Efficacy of Spinosad Against Eight Stored-Product Insect Species on Hard White Winter Wheat

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Biopestic. Int. 3(2): 117-125 (2007)

ABSTRACT The efficacy of spinosad on hard white winter wheat was evaluated in the laboratory by exposing 25 adults of six species of beetles or 50 eggs of two moth species to 100 g of untreated wheat and wheat treated with spinosad at the rates of 0.1, 0.5, and 1 mg(AI)/kg. Spinosad was more effective against insects at 1 mg(AI)/kg than at 0.1 and 0.5 mg(AI)/kg. All lesser grain borers, *Rhyzopertha dominica* (F.); rusty grain beetles, *Cryptolestes ferrugineus* (Stephens); rice weevils, *Sitophilus oryzae* (L.); maize weevils, *Sitophilus zeamais* Motschulsky; and > 94 per cent of the red flour beetles, *Tribolium castaneum* Herbst; and confused flour beetles, *Tribolium confusum* (Jacquelin du Val), were killed after 14 days of exposure to spinosad at 1 mg(AI)/kg. At 1 mg(AI)/kg, no live larvae of the Indian meal moth, *Plodia interpunctella* (Hübner), were found after 21 days of exposure, and progeny production of all species of beetles and egg-to-adult emergence of *P. interpunctella* and the Angoumois grain moth, *Sitotroga cerealella* (Olivier), was reduced by 98–100 per cent. Spinosad at 1 mg(AI)/kg provided 98–100 per cent protection of the hard white wheat kernels from damage by all insect species.

KEY WORDS: Hard white winter wheat, spinosad, stored grain insects, performance

INTRODUCTION

Hard white winter wheat acreage is steadily increasing in western Kansas and it is slowly replacing acreage devoted to traditionally grown hard red winter wheat (Paulsen, 1998). During 2003, Kansas producers planted 10.4 million acres of wheat, of which nearly 5 per cent was devoted for hard white wheat (Dempster *et al*., 2003). Hard white winter wheat is used to make pan bread, flat bread, and noodles. Asian, Middle Eastern, and African countries that utilize these products have relied on Australian grown hard white winter wheat. Producers in the United States are encouraged to grow hard white wheat to regain United States' presence in the Asian, Middle Eastern, and African markets (Lin and Vocke, 2004). Additionally, compared with hard red winter wheat, hard white wheat has a higher flour extraction rate and sweeter taste in whole-wheat products (Taylor, 2003). The United States government has recently passed and implemented a farm bill, the White Wheat Incentive Program, to encourage farmers to plant hard white winter wheat (Lin and Vocke, 2004). It is anticipated that the production of hard white winter wheat in the United States will continue to increase in the future.

Many white wheat growers, especially in Kansas,

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are also organic farmers. Typically hard white wheat is stored on the farm for a longer period (> 9 months) than hard red winter wheat (3–6 months) (Martin *et al*., 1997). Organophosphate (OP) insecticides, such as malathion and chlorpyrifos-methyl, have been traditionally used as grain protectants to manage insects in wheat stored on farms, and many insect species are resistant to these OPs (Subramanyam and Hagstrum, 1995). These OP grain protectants cannot be used on organic stored wheat. In the United States, chlorpyrifos-methyl is no longer legal to use on stored wheat as of December 31, 2004. Very few insecticides are approved for use on organic stored wheat.

The bacterial pesticide *Bacillus thuringiensis* (*Bt*) is registered for use on grain to control only moth larvae (Subramanyam and Cutkomp, 1985), but it is used by less than 0.3 per cent of wheat and corn producers (Storey *et al.*, 1984). In addition, the Indian meal moth, *Plodia interpunctella* (Hübner), can rapidly develop high levels of resistance to *Bt* within a few generations (McGaughey and Beeman, 1988).

Natural products such as inert dusts, especially diatomaceous earth dusts, are registered for empty storage facilities and direct grain treatment (Subramanyam and Roesli, 2000). Inert dusts can be used on stored organic wheat. However, they are not widely used by producers because coating of the dusts on the surface of grains affects flowability, increases the angle of repose, and lowers test weight (Jackson and Webbley, 1994, Korunic *et al*., 1996). Furthermore, inert dusts are ineffective on grain stored under humid conditions or on high moisture grain (le Patourel, 1986). Therefore, the white wheat organic growers have no available options other than aeration for managing insect pests. The organic white wheat growers and the related food industries are constantly seeking effective grain protectants to manage stored-product insects.

Spinosad is a reduced risk commercial insecticide manufactured by Dow AgroSciences (Indianapolis, Indiana), derived from the actinomycete bacterium *Saccharopolyspora spinosa* sp. *nov* (Mertz and Yao) (Mertz and Yao, 1990). Spinosyns A and D are the metabolites produced by the bacteria that are responsible for the insecticidal activity. Spinosad provides effective control of insects in the orders Lepidoptera and Coleoptera (Mertz and Yao, 1990). It is labeled for use on over 100 field crops to manage insects (Thompson *et al*., 2000). Spinosad has very low mammalian toxicity, unique mode of action, and degrades quickly when exposed to sunlight (Salgado, 1998; Thompson *et al.*, 2000). Spinosad residues persist on stored hard red winter wheat for six months to a year without loss of insecticidal activity (Fang *et al*., 2002a; Flinn *et al*., 2004). The insecticidal activity of spinosad is also not affected by wheat moisture and temperature (Fang and Subramanyam, 2003). These qualities make spinosad an excellent grain protectant. In addition, the United States Department of Agriculture's (USDA) National Organics Certification Board has recently approved spinosad. In January 2005, spinosad was approved by the United States Environmental Protection Agency for use on stored wheat, corn, sorghum, oats, rice, barley, millet, and birdseed at 1 mg(AI)/kg of grain, and the tolerance level was established at 1.5 mg(AI)/kg (Anonymous, 2005).

Prior to registration of spinosad in 2005, the performance of this commercial insecticide against several stored-grain insects was investigated on four classes of wheat including durum, hard red spring, hard red winter, and soft red winter wheats (Fang *et al*., 2002b). The susceptibility of insects to spinosad varied among the wheat classes. The excellent performance of spinosad on durum and hard red winter wheat (Fang *et al*., 2002b; Flinn *et al*., 2004) encouraged us to investigate if spinosad could be an effective grain protectant for hard white winter wheat. In the current study, we evaluated the performance of spinosad in the laboratory on hard white winter wheat against eight major stored-grain insects.

MATERIALS AND METHODS

Wheat and Grain Treatment

Clean organic hard white winter wheat provided by American White Wheat Producers Association (Atchison, Kansas) was frozen at –13˚C for one week to kill any live insects before use in tests. After thawing, the wheat was tempered and equilibrated to 12 per cent moisture in an environmental growth chamber at 28°C and 65 per cent RH. Spinosad (SpinTor 2SC) containing 240 mg(AI)/ml was provided by Dow AgroSciences (Indianapolis, Indiana). All insecticide dilutions were made in distilled water.

Insects

The insect species tested were the lesser grain borer, *Rhyzopertha dominica* (Fabricius); rusty grain beetle, *Cryptolestes ferrugineus* (Stephens); rice weevil, *Sitophilus oryzae* (Linnaeus); maize weevil, *Sitophilus zeamais* Motschulsky; red flour beetle, *Tribolium castaneum* (Herbst); confused flour beetle, *Tribolium confusum* Jacquelin du Val; Indian meal moth, *Plodia interpunctella* (Hübner); and Angoumois grain moth, *Sitotroga cerealella* (Olivier). Three insect species (*S. zeamais, T. confusum, and S. cerealella*) that have not been tested previously with spinosad on wheat were included in this study.

Hard red winter wheat was used for rearing *R. dominica*, *Sitophilus* species, and *S. cerealella*. *Tribolium* species were reared on wheat flour plus 5 per cent brewer's yeast diet, *C. ferrugineus* was reared on rolled oats plus 5 per cent brewer's yeast diet, and *P. interpunctella* was reared on a poultry-mash diet (Subramanyam and Cutkomp, 1987). All species were reared in a growth chamber at 28°C, 65 per cent RH, and L14 : 10D h photoperiod. All insect species have been maintained for more than seven years in the Department of Grain Science and Industry's laboratory at Kansas State University.

Bioassay Procedures

Wheat kernels were treated with spinosad to provide rates of 0 (control treatment), 0.1, 0.5, and 1 mg(AI)/kg. Each 100 g lot of wheat, placed in a 0.45-litre glass jar, was treated with 100 ㎕ spinosad solution. Control treatment consisted of wheat treated with aliquots of distilled water. Jars containing grain treated with spinosad or distilled water were tumbled on a ball-mill roller for 10 min to ensure uniform coverage of the insecticide or water on grains. After tumbling, 25 male and female beetle adults of mixed ages or 50 newly laid (£ 24 h) eggs of a moth species were introduced into each jar. Infested jars were closed with wire mesh and filter paper lids, and incubated at 28°C, 65 per cent RH with a L14 : 10D h photoperiod. Jars infested with beetle adults were examined after 7 and 14 days to determine the number of live adults and after 49 days to determine progeny production and kernel damage. Jars infested with *P. interpunctella* eggs were examined after 21 days to determine egg-to-larval survival and after 49 days to count egg-to-adult emergence and number of kernels that were damaged. Larvae and pupae of *S. cerealella* complete development inside kernels (Arbogast, 1991). Therefore, in bioassays with *S. cerealella*, we only recorded the number of adults that emerged and number of kernels that were damaged 49 days after egg introduction. To determine kernel damage, 100 wheat kernels were examined from each jar. Kernels with adult exit holes (for *R. dominica*, *Sitophilus* species, or *S. cerealella*) or removal of germ or endosperm due to larval and/or adult feeding (for all other species) were considered damaged. For each combination of observation time and spinosad concentration, there were six replications in tests with *S. cerealella* and three replications in tests with the other insect species. Each replication was treated separately with distilled water or spinosad as described above.

The number of progeny of the six beetle species produced was determined after subtracting the 25 beetle adults that were originally added to each jar at the beginning of the tests. Progeny data for *T. castaneum* and *T. confusum* represented all visible larvae, pupae, and adults, because a few larvae and pupae did not complete development to adulthood when jars were examined after 49 days. Progeny for *R. dominica, S. oryzae, S. zeamais*, and *C. ferrugineus* were based on the number of adults produced.

Data Analysis

Data were analyzed by species. Data on the number of live beetle adults, live larvae of *P. interpunctella*, progeny production, egg-to-adult emergence of moth species, and kernel damage for statistical analysis were transformed to log (x + 1) scale to normalize heteroscedastic treatment variances (Zar, 1984). The data for beetles were first analyzed by two-way analysis of variance to determine differences in insect survival or kernel damage between the two exposure periods and the four spinosad rates (including the control treatment). Data for each insect species and exposure time were further subjected to one-way analysis of variance using the GLM procedure (SAS Institute, 1999) to determine survival and kernel damage differences among spinosad rates. Treatment means were separated using the Fisher's protected least significant difference test at the $\alpha = 0.05$ level (SAS Institute,1999). Untransformed means and standard errors are presented in the tables.

RESULTS

Survival of Beetle Adults

More than 89 per cent of adults of each species were alive after 7 and 14 days exposure to untreated (control) wheat. Spinosad was extremely effective against adults of the six beetle species tested as indicated by fewer live insects observed on spinosad-treated grain at the labeled rate of 1 mg(AI)/kg (Table 1). Two-way analysis of variance showed that the average survival of insects at the four spinosad rates between 7 and 14 days was significant (*F*, range among species = 19.40–39.16; df = 1, 16; $P < 0.05$) for *T. castaneum*, *T. confusum*, *S. zeamais*, and *S. oryzae*, but was not significant ($F = 0.64–1.49$; df = 1, 16; $P > 0.05$) for *R. dominica* and *C. ferrugineus*. There were significant differences in the average survival of each of the six beetle species at the four rates tested (*F*, range among species = 28.82–7,896.29; df = 1, 3; $P < 0.05$). The interaction between exposure time and spinosad rate (df = 3, 16) was not significant ($P > 0.60$) only for *R. dominica* ($F = 0.64$) and *C. ferrugineus* ($F = 0.65$), because survival was similar at 7 and 14 days of exposure. Two-way analysis of variance showed that the kernel damage (*F*, range among species = 0.14–3.46; df = 1, 16; $P > 0.08$) was not significant between the two exposure times, but significant differences in kernel damage were observed among the four rates only for *T. castaneum*, *T. confusum*, *C. ferrugineus*, and *S. oryzae* ($F = 6.21–13.30$; df = 3, 16; $P < 0.05$). Except for *T. confusum* ($F = 3.33$; df = 3, 16; $P > 0.046$), the interaction between exposure time and spinosad rate was not significant for the other species ($F = 0.16–0.90$; df = 3, 16; $P > 0.46$).

One-way analysis of variance showed that the adult survival after 7 or 14 days exposure was significantly different among spinosad rates for each of the six beetle species (*F*, range among species = 10.34–616.09; df = 3, 8; $P < 0.004$). At $\geq$ 0.1 mg(AI)/kg, none of the *R. dominca* adults survived after 7 days. At 0.1 mg(AI)/kg, spinosad significantly ($P < 0.05$) reduced adult survival of *C. ferrugineus* and *S. oryzae* after 7 days of exposure and that of *S. zeamais* after 14 days. Adults of *C. ferrugineus* and *S. oryzae* did not survive on spinosad-treated wheat at 0.5 and 1 mg(AI)/kg after 7 days, and only one *C. ferrugineus* adult survived at 0.5 mg(AI)/kg after 14 days. A few adults of *S. zeamais* survived at 0.5 mg(AI)/kg (3 insects) and at 1 mg(AI)/kg (0.3 insects) after 7 days of exposure, but all *S. zeamais* adults died after 14 days of exposure. *Tribolium* species were least susceptible to spinosad, and adult survival did not approach zero even at the highest spinosad rate.

Progeny Production of Beetles

There were significant differences in progeny production among the four treatments for each of the six species of beetles ($F > 17.91$, df = 3, 8; $P < 0.0007$) (Table 1). On untreated wheat, 76 progeny of *R. dominica* were observed and > 95 per cent of these progeny were live adults, whereas progeny of *R. dominica* were not observed on wheat treated with spinosad at 0.1 mg/kg or greater. An average of 46 adult progeny of *C. ferrugineus* was observed on untreated wheat. In contrast, only a few progeny (3 adults) of *C. ferrugineus* were produced in wheat treated with spinosad at 0.1 mg(AI)/kg, and no progeny were observed at 0.5 and 1 mg(AI)/kg. Large numbers of progeny of *S. oryzae* and *S. zeamais* were produced on untreated wheat and in wheat treated with 0.1 mg(AI)/kg . At 0.5 and 1 mg(AI)/kg, the number of progeny of the two species decreased significantly ($P < 0.05$) when compared with those produced on untreated wheat, and the reduction in progeny production at these rates ranged from 94 to 99 per cent. Progeny production of *Tribolium* species decreased with an increase in spinosad rate and complete progeny suppression occurred at 0.5 mg(AI)/kg for *T. confusum* and at 1 mg(AI)/kg for *T. castaneum*.

Egg-to-Larval Survival of *P. interpunctella*

Spinosad affected egg-to-larval survival of *P. interpunctella*. On untreated control wheat, 21 live larvae were observed 21 days after egg introduction.

Table 1. Adult survival and progeny production of and kernel damage by six stored-product beetles on untreated and spinosad-treated hard white winter wheat.

Species	Rate,	Number of live adults at:		Number of	Number of kernels damaged[2,3]		
	mg(AI)/kg	7 days[1]	14 days[1]	progeny[1,2]	7 days[1]	14 days[1]	49 days[1]
R. dominica							
	0	24.7 ± 0.3[4]	23.3 ± 1.7[4]	76.0 ± 6.8[4]	0.7 ± 0.3 a	1.3 ± 0.9 a	8.7 ± 1.3 a
	0.1	0	0	0	0 a	0 a	1.0 ± 0.6 b
	0.5	0	0	0	0.7 ± 0.3 a	0.3 ± 0.3 a	0 c
	1.0	0	0	0	0 a	0.3 ± 0.3 a	0 c
C. ferrugineus							
	0	24.7 ± 0.3 a	24.3 ± 0.3 a	46.0 ± 1.0 a	1.7 ± 1.2[4]	1.3 ± 0.3 a	4.7 ± 1.2 a
	0.1	2.7 ± 0.9 b	3.3 ± 0.3 b	3.0 ± 1.7 b	0	0.3 ± 0.3 a	0.7 ± 0.7 b
	0.5	0 c	0.3 ± 0.3 c	0 c	0	0.3 ± 0.3 a	0.3 ± 0.3 b
	1.0	0 c	0 c	0 c	0	0 a	0 b
S. oryzae							
	0.0	25.0 ± 0.0 a	22.3 ± 1.2 a	647.3 ± 160.4 a	2.3 ± 0.3 a	2.7 ± 0.7 a	49.3 ± 7.9 a
	0.1	16.7 ± 0.3 b	8.7 ± 0.9 b	454.0 ± 46.5 a	1.7 ± 0.9 ab	1.3 ± 0.7 a	30.3 ± 3.2 a
	0.5	0 c	0 c	37.7 ± 7.8 b	0 c	0 b	2.7 ± 0.3 b
	1.0	0 c	0 c	11.3 ± 6.1 c	0.3 ± 0.3 bc	0 b	0.7 ± 0.7 c
S. zeamais							
	0	25.0 ± 0.0 a	24.7 ± 0.3 a	676.7 ± 97.9 a	0.6 ± 0.3 a	0.7 ± 0.3 a	57.3 ± 7.9 a
	0.1	21.3 ± 0.7 a	15.0 ± 2.5 b	329.3 ± 37.8 a	0.7 ± 0.3 a	1.7 ± 0.7 a	25.7 ± 0.9 b
	0.5	3.0 ± 0.6 b	0 c	29.3 ± 9.8 b	0.3 ± 0.3 a	0 a	0.7 ± 0.3 c
	1.0	0.3 ± 0.3 c	0 c	3.0 ± 1.7 c	0.3 ± 0.3 a	0.3 ± 0.3 a	0 d
T. castaneum							
	0	24.3 ± 0.3 a	22.7 ± 1.5 a	82.7 ± 15.8 a	4.3 ± 1.2 a	5.3 ± 1.3 a	32.7 ± 4.1 a
	0.1	23.3 ± 0.6 a	22.7 ± 0.9 a	33.0 ± 14.0 a	1.7 ± 0.9 a	3.3 ± 0.7 ab	15.3 ± 2.6 b
	0.5	17.5 ± 1.5 b	7.3 ± 2.8 b	1.3 ± 1.3 b	1.7 ± 0.9 a	1.3 ± 0.9 bc	3.0 ± 1.2 c
	1.0	15.7 ± 1.7 b	1.3 ± 0.7 c	0 b	1.0 ± 0.3 a	0.3 ± 0.3 c	0.3 ± 0.3 d
T. confusum							
	0	24.7 ± 0.3 a	24.7 ± 0.3 a	43.0 ± 6.6 a	1.7 ± 0.7 a	2.7 ± 0.3 a	22.0 ± 4.5 a
	0.1	25.0 ± 0.0 a	21.3 ± 0.9 a	19.7 ± 5.8 b	1.3 ± 0.3 a	1.0 ± 0.0 b	8.3 ± 1.3 b
	0.5	17.0 ± 3.5 b	7.3 ± 1.8 b	0 c	1.3 ± 0.3 a	0 c	1.7 ± 0.3 c
	1.0	9.0 ± 1.0 c	1.0 ± 0.1 c	0 c	0.7 ± 0.3 a	0 c	0 d

[1]For each insect species, means within a vertical column followed by different letters are significantly different ($P < 0.05$; by Fisher's protected least significant difference test).

[2]The number of progeny produced for the six beetle species was the total number of insects observed after subtracting the 25 beetle adults, which were originally released to infest the wheat. The progeny data for *R. dominica, C. ferrugineus, S. oryzae, and S. zeamais* represented the number of adults only. Progeny data for *T. castaneum* and *T. confusum* represented all visible larvae, pupae, and adults.

[3]Kernels with adult exit holes (*Sitophilus* species or *S. cerealella*) or damage to germ or endosperm due to larval and/or adult feeding were considered damaged.

[4]Data were not subjected to one-way analysis of variance, as three of the four treatments had zero values.

The number of larvae observed after 21 days was significantly different among treatments (F = 72.07; df = 3, 8; P < 0.001) (Table 2). A total of only one live larva was found at 0.1 mg(AI)/kg and 0.5 mg(AI)/kg, and live larvae were not observed at 1 mg(AI)/kg.

Egg-to-Adult Emergence of *P. interpunctella* and *S. cerealella*

The number of adults of the two species that emerged was significantly different among the treatments (F = 71.44; df = 3, 8; P < 0.0001 for *P. interpunctella* and F = 252.71; df = 3, 20; P < 0.0001 for *S. cerealella*) (Table 2). None of the introduced *P. interpunctella* eggs became adults at 0.5 and 1 mg(AI)/kg and only a mean of 1.3 adults was found in each jar at 0.1 mg(AI)/kg. Spinosad at 1 mg(AI)/kg provided 100 per cent reduction of egg-to-adult emergence of *S. cerallella.*

Kernel Damage

In general, kernel damage by the beetle species was minimal after 7 and 14 days of exposure. Kernel damage was not significantly different among treatments at the two exposure times for *R. dominica*, *C. ferrugineus*, *S. zeamais*, *T. castaneum,* and *T. confusum* (F, range among species £ 3.63; df = 3, 8; P > 0.06). Significant treatment differences were observed for *S. oryzae* after 7 days (F = 4.96; df = 3, 8; P = 0.03), but only < 3 per cent kernels were damaged across the treatments (Table 1). There were significant differences in 14 day kernel damage among treatments in tests with *S. oryzae* and *Tribolium* species (F > 7.21; df = 3, 8; P < 0.005), but the number of kernels damaged among treatments was £ 6 per cent. There were no significant differences in kernel damage among treatments for the remaining three beetle species (F < 4.02, df = 3, 8; P > 0.05). No kernels were damaged by *P. interpunctella* after 21 days on spinosad-treated wheat, while damage to untreated wheat was 3.3 per cent (Table 2) and this difference was significant (F = 29.86; df = 3, 8; P < 0.0001).

Damage to untreated wheat after exposure to the eight insect species after 49 days ranged from 5 per cent (*C. ferrugineus*) to 57 per cent (*S. oryzae*) (Tables 1 and 2). The number of kernels damaged was significantly different among treatments for each of the species (F = 252.71, df = 3, 20; P < 0.0001 for *S. cerealella* and F > 10.12, df = 3, 8; P < 0.0042 for the other species). In general, damage to wheat caused by each of the eight species at a spinosad rate of 1 mg(AI)/kg never exceeded 1 per cent.

Table 2. Egg-to-larva survival and kernel damage by *P. interpunctella* and *S. cerealella* on untreated and spinosad-treated hard white winter wheat.

Insect	Rate, mg(AI)/kg	Number of live larvae after 21 days[1]	Number of adults emerged after 49 days[1]	Number of kernels damaged	
				21 days[1]	49 days[1]
P. interpunctella	0	21.3 ± 2.6 a	11.7 ± 2.0 a	3.3 ± 0.7	35.7 ± 10.0 a
	0.1	0.3 ± 0.3 b	1.3 ± 0.9 b	0	2.7 ± 1.2 b
	0.5	0.3 ± 0.3 b	0 b	0	0 c
	1.0	0 b	0 b	0	0 c
S. cerealella	0	—[2]	39.5 ± 0.6 a	—[2]	44.6 ± 2.4 a
	0.1	—[2]	12.5 ± 2.2 b	—[2]	4.5 ± 1.1b
	0.5	—[2]	0.3 ± 0.3 c	—[2]	0 c
	1.0	—[2]	0 c	—[2]	0 c

[1]For each insect species, means within a vertical column followed by different letters are significantly different (P < 0.05; by Fisher's protected least significant difference test).

[2]Data on larval survival and kernel damage at 21 days for *S. cerealella* were not collected as larvae develop within kernels and all of the grain had to be radiographed to determine infested kernels.

DISCUSSION

Of all the beetles tested, *R. dominica* was the most susceptible to spinosad, followed by *C. ferrugineus*. The susceptibility of *S. oryzae*, *S. zeamais*, *T. castaneum*, and *T. confusum* increased with an increase in spinosad rate and exposure time. Fang *et al*. (2002b) evaluated the efficacy of spinosad on durum, hard red spring, hard red winter, and soft red winter wheat against *R. dominica, S. oryzae, T. castaneum, P. interpunctella,* and the sawthoothed grain beetle, *Oryzaephilus surinamensis* (L.), under test conditions similar to that used in the current study. They reported spinosad at 1 mg(AI)/kg to be effective against *R. dominica* and *P. interpunctella*, and spinosad performed consistently against these species on all four wheat classes (hard red winter, soft red winter, hard red spring, and durum wheats). Our results also showed that spinosad at 1 mg(AI)/kg was extremely effective against the two insect species on hard white winter wheat.

Unlike previous tests (Fang *et al*., 2002b) our present results show that spinosad at 1 mg(AI)/kg on hard white winter wheat was extremely effective against *S. oryzae* and *S. zeamais* based on complete mortality of adults within 14 days and near complete suppression of progeny production. Adults of *T. castaneum* are generally less susceptible to spinosad on hard red winter, soft red winter, and hard red spring wheats (Fang *et al*., 2002b), but in the present tests with hard white winter wheat we observed 95 per cent mortality after 14 days of exposure. The lack of progeny production of *T. castaneum* at 1 mg(AI)/kg (Fang *et al*., 2002a; Flinn *et al*., 2004) suggests that the neonates are highly susceptible to spinosad. Similar results in this study were also observed with *T. confusum.* Spinosad at 0.5 and 1 mg(AI)/kg on hard white winter wheat was effective against *C. ferrugineus*, and this finding is consistent with our previous reports on hard red winter wheat treated with spinosad against a field strain and a laboratory strain of *C. ferrugineus* (Huang *et al*., 2004). The moth, *S. cerealella,* is an important pest of stored grains. To our knowledge, there are no reports on the efficacy of spinosad against *S. cerealella*. Our current results showed that spinosad at 1 mg(AI)/kg on hard white winter wheat was effective against this important moth pest.

The reduced kernel damage after 7 and 14 days of infestation is expected, because of the short time insects were exposed to the grain. However, as expected, kernel damage increased with an increase in exposure time, especially at 49 days, as a result of adult feeding and insect development (Hagstrum and Subramanyam, 2006). Fang *et al*. (2002b) also observed an increase in kernel damage 49 days after infestation when compared to 7 or 14 days.

In summary, spinosad at the labeled rate of 1 mg(AI)/kg protected hard white winter wheat from infestation and damage by eight stored grain insect species. The active ingredient of spinosad is certified organic by the USDA's National Organic Standards Board. Additionally, spinosad has low mammalian toxicity and is persistent on hard red winter wheat for a period of 12 months (Fang *et al*., 2002a). These attributes make it an appealing grain protectant for organic or non-organic hard white winter wheat growers in Kansas and elsewhere.

Acknowledgements. The authors gratefully acknowledge the technical assistance of Muktinutalapati Laxminarayan, Carmelita Goossen, and Brandi Kaufman. American White Wheat Producers Association (Atchison, Kansas) provided the hard white winter wheat for the study. We thank the reviewers for their constructive comments about the manuscript. This article is Contribution Number 08-55-J of the Kansas Agricultural Experiment Station, Manhattan, Kansas, and was supported by a grant from US-EPA Region VII, Kansas City, Kansas, was partially funded by grants from USDA/CSREES (RAMP) under Agreement Numbers 2000-51101-9674 and 2004-51101-02226.

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Accepted 18 September 2007