grain on 11 May 1994. The grain was fumigated on 16 May 1994 to ensure that any insects present in the grain would be killed. Aeration was used from 23 May to 6 July to warm the grain. The 2nd experiment was started on 7 July 1994. At this time, the average grain temperature and moisture were 26.60 ± 0.05°C and 12.80 ± 0.03%.

In this 2nd field study, we wanted to determine if the wasps could control higher densities of beetles, so we released twice the number of beetles that were used in the 1st study. We released 540 *C. ferrugineus* and 540 *R. dominica* into the bins at monthly intervals starting 7 July up to 7 October, for a total of 4 releases. On 28 July 1994, 700 *C. waterstoni* and 2,160 *C. elegans* were released into each of the 3 treatment bins. On 4 August 1994, we released 1,080 *C. waterstoni* and 2,160 *C. elegans*, and on 8 September 1994 we released 1,600 *C. waterstoni* and 2,160 *C. elegans* into each of the 3 treatment bins. We attempted to release 4 times as many wasps as the initial number of beetles that were released, which we were able to do with *C. elegans*; however, we were unable to rear sufficient numbers of *C. waterstoni* for this release rate.

Grain sampling was conducted at monthly intervals using a pneumatic grain sampler (Probe-A-Vac, Cargill, Minneapolis, MN). Seven 3-kg samples in each of the three 66.6-cm layers of wheat were taken at 3 points near the center of the bin and at 4 points 2/3 the distance between the center and the outer wall. Control bins were sampled 1st to minimize accidental introduction of parasitoids into these bins. Samples were immediately placed in plastic containers. Grain samples were processed over an inclined sieve (89 by 43 cm, 1.6 mm aperture) (Hagstrum 1989). Adult insects were identified and counted (live and dead determined). Grain moisture was determined using a Dickey John GAC II (Auburn, IL). Grain temper-
nature was measured at monthly intervals using a Digi-Sense thermistor thermometer (Cole-Parmer, Chicago IL). Grain temperatures were measured in the center of the bin and at 2/3 the distance from the bin center and the outer wall in the northern and southern directions using a metal rod with 4 thermistors attached at 15, 55, 95, 134, and 174 cm from the bottom of the bin.

Analysis of variance (ANOVA) and t-test procedures, SYSTAT version 5.2 (Wilkinson et al. 1992), were used to test for differences between treatment and control bins. Treatment effects were considered significant at $P \leq 0.05$.

Results

1993 Field Study. The 3 bins with parasitoids added to them had much lower densities of *R. dominica* than the control bins (Fig. 1). Densities of *R. dominica* were much more variable in the control bins compared with the treatment bins. Because of the high variance, there were no significant differences ($P > 0.05, n = 63$) in treatment bins compared with the controls for a specific sampling date. However, there was a significant difference in treatment versus control bins when the data were analyzed using the last 3 sample dates (134, 166, and 198 d from initial beetle release) using ANOVA ($F = 4.7; df = 1, 372; P = 0.03$). Sample date was not significant ($F = 0.2; df = 2, 372; P = 0.8$), as was sample date treatment interaction ($F = 0.1; df = 2, 372; P = 0.9$). On the last 3 sample dates, the control bins averaged 2.09 *R. dominica* per kilogram and the treatment bins averaged 0.24 *R. dominica* per kilogram. Thus, *R. dominica* populations in the treatment bins were suppressed 85% compared with the controls. As expected, populations of *C. elegans* were much higher in the treatment bins than in the control bins (Fig. 2). A few *C. elegans* were detected in the control bins after 76 d from initial beetle release. However, none were detected in the control bins at 106, 134, and 166 d from initial beetle release.

Control of *C. ferrugineus* by released *C. waterstoni* could not be directly measured in this study because large numbers of wild *C. waterstoni* colonized the control bins (Fig. 3). Densities of *C. waterstoni* were similar in both the treatment and control bins. The only significant difference ($P < 0.05, n = 124$) in *C. waterstoni* density between treatment and control bins occurred at day 166 from initial beetle release. The source of *C. waterstoni* that colonized the control bins was probably a nearby bin that contained grain sorghum highly infested with *C. ferrugineus* and *C. waterstoni*. Population densities of *C. ferrugineus* were not significantly different ($P < 0.05, n = 124$) in
the control and treatment bins, except on days 45 and 107 from initial beetle release (Fig. 4).

Grain temperatures in all 6 bins were similar during the experiment (Fig. 5). The grain remained at 28°C until 76 d from initial beetle release (20 September), after which it steadily decreased to 7°C after 198 d from initial beetle release (20 January).

1994 Field Study. As in the 1993 study, the 3 bins with parasitoids added to them had much lower densities of R. dominica than the control bins (Fig. 6). R. dominica densities in the treatment and control bins were 6.94 ± 1.18/kg and 81.03 ± 15.46/kg, respectively, 131 d after the start of the experiment. Thus, R. dominica populations in the treatment bins were suppressed 91% in comparison with the control bins. The experiment was stopped after 131 d because of the very high R. dominica density in the control bins. As expected, populations of C. elegans were much higher in the treatment than in the control bins (Fig. 7). Only 1 C. elegans adult was found in 1 of the 63 grain samples taken in the control bins on the next to last sample date. Wasp density increased in the treatment bins during the study and reached a maximum of 1.17 ± 0.25 C. elegans per kilogram on the final sample date.

As in the 1993 study, C. waterstoni was present in both the treatment and control bins (Fig. 8). Thus, we were unable to directly estimate suppression of C. ferrugineus by C. waterstoni. The C. waterstoni that colonized the control bins may have come from the same bin of sorghum that colonized the control bins in 1993. Population densities of C. ferrugineus were not significantly different (P = 0.05, n = 124) in the control and treatment bins and reached a density of ≈8.5 adult
beetles per kilogram 131 d after initial beetle release (Fig. 9). Grain temperatures in the 6 bins were similar up to 80 d after initial beetle release. Grain temperatures in the control bins were higher than the treatment bins 100 d after initial beetle release (Fig. 10). After 131 d from initial beetle release (16 November), grain temperatures in the control and treatment bins averaged 31.41 ± 0.74°C and 26.11 ± 0.85°C, respectively.

Discussion

This study demonstrated that augmentative releases of *C. elegans* were effective in suppressing *R. dominica* populations in large bins of stored wheat. After 198 d from initial beetle release in 1993 and 131 d from initial beetle release in 1994, bins treated with parasitoids were suppressed 98 and 91% in comparison to control bins. The Federal Grain Inspection Service (FGIS) standard for insect infested wheat is 2 or more live insects per kilogram of wheat. After 131 d from initial beetle release in 1993, *R. dominica* densities in the treatment and control bins were 0.05 and 2.06 insects per kilogram, respectively. Thus, the *R. dominica* density in the treatment bin is well below the FGIS threshold. Because of the high *R. dominica* release rates in 1994, both the control and treatment bins were above the FGIS threshold (81.03 and 6.94 *R. dominica* per kilogram). Although we used a very high *R. dominica* release rate in 1994, the wasps still managed to suppress *R. dominica* by 91%, indicating the same level of effectiveness as in the 1993 study.

This study also inadvertently demonstrated the amazing ability of *C. waterstoni* to spread and colonize other grain bins, even though the bins were tightly sealed. The source of *C. waterstoni* that infested the control bins in both years of the study was probably a nearby bin that contained grain sor-
densities were 6.9 and 23.9/kg for 1993 and 1994, respectively. Predicted peak *C. ferrugineus* density was twice as high as the actual peak density in 1993 and 3 times as high as the actual peak density 1994. This suggests that *C. waterstoni* probably suppressed *C. ferrugineus* population growth by at least 50%. The simulation results agree with the observations of Hagstrum (1989) who observed that *C. ferrugineus* normally reach densities of 10–20/kg by November in farm-stored wheat under similar conditions in Kansas.

 Grain temperatures in treatment and control bins were similar in 1993. Grain temperatures in the center of the bin fell below 20°C after ≈120 d (18 November) from initial beetle release in 1993. These parasitoid wasps should continue to parasitize beetle larvae and develop into adult wasps until the grain temperature falls below 20°C (Flinn 1991, P.W.F., unpublished data). At this temperature, beetle development and reproduction would also cease (Howe 1965). In the 1994 study, grain temperatures were 5.3°C higher in the control bins than in the treatment bins on the last sampling date (16 November). It is probable that high densities of *R. dominica* in the control bins caused these higher grain temperatures. On the final sampling date, average *R. dominica* densities were 81.03 adults per kilogram in the control bins and 6.94 adults per kilogram in the treatment bins. High densities of *R. dominica* have been shown to cause heating in grain because of insect metabolic processes (Cofie-Agbolor et al. 1995). Temperatures in the control and treatment bins were similar up to 70 d from initial beetle release. We chose not to control the grain temperatures with aeration because we wanted to evaluate the wasps' suppression potential under un aerated storage conditions.

 This study showed that the parasitoid wasp *C. elegans* effectively suppressed *R. dominica* populations below economic levels for up to 198 d of storage. Cool temperatures in the fall helped suppress the beetle population in the 1st experiment. Grain naturally cools in the fall and this cooling can occur earlier if aeration is used. Under U.S. wheat storage conditions, parasitoids would need to suppress beetle populations for ≈60–90 d until the grain begins to cool in the fall.

 The wasps used in this study often occur naturally in stored grain (Hagstrum 1987). Grain managers need to be aware of the benefits these wasps have in suppressing beetle infestations and not confuse them with pest insects.

 The costs of biological control may be slightly higher compared with traditional chemical controls. Chemical protectants cost ≈$0.02/bu and biological control using predators and parasitoids cost ≈$0.04/bu (M. Maedgen, personal communication, Biofac). Given the increasing concern over pesticide residues in our food, biological control should be viewed as a reasonable alternative to chemical control in certain cases.

 We have developed a model of *C. waterstoni* and *C. ferrugineus* (Flinn and Hagstrum 1995) and are working on a model for *C. elegans* and *R. dominica*. These models will be incorporated into the Stored Grain Advisor expert system (Flinn and Hagstrum 1990) to provide advice on timing wasp releases and predicting effectiveness.

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 References Cited


 Howe, R. W. 1965. A summary of estimates of optimal and minimal conditions for population increase of


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