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Efficacy of methoprene for multi-year protection of stored wheat, brown rice,
rough rice and corn

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Abstract

Hard red winter wheat, brown rice, rough rice, and corn were treated with the insect growth regulator (IGR) methoprene at rates of 1.25 and 2.5 ppm, held for 24 months at ambient conditions in buckets on the floor of a grain bin, and sampled every two months. Bioassays were done by exposing 10 mixed-sex adults of *Rhyzopertha dominica* (F.), the lesser grain borer, and *Tribolium castaneum* (Herbst), the red flour beetle, on wheat, *R. dominica* and *Sitotroga cerealella* (Oliver), the Angoumois grain moth, on brown rice and rough rice, and *T. castaneum* and *S. cerealella* on corn. Sample size for all commodities was about 80 g, and these samples were held for 3 months at 27°C-60% r.h. Both rates of the IGR completely suppressed adult progeny development of *R. dominica* with little resulting feeding damage, sample weight loss, or insect damaged kernels (IDK). Some adult progeny production of *S. cerealella* and resulting IDK occurred at both rates on rough rice, brown rice, and corn, but was far less than in untreated controls. There was little adult progeny production but some feeding damage caused by larval *T. castaneum* in the treated wheat and corn but again far less than in untreated control. Allowing continual exposure of parental adults on grains treated with an IGR, rather than exposing those parental adults for a short time period, may give more accurate evaluations of residual efficacy. Results show that methoprene used as a grain protectant will give residual control of stored product beetles for 24 months, but complete control of *S. cerealella* may require inclusion of a contact insecticide.

Key Words: grain, *Rhyzopertha dominica*, *Sitotroga cerealella*, *Tribolium castaneum*, methoprene, storage

1. Introduction

The insect growth regulator methoprene, a juvenile hormone (JH) analog that inhibits molting and development in immature insects, has been utilized for many years as a grain protectant in Australia (Daglish, 2008). A commercial formulation was available in the United States (US) in the mid-1980s (Diacon[®]), relaunched in 1999, and in 2002 was replaced by s-methoprene with the name Diacon II[®] (EPA Registration Number 2724-427). All formulations were 33% active ingredient [AI], 288 mg AI/ml (Diacon[®] II, EPA Registration Number 2724-427). Label specifications allowed application at 1, 2.5, and 5 ppm (mg AI/kg). This formulation was replaced in 2011 by (Diacon[®] IGR), which had the same amount of AI, but the label rates were changed to 1.25 and 2.5 ppm (EPA Est. No. 2724-TX-1).

JH analogs such as methoprene are generally effective against externally-feeding stored grain insects because all life stages of those insects will be exposed to the insecticide as they develop from the egg to the adult stage (Athanassiou et al., 2011ab). They are also effective on internally-feeding stored grain insects such as *Rhyzopertha dominica* (F.), the lesser grain borer, and *Prostephanus truncatus* (Horn), the larger grain borer (Kavallieratos et al., 2012), because the egg is laid outside the grain kernel, and the neonate will be exposed to the insecticidal residues before it can bore into the grain kernel. *Sitotroga cerealella* (Olivier), the Angoumois grain moth, can infest stored corn and stored rice (Perez-Mendoza et al., 2004). The female also lays eggs outside the grain kernel and the larvae will bore into the kernel after hatching, thus it is also considered to be an internal feeder. There has been little recent research in the US regarding susceptibility of *S. cerealella* to insecticides, including IGRs, currently used as protectants in stored grain management. The effects of IGRs are generally manifest in the immature stages, and though they are not generally toxic to adults, there is some evidence of indirect effects from adult

exposure to methoprene, such as reduced fecundity (Daglish and Pulvirenti, 1997, Chanbang et al., 2008; Wijayaratne et al., 2012).

Wheat and small grains, and also corn kernels, can be readily infested by internally-feeding stored grain insects. Bulk rice in bins is generally stored in the husk (hull) and is classified as rough rice or paddy rice. The hull will offer some protection of the kernel, as it may limit penetration by neonates of *R. dominica* and *S. cerealella* (Cogburn, 1974; Chanbang et al., 2008, Kavallieratos et al., 2012, Arthur et al., 2013). However, *S. cerealella* can penetrate intact rice hulls (Cogburn et al., 1983). Once the hull is removed during the initial milling process, the rice is classified as brown rice, and the loss of the protective hull facilitates infestation by stored product insects (Sittisang and Imura, 1987). In addition, the red flour beetle, *Tribolium castaneum* (Herbst), a cosmopolitan grain pest, can readily feed and develop on brown rice (Kavallieratos et al., 2015). The US Food and Drug Administration classified brown rice as a whole grain in 2008, which opened up a new market for brown rice as a gluten-free replacement for wheat. Brown rice is generally stored in bags rather than in bins or flat storages, but there are currently little data regarding efficacy of methoprene as a protectant of brown rice. In addition, there are several recent studies that indicate efficacy of IGRs, when used alone and in combination with other insecticides as grain protectants, will vary depending on the specific grain commodity (Athanassiou et al. 2009, 2011a; Kavallieratos et al., 2012).

Laboratory trials evaluating IGRs for control of stored product insects usually involve exposure of adults for limited time periods, typically one or two weeks, and then assessing resulting progeny development (Athanassiou et al., 2011ab). Few tests have examined the impact of continual adult exposure for several months, including effects on quality parameters such as feeding damage and commodity weight loss. Also, residual efficacy is usually assessed for

different time periods for up to a year; there are no recent studies that have been conducted for a multiple-year storage period. The objectives of this study were to determine: 1) residual efficacy of methoprene for protection of multiple commodities, wheat, brown rice, rough rice, and corn, 2) species differences and commodity differences in terms of progeny production and selected quality parameters, and 3) progeny production and quality loss on different commodities due to continual adult exposure of different species for multiple weeks.

2. Materials and Methods

2.1. General methods. This test was initiated during the summer of 2012 at the USDA-ARS-Center for Grain and Animal Health Research (CGAHR), Manhattan, KS, USA. The methoprene formulation used was the current commercial product Diacon[®] IGR, 288 mg AI/ml (33% AI, Central Life Sciences, Schaumburg, IL, USA). The application rates were 1.25 and 2.5 ppm (mg/kg), the commodities were wheat, corn, brown rice, and rough rice, and the experimental replicate unit was an 11 kg lot for each of the commodities. Label directions specify different amounts of the formulation to be mixed with 8.92 L to treat each respective commodity. Thus, each replicate of each application rate was formulated in a 25 ml flask, and the amount dispensed for a given commodity was in proportion to the label directions. Experimental procedures will be described first for wheat, then for the other commodities.

2.2. Wheat. A ratio of 90% whole wheat and 10% cracked wheat comprised each 11-kg lot. The target concentrations for each replicate were prepared by measuring appropriate volumes of the commercial product. Each of the two rates were prepared using 7.7 ml of formulated spray per each of the four replicate 11 kg lots, which is proportional to the label volume spray rate of 18.92 L gallons of formulated spray per 27,272 kg of wheat (0.7 ml/kg). Separate solutions were

formulated for each replicate for each application rate. Each replicate was spread onto a cardboard form that was about 0.25 m². A Badger 100 artists' airbrush (Franklin Park, IL, USA) was used to mist the formulated spray directly onto the wheat. Approximately one-third of the formulated spray was dispensed at one time, the wheat was mixed using a piece of cardboard, and this procedure was repeated two more times. These treatments were done inside a laboratory room in one of the buildings at CGAHR.

The wheat was treated on 19 July, 2012. After each replicate was sprayed, it was emptied from the cardboard form into a 20-L capacity bucket (4 buckets for each of the two rates). Immediately after adding the wheat to the bucket, subsamples were taken to evaluate the efficacy of methoprene. Approximately 80 mg from each replicate was placed into each of two 120-ml vials. The same amount of untreated wheat, obtained from the laboratory, was placed into each of eight 120-ml jars for the untreated controls. These samples were termed the time 0 samples (immediately after treatment). After this first subsampling, all buckets containing the treated wheat were moved to the floor of a 27 metric ton (MT) capacity empty grain bin at the CGAHR. The treated wheat was held for 24 months inside the grain bin. A HOBO recording computer with two cable attached to an insulated metal rod was placed inside one of the replicate buckets to monitor temperature at approximate depths of 2.5 and 19 cm. The sampling procedure to evaluate residual activity described above was repeated every two months for 24 months. The final samples were taken on 23 July 2014.

The next day after the samples were taken from the buckets, including the time 0 samples, 10 mixed-sex adult *R. dominica* aged one week were added to one of the vials of wheat from each replicate sample for the two application rates (8 vials) and to each of 8 vials of untreated wheat. Ten one-week adult *T. castaneum* were added to the remaining vial of treated

129 wheat from each replicate and concentration and to the remaining 8 vials of untreated wheat.
130 The vials were then placed in a walk-in chamber set at 27°C and 60% r. h. on a 16:8 hour light:
131 dark cycle. They were held inside the chamber for 3 months, then the vials were removed, and
132 held for several days in a freezer at about -18C. The vials were removed from the freezer, and
133 allowed to warm to room temperature (about 25°C, according to random sampling with a HOBO
134 temperature recording unit). The contents were then weighed, the insects sieved, and all adults
135 tabulated. The number of original parental adults (10) was subtracted from this total. The wheat
136 was sieved again, and the feeding damage was weighed, and the whole wheat was weighed. One
137 hundred kernels from the each of the vials containing the *R. dominica* were removed and later
138 examined under a stereo microscope for adult emergence holes (classified then as insect
139 damaged kernels or IDK). The samples were then discarded.

140 *2.3 Brown Rice.* The same treatment procedures were followed for brown rice as for wheat, but
141 the test insect species were *R. dominica* and *S. cerealella* instead of *T. castaneum*. The volume
142 spray rates were adjusted to match the specific label instructions for rice (0.9 ml of formulated
143 spray per kg). The brown rice was treated on 14 August 2012, and samples were taken at time 0
144 as described for wheat. After the initial time 0 samples were taken, the buckets containing the
145 rice were moved to the same bin as the wheat. After samples were taken, 10 newly emerged
146 adult *S. cerealella* were put in each of the four replicate vials for the two treatments and the eight
147 jars for the controls. Ten adult *R. dominica* were placed in the remaining vials, again as
148 described above. Vials were held in the chamber for 3 months and then processed as described
149 above, with a random sample of 100 brown rice kernels taken from the vials containing *S.*
150 *cereaella* and *R. dominica* for IDK counts. Damage to the brown rice kernel caused by feeding of
151 *S. cerealella* larvae was also categorized as insect damaged kernels. Temperature in one of the

buckets containing brown rice was monitored as described for wheat. The brown rice was sampled every two months for 24 months as described for wheat. The final samples were taken on 18 September 2014.

2.4 Rough rice. The rough rice was treated on 20 September 2012, with *R. dominica* and *S. cerealella* as test insect species, and the application rate was the same as described for brown rice. All procedures were as previously described, and the rough rice was sampled for IDK counts for both species. Temperatures were monitored in the rough rice as previously described. The final samples were taken on 18 September 2014.

2.5. Corn. The corn was also treated on 14 August 2012, but the test insects were *T. castaneum* and *S. cerealella*, and the application rate adjusted for corn (0.75 ml of formulated spray per kg). All treatment, sampling and processing procedures were as previously described, except that no IDK counts were done for *T. castaneum*. Temperature was monitored in one of the buckets containing corn. The final samples were taken on 18 September 2014.

2.6. Experimental Design and Statistical analysis. The design of the experiment was a Completely Random Design (CRD). The amount of feeding damage, and the weight of commodity in each vial after the feeding damage and adult insects were sieved, were divided by the original weight of the sample to create two new variables, percentage weight loss due to infestation and percentage of feeding damage. These two variables, along with the number of adult progeny, and the percentage of IDK for all species except *T. castaneum*, were the variables of interest. The main effects were treatment (untreated control and the two application rates of methoprene), and time post-treatment (0 to 24 months). Data for each commodity and species were analyzed using a mixed-models procedure (PROC Mixed) in the Statistical Analysis

System (SAS Institute, version 9.2, Cary, NC, USA), with sample month as a random effect, to determine significance differences with respect to treatment. Means for treatment for each commodity and species for treatment on each sample date were separated ($P < 0.05$) using LS means with Tukey adjustment (SAS Institute). The Correlation Procedure in SAS (PROC Corr) was used to determine significant correlation between progeny production and feeding damage, IDK, and sample weight loss for each species on each commodity.

3. Results

3.1. Temperature profiles

Average daily temperature patterns were similar in all four commodities (Fig. 1), from about -10°C in winter to about 35°C in summer, which is typical for ambient seasonal temperatures in the southern plains of the US. There was a data gap from December of 2013 to mid-January of 2014 due to equipment malfunction. Although the commodities were held in buckets on the floor inside an empty grain bin, the starting bulk mass of each commodity was only 11.4 kg, which did not provide much insulation. Nevertheless, the temperatures inside the buckets would be analogous to temperatures on the top surface of a grain mass, and there was no indication of a temperature effect on methoprene efficacy.

3.2 Wheat

Progeny production of *R. dominica* from the original 10 mixed-sex parental adults ranged from 153.4 ± 18.1 to 755.6 ± 150.2 in untreated controls depending on the sample month, but there was no progeny production in either of the methoprene treatments for the entire two years of the study (Fig. 2A). This extensive progeny production in untreated controls resulted in considerable sample weight loss due to adult and larval feeding (Fig. 2B), which in turn led to high

percentages of IDK, again depending on sample month (Fig. 2C). There was also a reduction in sample weight after insects and feeding damage were removed, relative to the original sample weight (Fig. 2D), with little corresponding quality damage and loss in the treated wheat. All comparisons were significantly different ($P < 0.05$) between treatments and controls for the four measured variables (progeny production, feeding damage, weight loss, and % IDK) for all sample months, but there were no differences between the two methoprene treatments. Percentage of loss from feeding damage, percentage IDK, and percentage sample weight loss for the entire 2-year sample period were all strongly correlated ($P < 0.001$) with progeny production.

Progeny product of *T. castaneum* on untreated wheat was much lower than that by *R. dominica*, but there was no progeny in treated wheat at any time during the test (Fig. 3A). On 6 of the 13 sample dates, there was more feeding damage in either one or both of the methoprene treatments compared to the controls, possibly due to supernumary molts and resulting extension of the larvae stage (Fig. 3B). Larval feeding of *T. castaneum* did not generally lead to a reduction in the sample weight of wheat (Fig. 3C). Similar to *R. dominica*, feeding damage and sample weight loss were correlated with progeny production ($P < 0.001$).

3.3 Brown rice

Progeny production of *R. dominica* from the original 10 mixed-sex parental adults on brown rice ranged from 154.2 ± 26.5 to 1229.6 ± 76.7 in untreated controls, however, there was no progeny production in either of the methoprene treatments at any of the sample times (Fig. 4A). There was considerable weight loss from feeding damage in untreated controls and very little in the treatments (Fig. 4B), with a high proportion of IDK in controls (Fig. 4C). There was also considerable weight loss in the untreated controls, but little weight loss in the treatments

(Fig. 4D). There was no difference between the two methoprene concentrations for any of the four measured variables. Percentage of loss from feeding damage, percentage IDK, and percentage sample weight were all strongly correlated ($P < 0.001$) with progeny production, similar to results for wheat.

Progeny production of *S. cerealella* on untreated brown rice ranged from 65.4 ± 12.0 to 260.5 ± 23.0 over months (Fig. 5A), however, the total progeny may have been underestimated because production was so extensive during the 3-month holding period that the brown rice was clumped into a mass and it was difficult to separate out individual adults. Progeny adults were found in the treatments, though they were always less than the controls, with no difference between concentrations on most of the occasions, and with only a couple of instances where progeny adults differed between the two treatments. In contrast to *R. dominica*, there was little measurable feeding damage created by *S. cerealella* (Fig. 5B), but there was extensive IDK damage in controls, with less in treatments (Fig. 5C). However, the maximum percentage IDK in the treatments was as high as about 60%, possibly because visible feeding damage, such as tracks made by larvae in the brown rice kernel was classified as IDK, in addition to emergence holes created by adults as they exited the kernel. Weight loss occurred between controls and treatments in certain months post treatment, relative to the original sample weight (Fig. 5D), but this weight loss was low compared to *R. dominica* on brown rice. Weight loss was lower in treatments than in controls in 9 of the 13 sample times, but in the other 4 cases there was no difference between controls and treatments. Progeny production was correlated with the other three variables ($P < 0.001$)

3.4 Rough rice

Progeny production of *R. dominica* on untreated rough rice was very low compared to corresponding progeny production on brown rice, and was below 25 adults per sample until months 22 and 24 (Fig. 6A). Feeding damage (6B), IDK (6C), and sample weight loss (Fig. 6D) were all low as well, with no significant difference between controls and treatments until months 22 and/or 24. Progeny production was again strongly correlated ($P < 0.001$) with the other three variables.

In contrast, there was extensive progeny production of *S. cerealella* on untreated rough rice (range of 133.2 ± 16.8 to 295.0 ± 19.4), about 5 to 10x greater than the values for *R. dominica* (6.2 ± 2.2 for months 0 to 20, 33.2 ± 2.5 and 100.0 ± 11.5 for months 22 and 24, respectively (Fig. 7A). There was little measured feeding damage (Fig. 7B). The percentage of IDK in untreated *S. cerealella* controls ranged from 5.1 ± 1.4 to 25.4 ± 2.6 , which in this case were actual emergence holes in the hull or husk because the kernel was not visible (Fig. 7C). Feeding damage was not included in this assessment, as it was for brown rice. There was generally less IDK in the treatments compared to the controls. Similar to brown rice, there was little change in sample weight due to *S. cerealella* compared to *R. dominica*, with occasional greater loss in controls compared to treatments (Fig. 7D). Progeny production was correlated with feeding damage and IDK ($P < 0.001$) but not sample weight loss ($P = 0.29$).

3.5 Corn

Progeny production of adult *T. castaneum* on untreated corn did not exceed 40 adults per sample except at months 6, 8, and 12, while the only adult progeny found in treated corn was at month 4 (Fig. 9A). There was feeding damage in both controls and treatments, with occasional differences between treatments and controls (Fig. 9B). There was no measurable sample weight

loss for either treatments or controls. Progeny production was correlated with feeding damage ($P < 0.001$).

Progeny production of *S. cerealella* in untreated controls ranged from 53.6 ± 7.7 to 197 ± 19.1 , but adults were also found in the treatments (11.0 ± 2.8 to 105 ± 13.7 , depending on the methoprene rate and the sample month) On 3 of the 13 sample months there was no difference between controls and treatments. Feeding damage was very low and in most cases generally not different between treatments and controls. However, the percentage of IDK in the controls, which included visible feeding damage on the corn kernel itself, was 32.7 ± 2.4 to 87.4 to 6.8 , and most of the time was significantly greater than IDK in the treatments (Fig. 9C). There was no measurable sample weight loss. Progeny production was slightly correlated with feeding damage ($P = 0.043$) and strongly correlated with IDK ($P < 0.001$).

4. Discussion

The results of this study show both the 1.25 ppm and the 2.5 application rates of the commercial formulation of methoprene currently available in the US completely suppressed progeny production of *R. dominica* on wheat and brown rice, and *T. castaneum* on corn and wheat for 24 months, with reduced feeding damage or weight loss. While other studies have shown that neonate *R. dominica* were susceptible to methoprene (Chanbang et al., 2008); no studies have been conducted for a multi-year storage period under natural conditions. Although there was no progeny production of *T. castaneum* on treated wheat, the feeding damage and sample weight loss was occasionally comparable to that reported for untreated wheat. Thus, the exposure to methoprene, and the prolongation of the larval stages, could have resulted in increased larval feeding. Allowing the original parental adults to remain on the wheat for the 3-

month holding period increased the infestation potential, since adults of both species can feed and reproduce for several months (Rees, 2004). In addition, a second generation of adults of *R. dominica* likely occurred on the untreated wheat, but whole-kernel wheat is not an optimal diet for *T. castaneum*, thus the progeny adults in untreated controls could represent a single generation from the original parental adults.

Both *R. dominica* and *S. cerealella* were able to reproduce multiple generations on untreated brown rice, with some progeny production of *S. cerealella* on the treated brown rice. This is the first report regarding the effectiveness of methoprene on brown rice in the US, and the first study involving susceptibility of *S. cerealella* to insecticides since Cogburn (1988). Brown rice was highly susceptible to the neonates of both species, as evidenced by the extensive progeny production in the untreated controls, along with the high percentage of IDK, but this may not be surprising because the protective husk had been removed. However, the relatively low feeding damage of *S. cerealella* compared to *R. dominica* is surprising, but this is partially explained by the presence of adult *R. dominica*. Overall, the results show that bagged stored brown rice will be especially vulnerable to both *R. dominica* and *S. cerealella*, which should be recognized in management programs.

R. dominica did not reproduce well on untreated rough rice. Rice varieties differ in their susceptibility to both *R. dominica* and *S. cerealella* (Cogburn 1977ab), which is often attributed to structural differences in the husk or cracks and splits in the husks that enable neonates to more easily penetrate through the husk and feed on the kernel (Cogburn, 1974; 1977ab; Cogburn et al., 1983, Chanbang et al., 2008). Previous studies state that susceptibility of specific rice varieties does not usually differ between the two species (Cogburn, 1974, Cogburn and Bollich, 1990), but this was not true for the current study. Furthermore, there was some progeny production of *S.*

cerealella on the treated rough rice, similar to the results for treated brown rice. Neonates of *S. cerealella* can enter sound rough rice husks through the vascular bundles in the abscission scar of the husk, however; penetration through the husk was stated as being rare, and occurred only in a specific variety, Vista, that was regarded as being susceptible to both *S. cerealella* and *R. dominica* (Cogburn et al, 1983). Mixed-variety long grain rough rice was used the current study, and although examinations were not done to determine presence or percentage of sound versus cracked husks, the numbers of progeny in the untreated control would seem to indicate successful penetrations by the neonate *S. cerealella* compared to *R. dominica*. It is also possible that neonates of *S. cerealella* are more tolerant to methoprene than *R. dominica* neonates through natural tolerance, which has not previously been reported. Again, since the rough rice used in this test was mixed-variety long-grain rice, no inferences can be made regarding varietal susceptibility to either species.

There was little measurable feeding damage caused by *S. cerealella* even in untreated brown rice and rough rice, despite the high progeny production. These results are contradictory to those obtained by Takeshita and Imura (1990), who reported a range of weight loss values ranging from about 5 to 20%, depending on the variety and level of infestation, after 13 weeks of infestation by *S. cerealella*. The present study occasionally reported higher feeding damage for a similar time period. However, the Takeshita and Imura (1990) study examined sub-samples of 1,000 kernels or a 200-ml volume of kernels, a larger sample than what was measured in our study. The entire bioassay samples (about 80 g) in our study were compared between untreated controls and the IGR treatments. Even with the range of IDK in brown rice in the current study that were a result of larval feeding and adult emergence holes in *S. cerealella* and the IDK values in rough rice that were only adult emergence holes, there was little feeding damage. Feeding

330 damage of *S. cerealella* in untreated corn was negligible compared to progeny production, while
331 there was some feeding damage of *T. castaneum* on treated and untreated corn.

332 In conclusion, the methodology employed in this study whereby parental adults of *T.*
333 *castaneum* and *R. dominica* were allowed to remain on the commodities, and holding the
334 commodities so that more than one generation could be produced for the beetle species and *S.*
335 *cerealella*, is a realistic mimic of a natural infestation. Thus, the results show that methoprene
336 can give long-term protection from all three species. However, the apparent greater tolerance of
337 *S. cerealella* compared to *R. dominica* warrant further investigation. It may be necessary to
338 combine methoprene with a contact insecticide to limit entry of neonate *S. cerealla* into brown
339 rice kernels or rough rice husks.

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403 varnished wood, concrete, and wheat. J. Econ. Entomol. 105, 718-125.

Figure Captions

Fig. 1. Temperature ($^{\circ}\text{C}$) at the center of the grain mass of wheat (A), brown rice (B), rough rice (C), and corn (D) held in the buckets on the floor of the grain bins. Original starting mass was ca. 11.4 kg. Wheat was held from July 19 2012 to 23 July 2014, the other three commodities were held from 23 August 2012 to 18 September 2014. Missing data due to equipment malfunction in December 2013.

Fig. 2. Number of progeny (A), percentage of feeding damage relative to the bi-monthly wheat sample (B), % of insect-damaged kernels (C), and percentage of weight loss relative to the original sample (D) (means $\pm$ SE) three months after introduction of 10 mixed-sex adult *R. dominica* on ca. 80 g of untreated wheat or ca. 80 g of wheat treated with 1.25 and 2.5 ppm methoprene (M). No significant differences between methoprene treatments for any of the four variables, treatments different from untreated wheat on each sample date ($P < 0.05$). No data for month 16 for untreated wheat.

Fig. 3. Number of progeny (A), percentage of feeding damage relative to the bi-monthly wheat sample (B), and percentage of weight loss relative to the original sample (C) (means $\pm$ SE) three months after introduction of 10 mixed-sex adult *T. castaneum* on ca. 80 g of untreated wheat or ca. 80 g of wheat treated with 1.25 and 2.5 ppm methoprene (M). No significant differences between methoprene treatments for progeny production, treatments different from untreated wheat on each sample date ($P < 0.05$). Significant differences ($P < 0.05$) between all three treatments for the other two variables are denoted with different lower-case letters.

Fig. 4. Number of progeny (A), percentage of feeding damage relative to the bi-monthly brown rice sample (B), % of insect-damaged kernels (C), and percentage of weight loss relative to the original sample (D) (means $\pm$ SE) three months after introduction of 10 mixed-sex adult *R.*

dominica on ca. 80 g of untreated brown rice or ca. 80 g of brown rice treated with 1.25 and 2.5 ppm methoprene (M). No significant differences between methoprene treatments for any of the four variables, treatments different from untreated brown rice on each sample date ($P < 0.05$).

Fig. 5. Number of progeny (A), percentage of feeding damage relative to the bi-monthly brown rice sample (B), % of insect-damaged kernels (C), and percentage of weight loss relative to the original sample (D) (means $\pm$ SE) three months after introduction of 10 mixed-sex adult *S.*

cerealella on ca. 80 g of untreated brown rice or ca. 80 g of brown rice treated with 1.25 and 2.5 ppm methoprene (M). No significant differences between methoprene treatments for number of progeny, treatments different from untreated brown rice on each sample date ($P < 0.05$).

Significant differences ($P < 0.05$) between all three treatments for the other three variables are denoted with different lower-case letters.

Fig. 6. Number of progeny (A), percentage of feeding damage relative to the bi-monthly rough rice sample (B), % of insect-damaged kernels (C), and percentage of weight loss relative to the original sample (D) (means $\pm$ SE) three months after introduction of 10 mixed-sex adult *R.*

dominica on ca. 80 g of untreated rough rice or ca. 80 g of rough rice treated with 1.25 and 2.5 ppm methoprene (M). No significant differences between methoprene treatments for number of progeny on any sample date, treatments different from control ($P < 0.05$). Significant differences between treatments and controls for the other three variables occurred only on the last two sample dates and are denoted with lower case letters ($P < 0.05$).

Fig. 7. Number of progeny (A), percentage of feeding damage relative to the bi-monthly rough rice sample (B), % of insect-damaged kernels (C), and percentage of weight loss relative to the original sample (D) (means $\pm$ SE) three months after introduction of 10 mixed-sex adult *S.*

cerealella on ca. 80 g of untreated rough rice or ca. 80 g of rough rice treated with 1.25 and 2.5

ppm methoprene (M). No significant differences between methoprene treatments for number of progeny, treatments different from untreated rough rice on each sample date ($P < 0.05$). Significant differences ($P < 0.05$) between all three treatments for the other three variables are denoted with different lower-case letters.

Fig. 8. Number of progeny (A) and percentage of feeding damage relative to the bi-monthly wheat sample (B) (means $\pm$ SE) three months after introduction of 10 mixed-sex adult *T. castaneum* on ca. 80 g of untreated wheat or ca. 80 g of corn treated with 1.25 and 2.5 ppm methoprene (M). No significant differences between methoprene treatments for progeny production, treatments different from untreated wheat on each sample date, with an exception as noted for month 2 ($P < 0.05$). Significant differences ($P < 0.05$) between all three treatments for feeding damage noted with different lower case letters. No measureable difference in sample weight loss. No data for month 10 because corn was too moldy to process.

Fig. 9. Number of progeny (A), percentage of feeding damage relative to the bi-monthly rough rice sample (B), and % of insect-damaged kernels (C) (means $\pm$ SE) three months after introduction of 10 mixed-sex adult *S. cerealella* on ca. 80 g of untreated corn or ca. 80 g of corn treated with 1.25 and 2.5 ppm methoprene (M). No significant differences between methoprene treatments for number of progeny on most sample dates, treatments different from untreated corn on most sample dates ($P < 0.05$). Significant differences ($P < 0.05$) between all three treatments for the other two variables are denoted with different lower-case letters. No measureable difference in sample weight loss. No data for month 10 because corn was too moldy to process.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9