Effectiveness of Spinosad on Four Classes of Wheat Against Five Stored-Product Insects

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ABSTRACT Spinosad is a commercial reduced-risk pesticide that is naturally derived. Spinosad's performance was evaluated on four classes of wheat (hard red winter, hard red spring, soft red winter, and durum wheats) against adults of the lesser grain borer, *Rhyzopertha dominica* (F.); rice weevil, *Sitophilus oryzae* (L.); sawtoothed grain beetle, *Oryzaephilus surinamensis* (L.); red flour beetle, *Tribolium castaneum* (Herbst); and larvae of the Indianmeal moth, *Plodia interpunctella* (Hübner). Beetle adults (25) or *P. interpunctella* eggs (50) were exposed to untreated wheat and wheat treated with spinosad at 0.1 and 1 mg (AI)/kg of grain. On all untreated wheat classes, adult beetle mortality ranged from 0 to 6%, and *P. interpunctella* larval mortality ranged from 10 to 19%. The effects of spinosad on *R. dominica* and *P. interpunctella* were consistent across all wheat classes. Spinosad killed all exposed *R. dominica* adults and significantly suppressed progeny production (84–100%) and kernel damage (66–100%) at both rates compared with untreated wheat. Spinosad was extremely effective against *P. interpunctella* on all wheat classes at 1 mg/kg, based on larval mortality (97.6–99.6%), suppression of egg-to-adult emergence (93–100%), and kernel damage (95–100%), relative to similar effects on untreated wheats. The effects of spinosad on *S. oryzae* varied among wheat classes and between spinosad rates. Spinosad was effective against *S. oryzae, O. surinamensis* and *T. castaneum* only on durum wheat at 1 mg/kg. Our results suggest spinosad to be a potential grain protectant for *R. dominica* and *P. interpunctella* management in stored wheat.

KEY WORDS stored wheat, grain insects, spinosad, grain protectant, pest management

THE ORGANOPHOSPHATE, CHLORPYRIFOS-METHYL (Reldan), is currently registered by the United States Environmental Protection Agency (US-EPA) for treating stored wheat to manage insects. However, under the 1996 Food Quality Protection Act (Anonymous 1997), which set tougher standards for reviewing registered pesticides, the future of chlorpyrifos-methyl remains uncertain. In addition, resistance in key stored wheat insects has limited the effectiveness of chlorpyrifos-methyl (Zettler and Cuperus 1990, Subramanyam and Hagstrum 1995). Therefore, alternative pesticides or pest management strategies are urgently needed to replace chlorpyrifos-methyl.

In a laboratory evaluation, Subramanyam et al. (2002) found spinosad, the fermentation product of the bacterium *Saccharopolyspora spinosa* Mertz and Yao (Mertz and Yao 1990), to be an effective grain protectant on hard red spring, soft red winter, and hard red winter wheats against several stored-grain insect species. Spinosad is a broad-spectrum insecticide that provides effective control of insect pests in the orders Lepidoptera, Diptera, and Thysanoptera, and some species of Coleoptera and Orthoptera (Sparks et al. 1995, Cloyd and Sadof 2000, Peck and McQuate 2000, Thompson et al. 2000). Spinosad is a mixture of spinosyns A and D; the former is the predominant metabolite (Bret et al. 1997). Spinosad is toxic to insects by ingestion and contact (Adán et al. 1996, Liu et al. 1999, Wanner et al. 2000), and has a unique mode of action on the insect nervous system at the nicotinic acetylcholine receptor and GABA receptor sites (Salgado 1997, 1998). Spinosad has low mammalian toxicity (Thompson et al. 2000), and it degrades quickly when exposed to sunlight (UV light) (Brunner and Doerr 1996, Saunders and Bret 1997, Liu et al. 1999). Spinosad is labeled for use on >100 crops in the United States and is registered in 24 other countries (Thompson et al. 2000). Currently, spinosad is not registered for use on stored grains.

The present investigation characterizes the effectiveness of spinosad on four classes of wheat against five economically important stored product insect species. Insect mortality, progeny production or egg-to-adult emergence, and kernel damage were determined after exposure of insects to untreated wheats and wheats treated with two rates of spinosad.

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Materials and Methods

Wheat Classes. Durum, hard red spring, and soft red winter wheats were procured from commercial grain companies in the United States, and the hard red winter wheat was obtained from the milling laboratory in the Department of Grain Science and Industry, Kansas State University, Manhattan, KS. All wheats were frozen at –13°C for 1 wk to kill any residual insect infestation. Each wheat class was tempered to 13% moisture by adding distilled water and tumbled for 10 min on a ball-mill roller. Each wheat class was placed in separate 1.9-liter plastic containers with wire mesh lids. Wheats in plastic containers were then held in an environmental chamber at 28°C and 65% RH. At these conditions, all wheat classes equilibrate to 13% moisture (Sun and Woods 1994), and this was verified by testing (Motomco model 919 Automatic Grain Moisture Tester, Auburn, IL) before use in experiments.

Because the variety of each wheat class was unknown, common physical and chemical parameters of the wheat classes were determined. Grain moisture, kernel diameter, kernel weight, and hardness index were determined using the Perten Single Kernel Characterization System (model 4100, Perten Instruments, Reno, NV) (Gaines et al. 1996, Psotka 1999). The dockage (fine materials and broken kernels) in each wheat class was determined by sieving three 100 g samples over a 2.12-mm round-holed aluminum sieve. Dockage that passed through the sieve was weighed and expressed as a percentage of lot weight. Protein, ash, fat, and fiber content for each wheat class were determined using near infrared spectroscopy or standard official methods (AOAC International 1997, Wehling 1998).

Insects. Unsexed adults (1–3 wk old) of the lesser grain borer, *Rhyzopertha dominica* (F.) (Coleoptera: Bostrichidae); rice weevil, *Sitophilus oryzae* (L.) (Coleoptera: Curculionidae); sawtoothed grain beetle, *Oryzaephilus surinamensis* (L.) (Coleoptera: Silvanidae); red flour beetle, *Tribolum castaneum* (Herbst) (Coleoptera: Tenebrionidae); and eggs ($\leq$48 h old) of Indianmeal moth, *Plodia interpunctella* (Hübner) (Lepidoptera: Pyralidae) were used in the experiments. *Tribolium castaneum* and *O. surinamensis* were reared on diets of whole-wheat flour + 5% yeast (by weight) and rolled oats + 5% yeast, respectively. *Rhyzopertha dominica* and *S. oryzae* were reared on hard red winter wheat. *Plodia interpunctella* was reared on a chicken-mash diet (Subramanyam and Cutkomp 1987). All insects were reared at 28°C, 65% RH, and a photoperiod of 14:10 (L:D) h. Hatchability (mean $\pm$ SEM, $n = 15$ replications of 50 eggs each) of *P. interpunctella* eggs at the same environmental conditions was 99.9 $\pm$ 0.1%.

Spinosad. Spinosad (NAF-85; Lot No. NF16160P12; 480 mg [AI]/ml) was obtained from Dow AgroSciences, Indianapolis, IN. Stock solutions and spinosad dilutions for grain treatment were made in distilled water.

Grain Treatment. Spinosad solutions were applied at the rate of 1 ml per 1,000 g of wheat to provide 0.1 and 1 mg (AI)/kg. Untreated wheat (1,000 g) received 1 ml of distilled water. Wheat was treated with distilled water or spinosad in a 30-liter plastic drum, which was rotated on a ball-mill roller for 5 min to ensure uniform coverage of spinosad on kernels. Each combination of wheat class, rate, species, and exposure period was replicated five times, and each replicate was treated separately. After treatment, 50 g of untreated or spinosad-treated wheat was placed in 150-ml plastic containers. A 10-mm round hole was made in the lid of each container, and a piece of wire mesh screen (0.6-mm^2 openings) was glued to the lid to facilitate air diffusion.

Insect Exposure, Insect Responses, and Grain Damage. Each insect species was tested separately at 28°C, 65% RH, and a photoperiod of 14:10 (L:D) h. Insects (25 beetle adults or 50 *P. interpunctella* eggs) were introduced into a container of each wheat class. Eggs of *P. interpunctella* were used instead of neonate larvae to reduce handling losses. After insect introduction, containers were covered with lids and incubated under the same conditions used for rearing the insects. After 7 or 14 d, five containers for each wheat class-spinosad combination were examined to determine adult beetle mortality. At each exposure period, all dead and alive adults were separated from the wheat to assess mortality, and were discarded. At each exposure period, the wheat in three of the five containers was returned to the environmental chamber until adult progeny emerged. This incubation period from the time of insect introduction was exactly 45 d at which time adults were counted. The wheat from the remaining two containers at each exposure period was subjected to physical and chemical analyses (see above).

To determine the effect of continuous infestation on progeny production, at each combination of species, wheat class, and spinosad rate (including 0 mg/kg) five containers were infested with 25 beetles each. These containers were checked after 45 d to measure progeny production. For *P. interpunctella*, five of 10 containers for each wheat class-spinosad rate combination were examined 21 d after introducing 50 eggs per container to determine larval mortality, and the remaining five containers were checked after 42 d to count adults that emerged. Mortality of beetle adults and larvae of *P. interpunctella* were expressed as percentages of the total exposed.

Large numbers of progeny were produced by *S. oryzae*, especially on untreated wheat. To facilitate counting, wheat with *S. oryzae* progeny was passed once through a Boerner divider (Watson et al. 1970). The number of adults in this sample was doubled to express the number of beetles in the original wheat sample. Larvae, pupae, and adults of *T. castaneum* occurred in wheat infested for 7, 14, or 45 d. Therefore, progeny data for *T. castaneum* include all these stages. When expressing the number of beetle progeny produced, the 25 beetle adults originally used to infest the wheats were subtracted.

After determining progeny production (beetle) or egg-to-adult emergence (*P. interpunctella*), each

Table 1. Physical parameters (mean ± SEM) of wheat classes

Wheat class	Moisture (%)	Diameter (mm)	Wt of 1 kernel (mg)	Hardness index	Dockage[a] (%)
Durum	13.0 ± 0.0	2.6 ± 0.0	40.0 ± 0.7	89.2 ± 0.9	0.87 ± 0.1
Hard red spring	13.0 ± 0.0	2.3 ± 0.0	30.1 ± 0.4	71.6 ± 0.8	0.30 ± 0.1
Hard red winter	12.9 ± 0.0	2.3 ± 0.0	30.2 ± 0.5	67.2 ± 1.0	0.10 ± 0.0
Soft red winter	13.2 ± 0.0	2.3 ± 0.0	31.7 ± 9.1	11.8 ± 1.2	0.20 ± 0.1

Each mean is based on 300 wheat kernels, processed by the Perten Single Kernel Characterization System (Psotka 1999).
[a] Each mean is based on three, 100-g samples.

wheat sample was passed through the Boerner divider three times to get a sample of ≈6 g. From this sample, 100 kernels were selected to measure kernel damage. Damaged kernels included those without germs and those with irregular or round holes in the endosperm due to chewing or adult emergence. The number of kernels damaged out of the total examined was expressed as a percentage.

Data Analysis. The means and standard errors of the physical and chemical characteristics data were presented to show differences among the four wheat classes. Adult mortality, progeny production or egg-to-adult emergence, and kernel damage data were analyzed by species. The 7- and 14-d mortality, progeny production, and kernel damage data for beetles were subjected to three-way analysis of variance (ANOVA) using the PROC GLM procedure (SAS Institute 1988) to determine the significance of main (wheat class, spinosad rate, and exposure period) and interactive effects. For each combination of species and wheat class, mortality, progeny production, or kernel damage data at 7 or 14 d were subjected to one-way ANOVA to test for differences among spinosad rates; means were separated using the Fisher's protected least significant difference (LSD) test. Similarly, progeny production and kernel damage data for beetles exposed continuously (45 d) were also subjected to three-way ANOVA, one-way ANOVA, and the LSD test. The 21-d larval mortality, egg-to-adult emergence, and kernel damage data of *P. interpunctella* were subjected to two-way ANOVA to determine significant effects of main (wheat class and spinosad rate) and interactive effects. These data were sorted by wheat class and subjected to one-way ANOVA to test for differences among spinosad rates, and means were separated using the LSD test. Percentage data were transformed using arcsine$(x^{0.5})$, and beetle progeny and *P. interpunctella* egg-to-adult emergence data were transformed using log $(x + 1)$ to stabilize treatment variances for statistical analysis (Zar 1984). However, in tables untransformed means and standard errors are presented. Differences among treatments were considered significant at the $\alpha = 0.05$ level.

For each species, the relationship between each of the physical or chemical parameters (on untransformed scale) across wheat classes and untransformed mean mortality, mean progeny production, or kernel damage was determined using the PROC CORR procedure (SAS Institute 1988). For each combination of species and exposure period, the relationship between mean mortality and mean progeny production, and between mean progeny production and mean kernel damage, was determined using the PROC CORR procedure (SAS Institute 1988). The mean progeny data of beetles exposed continuously (45 d) included the 25 beetle adults originally introduced into containers, because these adults could have contributed to kernel damage.

Results

Physical and Chemical Parameters of Wheat Classes. Moisture contents or kernel diameters of the four wheat classes were similar (Table 1). Durum wheat kernels were 1.3 times heavier than kernels of the other wheats. Kernel hardness varied among the wheat classes, with durum being the hardest followed by hard red spring, hard red winter, and soft red winter wheats. Durum had 3–9 times more dockage than the other wheats. Hard red spring wheat contained the greatest amount of protein, followed by durum, hard red winter, and soft red winter wheats (Table 2). Ash, fat, or fiber content among the wheat classes showed minor differences.

Mortality of Beetle Adults After 7- and 14-d Exposures. Mortality of beetle adults on untreated wheats ranged from 0 to 6% (Table 3). On all wheat classes, spinosad at 0.1 and 1 mg/kg killed all exposed *R. dominica* adults within 7 d (Table 3). At 1 mg/kg, all *S. oryzae* adults were killed on durum wheat, and mortality ranged from 69 to 93% on other wheat classes. Mortality of *O. surinamensis* and *T. castaneum* after 7 and 14 d of exposure at the 1 mg/kg ranged from 46 to 76%, only on durum wheat, while mortality of these species on other wheat classes was <15% (Table 3).

Rhyzopertha dominica adult mortality was similar among the wheat classes ($F = 0.29$; df = 3, 96; $P = 0.829$) and exposure periods ($F = 0.92$; df = 1, 96; $P = 0.339$), but not among the rates ($F = 7{,}069.23$; df = 2,

Table 2. Chemical parameters (mean ± SEM) of wheat classes

Wheat class	Ash (%)	Fat (%)	Fiber (%)	Protein (%)
Durum	1.8 ± 0.0	2.0 ± 0.2	2.3 ± 0.0	15.37 ± 0.1
Hard red spring	2.1 ± 0.1	1.7 ± 0.1	3.0 ± 0.0	16.98 ± 0.2
Hard red winter	2.0 ± 0.0	1.6 ± 0.0	2.6 ± 0.0	13.98 ± 0.0
Soft red winter	1.9 ± 0.0	2.1 ± 0.2	2.7 ± 0.1	12.60 ± 0.2

Each mean, expressed on a 13% moisture basis, is based on two, 50-g samples.

Table 3. Mortality (mean ± SEM) of beetle adults exposed for 7 and 14 d to untreated and spinosad-treated wheat classes

Species	Wheat class	Spinosad rate (mg/kg)	% mortality at 7 d	% mortality at 14 d
R. dominica	Durum	0.0	1.6 ± 1.6b	0.8 ± 0.8b
		0.1	100.0 ± 0.0a	100.0 ± 0.0a
		1.0	100.0 ± 0.0a	100.0 ± 0.0a
	Hard red spring	0.0	1.6 ± 1.0b	0.9 ± 0.9b
		0.1	100.0 ± 0.0a	100.0 ± 0.0a
		1.0	100.0 ± 0.0a	100.0 ± 0.0a
	Hard red winter	0.0	0.0 ± 0.0b	2.4 ± 1.6b
		0.1	100.0 ± 0.0a	100.0 ± 0.0a
		1.0	100.0 ± 0.0a	100.0 ± 0.0a
	Soft red winter	0.0	1.6 ± 1.0b	3.2 ± 1.5b
		0.1	99.2 ± 0.8a	100.0 ± 0.0a
		1.0	100.0 ± 0.0a	100.0 ± 0.0a
S. oryzae	Durum	0.0	3.3 ± 1.6c	2.4 ± 1.0c
		0.1	43.1 ± 2.8b	62.2 ± 6.4b
		1.0	100.0 ± 0.0a	100.0 ± 0.0a
	Hard red spring	0.0	2.4 ± 1.6c	3.2 ± 1.5c
		0.1	35.1 ± 10.3b	41.6 ± 4.1b
		1.0	76.1 ± 2.3a	82.4 ± 6.5a
	Hard red winter	0.0	3.2 ± 1.5b	4.8 ± 2.3c
		0.1	58.0 ± 6.9a	53.1 ± 3.6b
		1.0	70.3 ± 8.3a	81.7 ± 2.7a
	Soft red winter	0.0	2.4 ± 1.5c	0.0 ± 0.0c
		0.1	32.6 ± 12.0b	50.5 ± 6.9b
		1.0	69.0 ± 6.7a	93.4 ± 1.0a
O. surinamensis	Durum	0.0	0.0 ± 0.0c	2.4 ± 1.0b
		0.1	2.4 ± 1.0b	5.6 ± 1.6b
		1.0	74.9 ± 2.7a	76.3 ± 3.2a
	Hard red spring	0.0	4.2 ± 1.4[a]	2.3 ± 1.6[a]
		0.1	5.6 ± 1.0	8.9 ± 2.8
		1.0	5.6 ± 1.6	4.1 ± 1.8
	Hard red winter	0.0	1.6 ± 1.0[a]	6.3 ± 2.3[a]
		0.1	7.2 ± 2.7	7.2 ± 2.7
		1.0	7.8 ± 2.4	14.4 ± 2.3
	Soft red winter	0.0	0.0 ± 0.0[a]	4.0 ± 0.1a
		0.1	2.4 ± 1.0	0.8 ± 0.8b
		1.0	2.7 ± 1.8	5.2 ± 1.0a
T. castaneum	Durum	0.0	0.0 ± 0.0b	2.4 ± 2.4b
		0.1	0.0 ± 0.0b	0.0 ± 0.0b
		1.0	46.4 ± 7.2a	54.7 ± 7.0a
	Hard red spring	0.0	0.0 ± 0.0	0.8 ± 0.8[a]
		0.1	0.0 ± 0.0	0.0 ± 0.0
		1.0	0.0 ± 0.0	1.6 ± 1.6
	Hard red winter	0.0	0.7 ± 0.7[a]	0.8 ± 0.8b
		0.1	0.8 ± 0.8	2.4 ± 1.6b
		1.0	7.5 ± 3.8	11.2 ± 3.7a
	Soft red winter	0.0	0.0 ± 0.0b	0.8 ± 0.8[a]
		0.1	0.0 ± 0.0b	2.2 ± 1.6
		1.0	7.8 ± 3.2a	2.4 ± 1.6

Each mean is based on five replications. For each species, wheat class, and exposure period, means among rates followed by different letters are significantly different ($P < 0.05$; Fisher's protected LSD).

[a] F, range = 0.34–3.49; df = 2, 12; P, range = 0.076–0.698 (one-way ANOVA).

96; $P = 0.001$). On each wheat class, mortality at 0.1 and 1 mg/kg was similar and significantly higher than on untreated wheat (Table 3). No significant interactions occurred among wheat class, exposure period, and spinosad rate.

The main and interactive effects of three-way ANOVA for *S. oryzae* and *O. surinamensis* showed similar significant differences, and therefore, are discussed together. Adult mortality was significantly different ($P < 0.008$) among wheat classes ($F = 14.27$ for *S. oryzae,* 47.05 for *O. surinamensis;* df = 3, 96), rates ($F = 610.65, 99.72$; df = 2, 96), and between exposure periods ($F = 8.97, 7.41$; df = 1, 96). Only the wheat class × spinosad rate interaction was significant ($F = 8.53, 59.03$; df = 6, 96; $P < 0.001$). This interaction indicated that the mortality of both *S. oryzae* and *O. surinamensis* adults at a given rate was not consistent across the wheat classes. On each wheat class, mortality of *S. oryzae* adults at 7 and 14 d was significantly greater on spinosad-treated wheats than on untreated wheats (Table 3). Furthermore, on all wheat classes, *S. oryzae* adult mortality was greater at 1 mg/kg than at 0.1 mg/kg. Mortality of *O. surinamensis* on durum wheat at 1 mg/kg was 5–28 times higher than mortality on other wheat classes (Table 3).

Tribolium castaneum mortality varied among wheat classes ($F = 31.77$; df = 3, 96; $P < 0.001$) and rates ($F = 94.48$; df = 2, 96; $P < 0.001$); and the greatest mortality was recorded on durum wheat. Mortality of adults was similar at the two exposure periods ($F = 3.03$; df = 1, 96; $P = 0.085$). The wheat class × rate interaction was significant ($F = 32.68$; df = 6, 96; $P < 0.001$).

Progeny Production of Beetles. All species produced progeny on untreated and spinosad-treated wheats (Table 4). However, progeny production of each species varied with the wheat class, spinosad rate, and exposure period (Table 4). At each spinosad rate, progeny production differences among exposure periods could be due to varying sex ratios, because unsexed adults were used to infest the wheats.

On each wheat class, regardless of the exposure period, progeny production on spinosad-treated wheats was significantly lower ($P < 0.05$) than on untreated wheats (Table 4). For *R. dominica,* the number of progeny ranged from 37 to 384 adults on untreated wheats and from 0 to 13 adults on spinosad-treated wheats. The 7- and 14-d progeny data of *R. dominica* showed significant differences among wheat classes ($F = 7.43$; df = 3, 48; $P < 0.001$) and rates ($F = 345.59$; df = 2, 48; $P < 0.001$). Progeny production also was different between 7 and 14 d ($F = 4.71$; df = 1, 48; $P = 0.035$). Only the wheat class × exposure period interaction was not significant ($F = 1.89$; df = 3, 48; $P = 0.143$). The number of progeny produced after 45 d of exposure was not different among wheat classes ($F = 1.29$; df = 3, 48; $P = 0.289$), but there were significant differences among rates ($F = 520.73$; df = 2, 48; $P < 0.001$). The interaction of wheat class and rate also was significant ($F = 13.65$; df = 6, 48; $P < 0.001$).

At 1 mg/kg, progeny production of *S. oryzae* was much lower on durum wheat than on other wheat classes (Table 4). A similar trend was observed for *T. castaneum.* The main and interactive effects for 7- and 14-d progeny production of *S. oryzae* and *T. castaneum* were similar, and therefore, are presented together. The number of progeny produced was significantly different among the wheat classes ($F = 29.46$ for *S. oryzae* and 24.47 for *T. castaneum;* df = 3, 48; $P < 0.001$), rates ($F = 71.72, 225.14$; df = 2, 48; $P < 0.001$), and between the exposure periods ($F = 56.17, 6.84$; df = 1, 48; $P < 0.012$). The only significant interactive effect was wheat class × rate ($F = 30.87, 21.89$; df = 6, 48; $P < 0.001$).

Table 4. Progeny production (mean ± SEM) of beetles after 7, 14, or 45 d exposure of parental adults to untreated and spinosad-treated wheat classes

Species	Wheat class	Spinosad rate (mg/kg)	No. progeny		
			7 d	14 d	45 d
R. dominica	Durum	0.0	75.3 ± 24.2a	145.3 ± 8.7a	80.6 ± 11.0a
		0.1	11.0 ± 1.5b	8.3 ± 2.0b	13.0 ± 1.6b
		1.0	1.0 ± 0.6c	0.3 ± 0.3c	0.2 ± 0.2c
	Hard red spring	0.0	218.7 ± 12.7a	280.7 ± 53.5a	192.6 ± 17.2a
		0.1	5.0 ± 5.0b	3.0 ± 1.5b	4.2 ± 1.5b
		1.0	1.0 ± 0.6b	1.0 ± 0.6b	3.0 ± 2.5b
	Hard red winter	0.0	384.0 ± 27.3a	368.7 ± 56.2a	364.2 ± 23.2a
		0.1	2.3 ± 0.3b	3.7 ± 0.7b	0.4 ± 0.2b
		1.0	0.0 ± 0.0c	0.7 ± 0.7c	0.4 ± 0.2b
	Soft red winter	0.0	37.3 ± 28.7[a,b]	358.3 ± 47.0a	314.2 ± 22.1a
		0.1	0.7 ± 0.7	0.7 ± 0.7b	2.8 ± 1.2b
		1.0	0.3 ± 0.3	0.0 ± 0.0b	0.6 ± 0.2b
S. oryzae	Durum	0.0	179.3 ± 34.7a	401.3 ± 45.7a	289.4 ± 11.1a
		0.1	337.3 ± 47.6a	424.0 ± 28.2a	346.2 ± 17.6a
		1.0	23.3 ± 6.4b	23.3 ± 4.7b	26.6 ± 2.9b
	Hard red spring	0.0	307.3 ± 64.7[a]	318.0 ± 75.7[a]	327.4 ± 55.8[c]
		0.1	221.3 ± 23.1	414.7 ± 40.1	403.8 ± 20.9
		1.0	160.7 ± 54.5	232.7 ± 7.9	324.2 ± 57.2
	Hard red winter	0.0	234.7 ± 60.6[a]	452.7 ± 55.4[a]	310.2 ± 35.4[c]
		0.1	170.0 ± 26.2	394.7 ± 16.7	289.0 ± 42.8
		1.0	186.0 ± 6.1	328.0 ± 76.0	211.4 ± 27.1
	Soft red winter	0.0	277.0 ± 29.3[a]	632.0 ± 91.5a	468.8 ± 45.7a
		0.1	185.3 ± 23.7	471.7 ± 24.3a	347.2 ± 23.9b
		1.0	236.3 ± 63.7	289.3 ± 20.9b	424.4 ± 21.7ab
O. surinamensis	Durum	0.0	62.3 ± 8.2a	64.0 ± 4.7a	52.2 ± 4.0a
		0.1	40.0 ± 13.1a	58.7 ± 3.3a	55.4 ± 4.3a
		1.0	4.0 ± 1.7b	12.3 ± 6.8b	13.0 ± 2.7b
	Hard red spring	0.0	50.3 ± 2.0[a]	43.3 ± 3.2[a]	48.8 ± 5.7[c]
		0.1	53.7 ± 2.2	39.7 ± 4.3	41.6 ± 3.7
		1.0	51.3 ± 4.1	35.3 ± 5.2	34.4 ± 1.6
	Hard red winter	0.0	43.3 ± 11.4[a]	36.7 ± 5.2[a]	28.4 ± 5.4[c]
		0.1	38.7 ± 1.2	24.3 ± 7.0	25.4 ± 2.4
		1.0	24.0 ± 2.5	29.7 ± 7.0	21.4 ± 2.6
	Soft red winter	0.0	145.0 ± 15.6a	143.3 ± 9.8ab	159.0 ± 22.6[c]
		0.1	135.7 ± 22.8a	170.0 ± 18.9a	134.4 ± 10.9
		1.0	77.0 ± 14.0b	86.7 ± 15.9b	127.0 ± 19.2
T. castaneum	Durum	0.0	154.7 ± 13.9a	144.0 ± 37.0a	142.2 ± 20.2a
		0.1	107.3 ± 7.1b	137.3 ± 18.3a	146.0 ± 19.3a
		1.0	0.0 ± 0.0c	0.0 ± 0.0b	0.6 ± 0.4b
	Hard red spring	0.0	176.3 ± 22.2a	195.0 ± 5.7a	191.8 ± 16.3[c]
		0.1	121.0 ± 9.7a	158.3 ± 11.3a	121.6 ± 31.9
		1.0	41.3 ± 5.4b	51.7 ± 9.2b	53.0 ± 7.2
	Hard red winter	0.0	81.0 ± 4.0[a]	129.0 ± 8.2a	125.2 ± 11.1a
		0.1	62.7 ± 12.9	86.3 ± 6.3b	67.0 ± 5.1b
		1.0	19.0 ± 9.1	24.0 ± 2.9c	15.4 ± 3.2c
	Soft red winter	0.0	111.3 ± 17.5a	227.7 ± 13.9a	186.4 ± 5.4a
		0.1	68.0 ± 11.0a	81.7 ± 10.3a	149.0 ± 11.9a
		1.0	5.7 ± 2.9b	12.3 ± 5.7b	22.0 ± 5.9b

Each 7- and 14-d mean is based on three replications, whereas each 45-d mean is based on five replications. For each combination of species, wheat class, and exposure period, means among rates followed by different letters are significantly different ($P < 0.05$; Fisher's protected LSD).

[a] F, range = 0.36–4.06; df = 2, 6; P, range = 0.077–0.713 (one-way ANOVA).

[b] In two of the three replications, the number of progeny produced was <10. The reasons for such low progeny production are unknown.

[c] F, range = 0.68–3.35; df = 2, 12; P, range = 0.084–0.523 (one-way ANOVA).

For both species, the number of progeny produced after 45 d of exposure on untreated and spinosad-treated wheats varied among wheat classes ($F = 49.09, 6.37$; df = 3, 48; $P < 0.001$) and rates ($F = 53.60, 68.22$; df = 2, 48; $P < 0.001$). The wheat class × spinosad rate interaction also was significant ($F = 35.14, 9.12$; df = 6, 48; $P < 0.001$).

More *O. surinamensis* progeny were produced on untreated and spinosad-treated soft red winter wheat when compared with the other wheats (Table 4). Progeny production after 7 and 14 d was different among wheat classes ($F = 64.51$; df = 3, 48; $P < 0.001$) and rates ($F = 38.26$; df = 2, 48; $P < 0.001$), but not between the two exposure periods ($F = 0.16$; df = 1, 48; $P = 0.692$). The wheat class × exposure period ($F = 4.12$; df = 3, 48; $P = 0.011$), and wheat class × rate ($F = 13.93$; df = 6, 48; $P < 0.001$), were the only significant interactions.

Differences in progeny production of *O. surinamensis* after 45 d of exposure were significant ($P < 0.001$) among wheat classes ($F = 94.24$; df = 3, 48) and spinosad rates ($F = 20.30$; df = 2, 48). The wheat class × rate interaction also was significant ($F = 7.50$; df = 6, 48; $P < 0.001$). Progeny production among rates on hard red spring wheat or hard red winter wheat was not significant ($P > 0.05$). In general, a significant impact on progeny production occurred only on durum wheat treated with 1 mg/kg (Table 4).

Kernel Damage Caused by Beetles. For each beetle species, kernel damage following progeny production after 7-, 14-, or 45-d adult exposure is shown in Table 5. In the case of *R. dominica* in durum wheat, *P. interpunctella* contamination especially in the 7 d treatment inflated the damage estimates. This contamination occurred because *P. interpunctella* eggs used for the hatchability tests were in close proximity to the durum wheat containers, and some newly hatched larvae were successful in entering through the wire mesh partially covering the container lids.

Kernel damage caused by *R. dominica* in the 7- and 14-d exposure treatments varied among wheat classes ($F = 10.53$; df = 3, 45; $P < 0.0001$) and rates ($F = 101.63$; df = 2, 45; $P < 0.0001$). Kernel damage between the two exposure periods was similar ($F = 1.08, 3.18$; df = 1, 45; $P > 0.3$). The wheat class × exposure period ($F = 6.68$; df = 3, 45; $P < 0.001$) and wheat class × exposure period × spinosad rate ($F = 2.68$; df = 6. 45; $P = 0.026$) interactions were significant. Kernel damage in the 45-d exposure treatment was not different among wheat classes ($F = 2.52$; df = 3, 41; $P = 0.07$), but was different among the rates ($F = 110.83$; df = 2, 41; $P < 0.0001$). The wheat class × rate interaction was not significant ($F = 1.97$; df = 6, 41; $P > 0.09$).

Kernel damage caused by *S. oryzae* in the 7- and 14-d treatments was significantly affected by spinosad rates ($F = 20.48$; df = 2, 41; $P < 0.001$). The wheat class × rate interaction ($F = 5.92$; df = 6, 41; $P = 0.0002$) also was significant, indicating that the kernel damage within a rate varied among the wheat classes. Kernel damage after 45-d exposure was significant among wheat classes ($F = 6.56$; df = 3, 39; $P < 0.03$) and spinosad rates ($F = 4.15$; df = 2, 39; $P < 0.03$), but the interaction of these two main effects was not significant ($F = 2.10$; df = 6, 39; $P > 0.07$). At 7-, 14-, or 45-d exposure period, kernel damage at 1 mg/kg was significantly lower ($P < 0.05$) than at 0 and 0.1 mg/kg only on durum wheat.

All main and interactive effects for kernel damage caused by *O. surinamensis* in 7- and 14-d exposure treatments were significant ($P < 0.001$; three-way ANOVA). Kernel damage caused by *O. surinamensis* after 45-d exposure was different among wheat classes ($F = 16.5$; df = 3, 37; $P < 0.0001$) and rates ($F = 3.60$; df = 2, 37; $P = 0.037$). The wheat class × rate interaction was not significant ($F = 1.33$; df = 6, 37; $P = 0.268$). Kernel damage caused by *O. surinamensis,* with rare exceptions, was <14% (Table 5). In some treatments, *P. interpunctella* larval contamination resulted in >14% kernel damage.

Kernel damage following progeny emergence of *T. castaneum* after 7- and 14-d exposures was significantly different ($P < 0.01$) among wheat classes ($F = 11.16$; df = 3, 35) and rates ($F = 65.52$; df = 2, 35), but it was not different ($P > 0.35$) between the two exposure periods ($F = 0.87$; df = 1, 35). The wheat class × rate ($F = 65.52$; df = 2, 35; $P < 0.0001$) and wheat class × exposure period × rate ($F = 3.55$; df = 6, 35; $P < 0.008$) interactions were significant. Kernel damage after 45-d exposure was significant among the wheat classes ($F = 5.44$; df = 3, 40; $P = 0.003$) and rates ($F = 32.51$; df = 2, 40; $P < 0.003$). The wheat class × rate interaction was not significant ($F = 2.19$; df = 6, 40; $P > 0.06$). In most cases, kernel damage to spinosad-treated wheat was less than damage to untreated wheat. The damage at 1 mg/kg was significantly lower ($P < 0.05$) than at 0.1 and 0 mg/kg, especially on durum wheat in 7-, 14-, or 45-d exposure treatment.

Mortality of *P. interpunctella* Larvae. Mortality of *P. interpunctella* larvae after 21 d was similar across wheat classes ($F = 1.01$; df = 3, 48; $P = 0.395$), but it was different among rates ($F = 739.71$; df = 2, 48; $P < 0.001$). The wheat class × rate interaction also was significant ($F = 4.71$; df = 6, 48; $P < 0.001$). Larval mortality on untreated wheat classes ranged from 10 to 19% (Table 6). On all wheat classes, mortality at 1 mg/kg was 98–100%.

Egg-to-Adult Emergence of *P. interpunctella* and Kernel Damage. The number of *P. interpunctella* adults that emerged was significantly different ($P < 0.015$) among wheat classes ($F = 3.41$; df = 4, 60) and rates ($F = 209.15$; df = 2, 60) (Table 6). The interaction of wheat class and rate also was significant ($F = 4.44$; df = 8, 60; $P < 0.001$). On durum, hard red winter, and hard red spring wheats, emergence was similar between untreated wheat and wheat treated with 0.1 mg/kg (Table 6). No or very few (2%) eggs became adults at 1 mg/kg, and emergence at this rate on all wheat classes was significantly lower than emergence at 0 and 0.1 mg/kg.

Kernel damage caused by *P. interpunctella* larvae was similar among wheat classes ($F = 1.8$; df = 3, 41; $P > 0.16$) (Table 6). However, it was highly significant ($P < 0.0001$) among rates ($F = 174.23$; df = 2, 41). The wheat class × rate interaction was not significant ($F = 1.51$; df = 6, 41; $P > 0.2$). On soft red winter wheat, damage at 0.1 and 1 mg/kg was similar and significantly lower than damage at 0 mg/kg.

Correlation Analysis. For each species, each physical and chemical parameter of wheat classes did not correlate well ($P > 0.05$; H_o: $\rho = 0$), or show any consistent trend, with mortality, progeny production, *P. interpunctella* egg-to-adult emergence, or kernel damage. A significant inverse relationship ($P < 0.05$) was found between mean mortality and mean progeny production for *R. dominica* ($r = -0.73$ and -0.93 for 7 and 14 d, respectively) and *S. oryzae* ($r = -0.63$, -0.69). For *T. castaneum,* this relationship was significant only at the $\alpha \leq 0.07$ level ($r = -0.56, -0.54$; $P = 0.05, 0.07$). For *O. surinamensis*, there was no correlation between mortality and progeny production ($r = -0.49, -0.41$; $P = 0.106, 0.189$). For *P. interpunctella,* mortality was inversely related to the egg-to-adult emergence ($r = -0.79$; $P < 0.003$).

The 7-, 14-, or 45-d mean progeny and mean kernel damage data for *T. castaneum* were positively correlated (r, among exposure periods = 0.641–0.831; $P < 0.05$). Correlation between progeny and kernel damage was significant ($P < 0.05$) only for the 14- and 45-d

Table 5. Kernel damage (mean ± SEM) following progeny emergence after 7, 14 or 45 d exposure of beetles to untreated and spinosad-treated wheat classes

Species	Wheat class	Spinosad rate (mg/kg)	% kernel damage 7 d	% kernel damage 14 d	% kernel damage 45 d
R. dominica	Durum	0.0	61.0 ± 18.7a	27.3 ± 9.2a	23.8 ± 7.2a
		0.1	20.5 ± 13.5ab	3.0 ± 1.7b	4.7 ± 2.2b[a]
		1.0	1.7 ± 1.2b[b]	1.3 ± 1.3b	2.7 ± 1.8b[a]
	Hard red spring	0.0	19.5 ± 8.5a[b]	20.3 ± 1.7a	14.2 ± 0.6a
		0.1	3.5 ± 1.5b[b]	1.3 ± 0.3b	1.8 ± 0.6b
		1.0	0.3 ± 0.3b	0.7 ± 0.7b	0.4 ± 0.2c
	Hard red winter	0.0	24.0 ± 3.5a	23.3 ± 0.9a	24.0 ± 5.5a[a]
		0.1	2.0 ± 1.0b	0.7 ± 0.3b	0.4 ± 0.2b
		1.0	0.3 ± 0.3b	0.0 ± 0.0b	0.2 ± 0.2b
	Soft red winter	0.0	3.7 ± 2.7[c]	28.7 ± 5.0a	27.2 ± 2.2a
		0.1	1.3 ± 0.9	0.0 ± 0.0b	1.0 ± 0.8b
		1.0	0.0 ± 0.0	0.7 ± 0.3b	0.5 ± 0.5b[d]
S. oryzae	Durum	0.0	48.0 ± 22.5a	63.0 ± 10.6a	24.4 ± 5.2a
		0.1	37.3 ± 2.7a	27.7 ± 3.5b	22.8 ± 2.7a
		1.0	1.0 ± 0.6b	2.3 ± 0.9c	3.6 ± 0.9b
	Hard red spring	0.0	33.0 ± 5.9	28.3 ± 7.0[c]	19.6 ± 3.4[e]
		0.1	16.3 ± 3.7	24.3 ± 5.0	15.2 ± 3.2
		1.0	11.0 ± 6.0[b]	19.3 ± 4.5	23.4 ± 4.8
	Hard red winter	0.0	29.3 ± 1.8a	17.0[f,g]	17.5 ± 4.5a[b]
		0.1	8.5 ± 0.5b[b]	17.5 ± 0.5[b]	17.3 ± 1.8a[a]
		1.0	8.5 ± 2.5b[b]	17.5 ± 7.5[b]	3.3 ± 0.9b[a]
	Soft red winter	0.0	26.3 ± 8.4[c]	36.3 ± 11.2[c]	33.7 ± 8.4[a,h]
		0.1	17.3 ± 2.7	25.7 ± 3.7	37.0 ± 13.4
		1.0	20.0 ± 6.1	18.0 ± 1.2	31.8 ± 7.8
O. surinamensis	Durum	0.0	63.0 ± 3.6a	11.0 ± 4.5[c]	3.7 ± 1.2[a,i]
		0.1	10.7 ± 2.7b	2.0 ± 0.6	4.5 ± 1.8[d]
		1.0	0.0 ± 0.0c	2.7 ± 0.9	2.7 ± 1.2[a]
	Hard red spring	0.0	5.0 ± 0.0a	10.0 ± 3.1[c]	12.2 ± 1.5[e]
		0.1	5.3 ± 0.3a	5.7 ± 1.5	8.2 ± 2.6
		1.0	2.5 ± 0.5b[b]	6.3 ± 2.2	8.6 ± 1.3
	Hard red winter	0.0	9.0 ± 9.0[b,j]	3.0 ± 3.0[b,j]	1.0 ± 1.0[a,k]
		0.1	11.0 ± 1.0[b]	2.5 ± 2.5[b]	0.3 ± 0.3[d]
		1.0	0.0 ± 0.0[b]	1.0 ± 1.0[b]	0.5 ± 0.5[d]
	Soft red winter	0.0	38.7 ± 5.8a	1.5 ± 0.5[b,l]	13.8 ± 5.2a
		0.1	3.7 ± 1.8b	1.3 ± 0.9	2.0 ± 0.6b[a]
		1.0	2.0 ± 0.0b[b]	4.0 ± 2.0	2.4 ± 0.7b
T. castaneum	Durum	0.0	31.0 ± 0.0a[b]	25.3 ± 6.6a	34.5 ± 4.9a[d]
		0.1	19.0 ± 1.0b[b]	34.5 ± 9.5a[b]	31.0 ± 1.0a[a,d]
		1.0	0.7 ± 0.3c	1.0 ± 1.0b[b]	5.2 ± 2.1b
	Hard red spring	0.0	45.7 ± 10.5[c]	38.3 ± 6.2[l]	46.6 ± 3.3a
		0.1	30.7 ± 1.2	26.7 ± 3.2	40.0 ± 1.5a
		1.0	18.0 ± 3.0	26.5 ± 6.5[b]	25.8 ± 3.1b
	Hard red winter	0.0	21.5 ± 3.5a[b]	55.0 ± 5.0a[b]	54.0 ± 5.6a[a]
		0.1	32.5 ± 0.5b[b]	32.0 ± 2.0b[b]	30.8 ± 1.1b[d]
		1.0	9.0 ± 0.6c	13.3 ± 0.9c	23.0 ± 4.9b[a]
	Soft red winter	0.0	54.5 ± 4.5a	25.0 ± 22.0[j]	40.0 ± 9.8a
		0.1	17.3 ± 2.6b	22.0 ± 5.0	44.0 ± 5.4a
		1.0	1.0 ± 0.6c	4.0 ± 1.0	11.6 ± 1.6b

Unless otherwise indicated, each 7- and 14-d mean is based on three replications, while each 45-d mean is based on five replications. For each combination of species, wheat class, and exposure period, means among rates followed by different letters are significantly different ($P < 0.05$; Fisher's protected LSD).

[a] Each mean is based on three replications.
[b] Each mean is based on two replications.
[c] F, range = 0.52–5.06; df = 2, 6; P = 0.052–0.619 (one-way ANOVA).
[d] Each mean is based on four replications.
[e] F, range = 0.94–1.22; df = 2, 12; P = 0.33–0.416 (one-way ANOVA).
[f] Rate 0 mg/kg datum is based on one replication.
[g] $F = 0.00$; df = 2, 10; $P = 0.912$ (one-way ANOVA).
[h] $F = 0.09$; df = 2, 10; $P = 0.912$ (one-way ANOVA).
[i] $F = 0.40$; df = 2, 7; $P = 0.683$ (one-way ANOVA).
[j] F, range = 0.07–1.83; df = 2, 3; P = 0.303–0.934 (one-way ANOVA).
[k] $F = 0.18$; df = 2, 8; $P = 0.841$ (one-way ANOVA).
[l] F, range = 1.26–1.66; df = 2, 5; P = 0.28–0.36 (one-way ANOVA).

data of *R. dominica* ($r = 0.911$ for 14 d, 0.876 for 45 d), and for the 7 and 45 d of *S. oryzae* ($r = 0.652$ for 7 d, 0.764 for 45 d). Significant correlation for the 14-d *S. oryzae* data were present at the $\alpha = 0.08$ level ($r = 0.537$). In the case of *O. surinamensis,* no correlation was found between progeny production and kernel

Table 6. Larval mortality, number of adults emerged, and kernel damage (mean ± SEM) after exposure of *P. interpunctella* eggs to untreated and spinosad-treated wheat classes

Wheat class	Spinosad rate (mg/kg)	% mortality	No. adults emerged	% kernel damage
Durum	0.0	19.4 ± 6.1c	9.4 ± 1.1a	56.6 ± 8.6a
	0.1	69.6 ± 4.8b	11.2 ± 2.3a	18.3 ± 2.3b
	1.0	97.6 ± 2.4a	0.4 ± 0.2b	0.8 ± 0.5c
Hard red spring	0.0	16.2 ± 2.2c	6.6 ± 1.1a	74.0 ± 3.0a
	0.1	73.6 ± 3.1b	6.6 ± 1.9a	27.8 ± 9.7b
	1.0	99.6 ± 0.4a	0.0 ± 0.0b	0.2 ± 0.2c
Hard red winter	0.0	12.1 ± 4.4c	16.2 ± 3.1a	79.6 ± 3.5a
	0.1	83.2 ± 4.0b	8.4 ± 1.4a	28.7 ± 7.5b
	1.0	98.8 ± 0.5a	1.2 ± 0.7b	0.8 ± 0.5c
Soft red winter	0.0	9.9 ± 1.7c	23.8 ± 1.7a	63.6 ± 9.2a
	0.1	90.8 ± 2.7b	6.6 ± 3.2b	15.0 ± 7.7b
	1.0	98.8 ± 0.5a	0.0 ± 0.0c	3.4 ± 2.7b

Each mean is based on five replications. For each wheat class and response variable, means among rates followed by different letters are significantly different ($P < 0.05$; Fisher's protected LSD).

damage ($r = 0.34$ for 7 d, - 0.25 for 14 d, 0.33 for 45 d; $P > 0.27$). For *P. interpunctella,* egg-to-adult emergence and kernel damage were positively correlated ($r = 0.75$; $P < 0.005$).

Discussion

There were six physical and chemical parameters that were different among the four wheat classes. These parameters were kernel diameter, kernel weight, kernel hardness, dockage, fiber, and protein. Lack of significant correlations or trends indicated that the observed mortality of beetles, progeny production, or kernel damage among the wheat classes could not be attributed to differences in any of the physical and chemical parameters. Larval mortality, egg-to-adult emergence, and kernel damage of *P. interpunctella* also were unrelated to the physical and chemical parameters of the wheat classes. However, there are conflicting reports in literature on the effect of kernel weight, kernel hardness, and protein content on progeny production of stored-product beetles. For species such as *R. dominica* and *S. oryzae,* the size or weight of kernels may be important, because immature stages of these species develop inside kernels (Arbogast 1991). Amos et al. (1986) reported that kernel weight significantly affected *R. dominica* reproduction, but McGaughey et al. (1990) and Toews et al. (2000) did not find any relationship between kernel weight and the number of *R. dominica* progeny produced. Our results are consistent with those reported by McGaughey et al. (1990) and Toews et al. (2000). In our study, durum wheat had the heaviest kernels, but the number of *R. dominica* and *S. oryzae* adults produced on untreated wheat after short-term (7 and 14 d) or long-term exposure (45 d) was equal to, or less than, those produced on hard red winter, hard red spring, and soft red winter wheats.

Kernel hardness is related to functional properties of different wheat classes (Pomeranz et al. 1988). McGaughey et al. (1990) reported that *S. oryzae* progeny production was correlated with kernel hardness, but no such correlation was found for *R. dominica.* Toews et al. (2000) did not find a correlation between kernel hardness and *R. dominica* progeny production. Our results showed that kernel hardness and progeny production by *S. oryzae* or *R. dominica* were unrelated.

Protein content was implicated as influencing *R. dominica* reproduction (Amos et al. 1986). Toews et al. (2000) conducted three experiments and failed to establish a relationship between kernel protein content and *R. dominica* reproduction. In our tests, hard red spring wheat had the highest protein content, but the number of *R. dominica* and *S. oryzae* progeny produced on this wheat was equal to, or less than, those produced on the other wheats.

Kernel weight, kernel hardness, and protein content did not influence the progeny production by *O. surinamensis* and *T. castaneum.* These two species prefer to feed on broken kernels and dockage (Sinha 1975). However, the amount of dockage also failed to explain progeny production of these two species. Progeny production on durum wheat, which had the highest amount of dockage, was less than production on soft red winter wheat. These findings suggested that within each wheat class and across wheat classes, the responses of the four species of beetles and *P. interpunctella* on treated grain could be attributed to the activity of spinosad, and not due to any physical and chemical parameters. However, physical and chemical differences may explain the interactions among wheat class, rate, and exposure period.

On all wheat classes, *P. interpunctella* was highly susceptible to spinosad at 1 mg/kg than at 0.1 mg/kg. At 1 mg/kg, *P. interpunctella* larval mortality and egg-to-adult emergence was 98–100%. Neonate larvae of *P. interpunctella* feed on the germ and endosperm of wheat (Madrid and Sinha 1982), and this may explain the increased susceptibility of neonate larvae to spinosad. Brunner and Doerr (1996) also reported the mortality of neonate larvae of the pandemis leafroller, *Pandemis pyrusana* Kearfott, and obliquebanded leafroller, *Choristoneura rosacena* (Harris), to increase with an increase in spinosad rate.

Wanner et al. (2000) reported that the mortality of second instars of the gypsy moth, *Lymantria dispar* L., exposed to spinosad-treated oak leaves was stable after 9 d. In our study, mortality of *R. dominica* and *T. castaneum* adults was stable within 7 d, because no additional mortality occurred between 7 and 14 d. However, the 14-d mortality of *S. oryzae* and *O. surinamensis* was higher than 7-d mortality. Therefore, the period at which spinosad-induced mortality stabilizes may vary from species to species.

Subramanyam et al. (2002) evaluated spinosad at 1–20 mg/kg on 15% moisture hard red spring wheat against the same five insect species tested in our study. The trend in susceptibility of the species was similar to that reported here. Subramanyam et al. (2002) also tested spinosad applied to hard red winter wheat against three additional stored-product insects. These additional species were the rusty grain beetle, *Cryptolestes ferrugineus* (Stephens), flat grain beetle, *Cryp-*

tolestes pusillus (Schöenherr), and confused flour beetle, *Tribolium confusum* Jacquelin duVal. Spinosad killed all exposed *C. ferrugineus* and *C. pusillus* at 0.5 mg/kg, and all *T. confusum* at 1 mg/kg. However, progeny production by all three species was completely suppressed at 0.5 mg/kg. Subramanyam et al. (2002) reported complete mortality of *R. dominica* adults within 8 d at 1 mg/kg. In this study, we observed 100% mortality of *R. dominica* adults at 0.1 and 1 mg/kg rates on all wheat classes within 7 d. Mortality of *S. oryzae, O. surinamensis,* and *T. castaneum* adults observed on hard red spring wheat in our study differed considerably from those reported by Subramanyam et al. (2002). For example, Subramanyam et al. (2002) reported 100, 60, and 25% mortality of *S. oryzae, O. surinamensis,* and *T. castaneum* adults, respectively, after 14 d of exposure to wheat treated with 1 mg/kg of spinosad. In our study, the corresponding 14-d mortality on hard red spring wheat was ≈82, 4, and 2%, respectively. Differences in the mortality of these three species between the two studies may be related to strain differences. Subramanyam et al. (2002) used insects obtained from Oklahoma State University, and in this study all insect species were from cultures maintained for over a decade at Kansas State University. Moulton et al. (2000) observed a 2.5- to 20-fold difference in susceptibility of the beet armyworm, *Spodoptera exigua* (Hübner) to spinosad-treated cotton leaves among six strains representing different geographical regions within the United States.

It is difficult to explain the increased susceptibility of *S. oryzae, O. surinamensis,* and *T. castaneum* adults on spinosad-treated durum wheat. We did not characterize the distribution of spinosad residues on different wheats and their availability to insects. Additional work in these aspects may explain the greater performance of spinosad on durum wheat.

Despite eventual 100% mortality, progeny production was evident on all spinosad-treated wheat classes infested with *R. dominica,* and on treated durum wheat infested with *S. oryzae.* This result indicated that spinosad did not kill adults before they had a chance to lay eggs outside (*R. dominica*) or inside kernels (*S. oryzae*). Similar findings were reported by Subramanyam et al. (2002). Several researchers have reported spinosad to be slow acting on insects, with mortality increasing as a function of exposure time (Adán et al. 1996, Foster et al. 1996, Scott 1998, Wanner et al. 2000). Unlike *S. oryzae,* whose eggs, larvae, and pupae develop inside kernels, first instars of *R. dominica* burrow into the kernels, where they complete five instars and the pupal development (Arbogast 1991). This behavior may explain the lower progeny production of *R. dominica* on spinosad-treated wheats than that of *S. oryzae.*

Correlation analysis indicated that the number of progeny of *R. dominica, S. oryzae,* and *T. castaneum* produced on the wheat classes decreased with an increase in the 7- or 14-d mortality. The number of adult *P. interpunctella* that developed from eggs was correlated with larval mortality. For *O. surinamensis,* this relationship was not evident because of reduced susceptibility to spinosad on hard red spring, hard red winter, and soft red winter wheats. Although there were a few anomalous results because of *P. interpunctella* contamination, the number of damaged kernels correlated well with the number of progeny produced by *R. dominica, S. oryzae,* and *T. castaneum,* and with the number of *P. interpunctella* adults that developed from eggs. For *O. surinamensis* kernel damage or progeny production across rates was similar on hard red spring, hard red winter, and soft red winter wheats, and kernel damage did not increase proportionally with progeny production.

In summary, spinosad at 0.1 and 1 mg/kg provided consistent and effective suppression of *R. dominica* on all four wheat classes. Against *S. oryzae,* spinosad provided effective control of adults and suppression of progeny only on durum wheat. Adults of both *O. surinamensis* and *T. castaneum* were more susceptible to spinosad on durum wheat than on other wheat classes, based on adult mortality and progeny suppression. The results obtained here may or may not apply to all varieties within a wheat class, because only one variety represented each wheat class. On hard red spring wheat, Subramanyam et al. (2002) have shown that spinosad rates of 3–6 mg/kg were necessary for effective suppression of *S. oryzae, O. surinamensis,* and *T. castaneum* progeny production. However, using high rates of spinosad may be cost-prohibitive. The effectiveness of other nonchemical methods such as aeration (Reed and Arthur 2000) or biological control (Schöller and Flinn 2000) in conjunction with low rates of spinosad should be tested to suppress *S. oryzae, O. surinamensis,* and *T. castaneum* in hard red winter, hard red spring, and soft red winter wheats.

In the United States, *R. dominica* and *P. interpunctella* are commonly associated with farm-stored wheat (McGaughey et al. 1978, Reed et al. 1991, Vela-Coiffier et al. 1997). The organophosphates, malathion and chlorpyrifos-methyl, currently registered for use on stored wheat, as well as other classes of insecticides, are partially or completely ineffective against *R. dominica* and *P. interpunctella* (Subramanyam and Hagstrum 1995, Guedes et al. 1996). Therefore, spinosad appears to be a viable replacement for existing grain protectants, especially for *R. dominica* and *P. interpunctella* management in stored wheat.

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