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Influence of growing location and cultivar on *Rhyzopertha dominica* (Coleoptera: Bostrichidae) and *Sitophilus oryzae* (Coleoptera: Curculionidae) infestation of rough rice

FRANK H. ARTHUR[1], RUSTY C. BAUTISTA[2] and TERRENCE J. SIEBENMORGEN[2]

[1]USDA-ARS Grain Marketing and Production Research Center, Manhattan, Kansas and [2]Department of Food Science, University of Arkansas, Fayetteville, Arkansas, USA

Abstract Long-grain rice cultivars Cocodrie, Wells, and XP 723 grown in three locations (Hazen, MO; Essex and Newport, AR, USA), and medium-grain rice cultivars Bengal and XP 713 grown in two locations (Jonesboro and Lodge Corner, AR, USA), were harvested and assayed for susceptibility to *Rhyzopertha dominica* (F.) (Coleoptera: Bostrichidae), the lesser grain borer, and *Sitophilus oryzae* (L.) (Coleoptera: Curculionidae), the rice weevil, on rice held at 27°C, 57% and 75% relative humidity (RH). Separate samples from the same harvest lots were also analyzed for the physical characteristics of brown rice yield, percentage whole kernels and kernel thickness. Progeny production and feeding damage of *R. dominica* were significantly different among long-grain cultivars within two of the three locations ($P < 0.05$), but not for location or RH ($P \geqslant 0.05$), while progeny production of *S. oryzae* was different among cultivars, location, and RH ($P < 0.05$). On medium-grain rice, both cultivar and location were significant for progeny production of *R. dominica*, but not RH, while cultivar and RH were significant for progeny production of *S. oryzae*, but not location. On both rice types, feeding damage of *R. dominica* followed the same trends and was always strongly positively correlated with progeny production ($P < 0.05$), but for *S. oryzae* there were several instances in which progeny production was not correlated with feeding damage ($P \geqslant 0.05$). Physical characteristics of both rice types were statistically significant ($P < 0.01$) but actual numerical differences were extremely small, and were generally not correlated with progeny production of either species. Results indicate that the location in which a particular rice cultivar is grown, along with its characteristics, could affect susceptibility of the rice to *R. dominica* and *S. oryzae*.

Key words rough rice, cultivars, stored-product insects, *Rhyzopertha dominica*, *Sitophilus oryzae*
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Introduction

The lesser grain borer, *Rhyzopertha dominica* (F.), and the rice weevil, *Sitophilus oryzae* (L.), are serious pests of stored grains, including rough rice (Howell & Cogburn, 2004). These insects are often difficult to kill with insecticides because the majority of the lifecycle is spent inside the kernel. In most grains the female *R. dominica* lays an egg on the exterior of the kernel, and the first-instar larva will either bore through the hull or exterior, or enter the hull through a crack or a breach, and feed on the kernel itself. Once the larva develops to the adult stage, it will bore through the hull, thereby creating a large exit hole. The female *S. oryzae* will

Correspondence: Frank H. Arthur, USDA-ARS, 1515 College Avenue, Manhattan, KS66502, USA. Tel: +1 (785) 776 2783; fax: +1 (785) 537 5584; email: frank.arthur@gmprc.ksu.edu

deposit an egg directly into the kernel and the larva hatches and completes development to the adult stage, then exits by boring through the hull. Progeny production and survival of both species generally increases with increases in grain moisture content or relative humidity (Howe, 1965; Fields, 1992), and recent studies with both species on wheat have shown that 27°C is well within the optimum temperature range for progeny production (Arthur & Throne, 2003; Arthur, 2004).

There have been several published studies whereby physical characters of grain kernels have been used to estimate susceptibility to either *R. dominica* or *S. oryzae*, with mixed results. McGaughey *et al*. (1990) found differences in progeny production among different wheat classes, but could not correlate progeny production with kernel characteristics. In studies with different wheat cultivars, there were more progeny of *R. dominica* on small kernels versus large kernels of the same cultivar and differences among cultivars (Toews *et al*., 2000). Rout *et al*. (1976) reported a negative correlation between grain hardness and susceptibility of rice to *S. oryzae*. Feeding damage through frass production (excreted material), grain dust, and other materials produced through insect feeding are examples of physical characters that have also been used to determine susceptibility of grain types or different cultivars within a particular type (Baker *et al*., 1991).

The site where a grain is grown or cultivated can also influence susceptibility to stored-product insects. In studies with *Sitotroga cerella* (Olivier), the Angoumois grain moth, rice cultivars grown in different locations varied in susceptibility (Cogburn *et al*., 1980), indicating that the actual growing environment may have some effect on insect population growth and development. Similarly, differences in progeny production among cultivars have been reported for triticale, a wheat-rye hybrid (Baker *et al*., 1991), wheat (Toews *et al*., 2000), oats (Throne *et al*., 2003), and tripsacorn, a hybrid maize (Throne & Eubanks, 2002). The actual physical condition of grains, which may be a result of the environment where a cultivar is grown or from the kernel characteristics of a particular cultivar, also influences susceptibility to stored-product insects (Athanassiou *et al*., 2003).

Rough rice may be different from other cereal grain crops because the hull offers some degree of protection from insect damage (Cogburn, 1974). Regardless, there are no published studies of the effect of location or cultivar on kernel characteristics as they affect progeny production of *R. dominica* or *S. oryzae*. Therefore, the objectives of this study were to: (i) examine the effect of location and cultivar on progeny production of these two species on rough rice; and (ii) correlate progeny production with specific physical kernel characteristics.

Materials and methods

Rice cultivars and milling

Three cultivars of long-grain rice (Cocodrie, Wells, and XP 723), grown in Hazen, MO, USA, and Essex and Newport, AR, USA, and two cultivars of medium-grain rice (Bengal and XP 716), grown in Jonesboro and Lodge Corner, AR, USA, were part of a long-term research programs within the Rice Processing Program, University of Arkansas, Fayetteville, AR, USA. Standard 150-g samples from each cultivar and location were de-hulled using a laboratory huller (THU, Satake, Tokyo, Japan). The resultant brown rice was weighed; this mass divided by the original 150 g mass represents the brown rice yield. The brown rice was then milled in a laboratory mill (McGill #2, RAPSCO, Brookshire, TX, US) for 40 seconds with a 1.5 kg weight placed on the lever arm of the mill, 15 cm from the centerline of the mill chamber. The amount of head rice, milled kernels that are at least three-fourths of the original kernel length (USDA, 1997), in each resulting milled rice sample, was determined with an image analysis system (Graincheck 2312 Analyzer, Foss Tecator, Höganäs, Sweden). Head rice yield was then calculated as the mass percentage of rough rice that remained as head rice. The thickness of each of 200 head rice kernels from each sample were measured using an image analyzer (RIA 1, Satake Co., Higashi-Hiroshima, Japan). Brown rice is rice with the hulls removed, which is the interior kernel where the insect would be feeding. Head rice yield was selected because this is an important quality parameter for rice milling, and is based on percentage of whole kernels.

Insect bioassays

Approximately 1 kg of rough rice samples from each lot were sent to the Grain Marketing and Production Research Center in Manhattan, KS, USA, and stored for about 3 months at approximately 4°C. The samples were removed from cold storage and warmed for 24 h in the laboratory at approximately 25°C, and after this warming period the moisture content was then analyzed using a moisture meter (GAC 2000, Dickey-John, Auburn, IL, USA). The moisture content of the samples was approximately 12.5% on a wet basis, which is the standard measurement of grain moisture content. Half of the rice (500 g) was tempered to a desired moisture content of about 14.5% by spreading the rice on a thick sheet of paper measuring approximately 0.6 × 0.3 m, spraying about 30 mL of tap water on the rice, and then allowing the rice and water to equilibrate for a week in a closed 0.95-L glass jar. The moisture contents of this lot and the original half of the rice sample that had been dried to 12.5% were verified using the moisture meter. Four humidity chambers were created in plastic boxes measuring 26.0 × 36.5 × 15.0 cm, with a waffle-style grid cut to fit the bottom to provide a substrate for the placement of sample vials. Two of the chambers contained saturated NaBr and the other two contained saturated NaCl to maintain relative humidity (RH) at 57% and 75%, respectively, which corresponds to grain moisture contents of about 12.5% and 14.5% (Greenspan, 1977). The level of the salt solutions inside the box was just below the top of the waffle grid.

Test insects of both species were obtained from laboratory colonies that were reared inside a Percival incubator (Percival Scientific, Perry, IA, USA), on whole kernel long-grain rice of cultivar Francis, at standard rearing conditions of 27 ± 2°C, 60% ± 2% RH. Individual test arenas consisted of 20-mL plastic vials, which held about 20 g of rough rice. For each sample lot in each replicate, there were four vials; in each of two vials, 20 1–2-week-old adult *R. dominica* were placed in the vials, while 20 1–2-week-old adult *S. oryzae* were placed in the other two vials. Two vials, each vial containing one of the species was put in the 57% RH chamber and the other two vials were put in the 75% RH chamber. The parent adults were held in the vials for 5 days in a Forma-Scientific incubator set at 27 ± 1°C, and then adults were removed. The rough rice and all feeding damage, which was defined as ground rice kernels or portions of kernels produced through feeding action and frass (excreted material from insects), was placed back into the vials. The humidity chambers were returned to the incubators and held for 8 weeks. The emerged F_1 progeny adults were then tabulated and the feeding damage was weighed. The mass of the individual progeny adults was estimated by weighing all emerged adults in a sample and dividing the total mass by the number that had emerged.

Statistical analysis

Six replicates were conducted as blocks whereby each block was set up at weekly intervals. The statistical analysis was done by separating the rice types (long- and medium-grain rice), and analyzing the bioassay data for each species with RH, growing location, and cultivar as main effects. The analysis variables were the number of F_1 progeny, mass of the insect damage, and mass of individual insects. Significance was determined using the General Linear Models (GLM) Procedure of the Statistical Analysis System (SAS Institute, 2001). Treatment means for the long-grain rough rice samples were separated using the Waller-Duncan *k*-ratio *t*-test of SAS, the standard *t*-test (PROC *t*-test) was used for the medium-grain rice. Correlations were done using the Correlation Procedure (PROC CORR) of SAS. Physical parameter data for brown rice content, percentage of whole kernels, kernel thickness, and head rice yield were correlated with each other and with the data for progeny production. All of the samples used for the quality measurements and the bioassays came from the same harvest lot for each cultivar and growing location; therefore the data for progeny production were also analyzed for correlation with the physical parameters.

Results

Long-grain rice

The results from the general ANOVA analysis show that growing location was significant for progeny production of *R. dominica* for specific cultivars ($F = 3.4$; df = 2,90; $P = 0.04$), but not RH or rice cultivar within a location ($F = 0.2$; df = 1,90; $P = 0.68$; $F = 2.8$; df = 2,90; $P = 0.06$, respectively). No interactions were significant ($P \geqslant 0.05$). Fewer progeny were produced on rice from Cocodrie and Wells cultivars from Hazen, AR, USA compared to Newport, AR, USA, but there was no difference in progeny production on XP 723 rice from the three locations (Table 1). Results were similar for feeding damage, which was the total amount of damage produced by the exposed parental adults plus damage caused by the F_1 progeny. Location was again significant ($F = 3.3$; df = 2,90; $P = 0.04$), but not RH or rice cultivar ($F = 0.2$; df = 1,90; $P = 0.64$; $F = 1.2$; df = 2, 90; $P = 0.20$, respectively), with no significant interactions ($P \geqslant 0.05$). The amount of feeding damage on Wells from Newport was greater than that produced on the rice from Hazen, and while patterns were similar for feeding damage on Cocodrie, the variation in the data set limited statistical precision (Table 1). The mass of individual insects was not significant with respect to any main effect ($P \geqslant 0.05$), and averaged 1.2 ± 0.03 mg (data pooled for all combinations).

The number of F_1 progeny of *S. oryzae* was significant ($P < 0.01$) for RH, cultivar, and location ($F = 73.5$, df = 1,90; $F = 14.0$, df = 1,90; $F = 37.8$, df = 1,90; respectively, but the only interaction that was significant was variety × location ($P < 0.01$, all others $P \geqslant 0.05$). In general, more progeny and feeding damage were produced on Cocodrie and Wells from Newport compared to Hazen (Table 2). However, the amount of feeding damage caused by *S. oryzae* (average of 4.2 ± 0.2 mg/progeny) was far less than the feeding damage caused by *R. dominica* (average of 7.3 ± 0.3 mg/progeny), reflecting a greater feeding capacity of *R. dominica*. There were also indications of a cultivar effect, with fewer progeny produced on XP 723 at Newport

Table 1 Number of F_1 *R. dominica* progeny from the introduction of 20 mixed-sex-parental adults and feeding damage (in mg) from those parental adults and offspring (means ± SEM), produced on 20 g of three cultivars of long-grain rough rice from Essex MO, Hazen AR, and Newport AR, USA (data pooled for relative humidity)[†].

Location		Cultivar		
		Cocodrie	Wells	XP 723
Essex MO	Progeny	13.2 ± 2.6 a	12.8 ± 4.1 a	4.9 ± 1.3 a
Hazen AR		8.1 ± 2.6 b	3.3 ± 1.0 b	7.2 ± 1.5 a
Newport AR		18.3 ± 4.6 a	17.4 ± 4.9 a	7.0 ± 1.8 a
Essex MO	Damage	88.2 ± 19.2 a	73.9 ± 21.7 a	43.0 ± 9.9 a
Hazen AR		61.9 ± 27.8 a	27.7 ± 8.9 b	63.0 ± 17.0 a
Newport AR		159.6 ± 62.5 a	118.9 ± 35.5 a	53.5 ± 13.5 a

[†]Means for progeny production for growing location with respect to a specific cultivar followed by the same letter are not significantly different for growing location of that cultivar ($P \geqslant 0.05$, Waller-Duncan *k*-ratio *t*-test, SAS Institute).

Table 2 Number of F_1 *S. oryzae* progeny from the introduction of 20 mixed-sex-parental adults, and feeding damage (in mg) from those parental adults and offspring (means ± SEM), produced on 20 g of three cultivars of long-grain rough rice from Essex MO, Hazen AR, and Newport AR, USA[†].

RH	Location		Cultivar		
			Cocodrie	Wells	XP 723
57%	Essex MO	Progeny	4.3 ± 1.1 bA	4.7 ± 1.1 bA	4.9 ± 1.3 aA
	Hazen AR		3.8 ± 2.6 bA	3.2 ± 0.9 bA	3.8 ± 1.5 aA
	Newport AR		9.5 ± 1.5 aB	16.8 ± 2.4 aA	2.8 ± 0.6 aC
75%	Essex MO		8.3 ± 0.7 bA	9.8 ± 1.4 bA	4.7 ± 1.2 bA
	Hazen AR		9.7 ± 1.8 bA	7.2 ± 1.5 bA	12.2 ± 1.4 aA
	Newport AR		22.3 ± 1.6 aA	27.8 ± 3.2 aA	8.8 ± 1.8 aB
57%	Essex MO	Damage	19.8 ± 4.3 bA	17.0 ± 4.3 bA	10.3 ± 2.4 aA
	Hazen AR		13.0 ± 3.4 bA	11.0 ± 3.79 bA	20.4 ± 4.9 aA
	Newport AR		36.9 ± 6.8 aB	55.2 ± 9.7 aA	11.1 ± 2.76 aC
75%	Essex MO		34.9 ± 3.2 bA	30.9 ± 4.8 bA	22.1 ± 4.4 bA
	Hazen AR		34.3 ± 8.2 bA	25.9 ± 4.9 bA	47.7 ± 11.2 aA
	Newport AR		83.1 ± 6.1 aA	105.3 ± 15.7 aA	36.9 ± 7.6 abB

[†]Means within columns followed by the same lower case letter for each location with respect to a specific cultivar at each RH are not significantly different for growing location of that cultivar. Means within rows followed by the same upper case letter are not significant for progeny production for a specific cultivar among the three locations ($P \geqslant 0.05$, Waller-Duncan *k*-ratio *t*-test, SAS Institute).

compared to cultivars Cocodrie and Wells. More *S. oryzae* progeny were produced at 75% than at 57% RH on all combinations except Cocodrie cultivar grown at Newport, and more feeding damage at 75% than at 57% RH on all combinations except Cocodrie cultivar grown at Essex and Hazen ($P < 0.05$, Proc *t*-test, SAS Institute). The average mass of individual F_1 adult *S. oryzae* was not different with respect to main effects ($P \geqslant 0.05$), and averaged 1.3 ± 0.04 mg (data pooled). For both *R. dominica* and *S. oryzae*, a strong positive correlation was found between progeny production and feeding damage (Table 3).

Data for brown rice yield, percentage of whole kernels, kernel thickness, and the data for head rice yield showed mean values in an extremely narrow range, with low variation about those means (Table 4). The range for values for brown rice yield, percentage of whole kernels, kernel thickness, and head rice yield were 83.3% ± 0.03% to 84.0% ± 0.04%, 89.3% ± 0.20% to 95.0% ± 0.36%, 1.64% ± 0.004% to 1.75% ± 0.005%, and 64.4% ± 0.41% to 68.9% ± 0.25%, respectively. Progeny of *R. dominica* was negatively correlated with kernel thickness, but the only other significant correlation was between head rice yield and the

Table 3 Correlation (*r*) and probability (*P*) of progeny production with feeding damage for *R. dominica* and *S. oryzae* exposed to 20 g of rough rice from three cultivars at three locations.

Species	Location	Cultivar					
		Cocodrie		Wells		XP 723	
		r	*P*	*r*	*P*	*r*	*P*
R. dominica	Essex MO	0.97	< 0.01	0.97	< 0.01	0.94	< 0.01
	Hazen AR	0.97	< 0.01	0.98	< 0.01	0.95	< 0.01
	Newport AR	0.98	< 0.01	0.99	< 0.01	0.95	< 0.01
S. oryzae, 57% RH	Essex MO	0.98	< 0.01	0.97	< 0.01	0.41	0.41
	Hazen AR	0.78	0.07	0.88	0.02	0.86	0.03
	Newport AR	0.98	< 0.01	0.94	< 0.01	0.84	0.04
S. oryzae, 75% RH	Essex MO	0.94	< 0.01	0.89	0.02	0.76	0.08
	Hazen AR	0.87	0.03	0.86	0.03	0.71	0.11
	Newport AR	0.30	0.55	0.90	0.02	0.94	0.01

Table 4 Brown rice yield (BR, in %), whole kernels (WK, in %), thickness of milled rice kernels (KT, in mm), and head rice yield (HRY, in %) (means ± SE) after 40 seconds of milling in three cultivars of long-grain rough rice from Essex MO, Hazen and Newport AR, USA.

Location	Measure	Cultivar		
		Cocodrie	Wells	XP 723
Essex MO	BR	83.4 ± 0.07	83.2 ± 0.06	83.3 ± 0.03
Hazen AR		84.0 ± 0.03	84.0 ± 0.03	83.4 ± 0.03
Newport AR		83.7 ± 0.08	84.0 ± 0.04	83.3 ± 0.06
Essex MO	WK	94.1 ± 0.28	89.3 ± 0.20	91.0 ± 0.72
Hazen AR		94.7 ± 0.30	91.6 ± 0.25	91.9 ± 0.26
Newport AR		92.1 ± 0.21	91.7 ± 0.15	95.0 ± 0.36
Essex MO	KT	1.654 ± 0.003	1.702 ± 0.004	1.746 ± 0.005
Hazen AR		1.662 ± 0.003	1.696 ± 0.004	1.724 ± 0.004
Newport AR		1.641 ± 0.004	1.671 ± 0.003	1.700 ± 0.003
Essex MO	HRY	67.9 ± 0.28	64.4 ± 0.41	64.6 ± 0.35
Hazen AR		68.9 ± 0.25	67.2 ± 0.19	66.9 ± 0.15
Newport AR		65.5 ± 0.34	67.1 ± 0.34	68.8 ± 0.17

percentage of whole kernels (Table 5). The mean progeny values for *S. oryzae* at 57% and 75% RH were not correlated with any of the physical measurements (Table 5), and again the only significant correlations at both RH levels was between head rice yield and percentage of whole kernels.

Medium-grain rice

The results from the general ANOVA analysis for medium-grain rice show that both location ($F = 7.7$; df = 1,40; $P < 0.01$) and cultivar ($F = 7.6$; df = 1,40; $P < 0.01$) were significant for progeny production of *R. dominica*, but not RH ($F = 0.5$; df = 1,40; $P = 0.53$). Only the location × cultivar interaction was significant ($P = 0.02$, all others $P = 0.05$). More progeny were produced on Bengal rice from Jonesboro than from Lodge Corner, and more progeny were produced on XP 713 than on Bengal at Lodge Corner (Table 6).

The feeding damage mass was also significant for location ($F = 6.0$; df = 1,40; $P < 0.02$) and rice cultivar ($F = 4.4$;

Table 5 Correlation (*r*) and probability (*P*) of the means for brown rice content (BR), percentage whole kernels (PK), kernel thickness (KT), and head rice yield (HRY) from Table 4, and the means for progeny (PR) of *R. dominica*, from Table 1, and *S. oryzae*, from Table 2.

Species		WK		KT		HRY		PR	
		r	*P*	*r*	*P*	*r*	*P*	*r*	*P*
R. dominica	BR	0.16	0.68	−0.54	0.17	0.30	0.44	0.14	0.71
	WK	–	–	−0.51	0.16	0.95	0.01	−0.11	0.77
	KT	–	–	–	–	−0.64	0.07	−0.69	0.03
	HRY	–	–	–	–	–	–	−0.33	0.38
S. oryzae, 57% RH	BR	0.16	0.69	−0.51	0.16	0.47	0.20	0.47	0.20
	WK	–	–	−0.39	0.29	0.95	0.01	−0.25	0.52
	KT	–	–	–	–	−0.26	0.49	−0.35	0.29
	HRY	–	–	–	–	–	–	−0.22	0.57
S. oryzae, 75% RH	BR	0.16	0.68	−0.51	0.16	0.30	0.44	0.49	0.17
	WK	–	–	−0.39	0.29	0.94	0.01	−0.12	0.75
	KT	–	–	–	–	−0.26	0.50	−0.50	0.17
	HRY	–	–	–	–	–	–	−0.18	0.65

df = 1,40; $P < 0.04$, respectively), but not RH ($F = 0.1$; df = 1,40; $P = 0.78$). Again, only the location × cultivar interaction was significant ($P < 0.01$, all others $P \geqslant 0.05$), and the significance for feeding damage was the same as for progeny production. No main effect or interaction was significant for mass of individual *R. dominica*, and the average mass, combined over all treatment combinations and replicates, was 1.27 ± 0.09 mg.

The progeny production of *S. oryzae* was significant ($P < 0.01$) for RH and cultivar ($F = 18.4$; df = 1,40; $F = 13.8$; df = 1,40; respectively), but not location ($F = 0.4$; df = 1,40; $P = 0.52$). No interaction was significant ($P \geqslant 0.05$). More progeny were produced on Bengal cultivar rice than on XP716 cultivar rice grown at Jonesboro and held at 75% RH. However, this was the only significant difference for progeny production (Table 7). The feeding damage mass followed the same pattern, with significance at $P < 0.01$ for RH and cultivar ($F = 21.6$; df = 1,40; $F = 12.5$; df = 1,40;

Table 6 Number of F_1 *R. dominica* progeny from the introduction of 20 mixed-sex-parental adults, and feeding damage (in mg) from those parental adults and offspring (means ± SEM), produced on 20 g of two cultivars of medium-grain rough rice from Jonesboro and Lodge Corner AR, USA†.

Location		Cultivar	
		Bengal	XP 716
Jonesboro	Progeny	10.7 ± 2.1 aA	7.7 ± 2.7 aA
Lodge Corner		2.0 ± 0.9 bB	7.8 ± 1.8 aA
Jonesboro	Damage	75.3 ± 17.9 aA	44.1 ± 16.5 aA
Lodge Corner		14.4 ± 7.4 bB	56.2 ± 13.4 aA

†Data pooled for RH, means within columns followed by the same lower case letter for each location with respect to a specific cultivar are not significantly different for growing location of that cultivar. Means within rows followed by the same upper case letter are not significant for progeny production for a specific cultivar among the two locations ($P \geqslant 0.05$, PROC *t*-test, SAS Institute).

Table 7 Number of F_1 *S. oryzae* progeny from the introduction of 20 mixed-sex-parental adults and feeding damage (in mg) from those parental adults and offspring (means ± SEM), produced on 20 g of two cultivars of medium-grain rough rice from Jonesboro and Lodge Corner AR, USA†.

RH	Cultivar		Jonesboro	Lodge Corner
57%	Bengal	Progeny	3.3 ± 1.7 a	2.3 ± 0.8 a
	XP 716		1.5 ± 0.7 a	1.7 ± 0.3 a
75%	Bengal		9.5 ± 1.9 a	6.5 ± 1.7 a
	XP 716		2.7 ± 0.5 b	3.2 ± 0.7 a
57%	Bengal	Damage	13.7 ± 6.4 a	12.6 ± 5.2 b
	XP 716		5.7 ± 3.2 a	5.6 ± 1.3 a
75%	Bengal		35.5 ± 7.1 a	27.6 ± 7.9 a
	XP 716		14.9 ± 2.1 b	14.7 ± 2.8 b

†Means within columns followed by the same lower case letter for each location with respect to a specific cultivar at each RH are not significantly different for growing location of that cultivar ($P \geqslant 0.05$, PROC *t*-test, SAS Institute).

respectively), no significance for location ($F = 0.1$; df = 1, 40; $P = 0.77$), no significant interactions ($P \geqslant 0.05$), and the same differences between means as reported for progeny production (Table 7). The mass of individual weevils was not significant for any main effect, and averaged 1.32 ± 0.07 mg among all samples and replicates. Progeny production of *R. dominica* was always correlated with feeding damage regardless of location or cultivar; however, there were several cases where progeny of *S. oryzae* on variety XP713 was not correlated with feeding damage (Table 8). Again, there was a narrow range of values for each of the physical characteristics and head rice yield, with low variation about the means (Table 9). The only correlations that were significant ($P < 0.05$) for either species was the correlation of progeny production of *S. oryzae* with brown rice content at 57% and 75% RH (Table 10).

Discussion

The results indicate that the location or site where a particular rice cultivar is grown, as well as the inherent characteristics of that cultivar, may affect susceptibility to stored-product insects. Cogburn (1977) screened different

Table 8 Correlation (r) and probability (P) of progeny production with feeding damage for *R. dominica* and *S. oryzae* exposed on 20 g of medium-grain rough rice from two cultivars at two locations.

Species	Location	Cultivar			
		Bengal		XP 716	
		r	P	r	P
R. dominica	Jonesboro	0.98	< 0.01	0.99	< 0.01
	Lodge Corner	0.95	< 0.01	0.91	< 0.01
S. oryzae, 57% RH	Jonesboro	0.98	< 0.01	0.91	< 0.03
	Lodge Corner	0.83	0.04	0.70	0.12
S. oryzae, 75% RH	Jonesboro	0.78	0.07	0.54	0.27
	Lodge Corner	0.96	0.01	0.77	0.07

Table 9 Brown rice (BR, in %), whole kernels (WK, in %), thickness of milled rice kernels (KT, in mm) and head rice yield (HRY, in %) (means ± SE) after 40 seconds of milling in two cultivars of medium-grain rough rice from Jonesboro and Lodge Corner AR, USA.

Location	Measure	Cultivar	
		Bengal	XP 716
Jonesboro	BR	83.5 ± 0.19	83.0 ± 0.20
Lodge Corner		82.4 ± 0.06	82.7 ± 0.19
Jonesboro	WK	94.29 ± 0.30	96.9 ± 0.22
Lodge Corner		95.7 ± 0.16	95.1 ± 0.51
Jonesboro	KT	1.842 ± 0.004	1.745 ± 0.004
Lodge Corner		1.794 ± 0.004	1.784 ± 0.002
Jonesboro	HRY	72.2 ± 1.17	74.2 ± 0.78
Lodge Corner		70.8 ± 0.81	71.7 ± 0.88

Table 10 Correlation (r) and probability (P) of the means for brown rice content (BR), percentage whole kernels (PK), kernel thickness (KT), and head rice yield (HRY) from Table 8 and the means for progeny (PR) of *R. dominica*, from Table 6, and *S. oryzae*, from Table 7.

Species		WK		KT		HRY		PR	
		r	P	r	P	r	P	r	P
R. dominica	BR	–0.47	0.53	0.50	0.50	0.14	0.87	0.89	0.11
	WK	–	–	–0.94	0.06	0.80	0.20	–0.44	0.56
	KT	–	–	–	–	–0.77	0.22	0.32	0.68
	HRY			–	–	0.18	0.82		
S. oryzae, 57% RH	BR	–0.47	0.54	–0.50	0.50	0.14	0.86	0.99	0.01
	WK	–	–	–0.94	0.06	0.80	0.20	–0.47	0.52
	KT	–	–	–	–	0.55	0.45	0.55	0.45
	HRY					–	–	0.09	0.91
S. oryzae, 75% RH	BR	–0.47	0.54	–0.50	0.50	0.14	0.86	0.98	0.02
	WK	–	–	–0.94	0.06	0.80	0.20	–0.35	0.65
	KT	–	–	–	–	–0.77	0.23	0.44	0.56
	HRY	–	–	–	–	–	–	0.22	0.78

cultivars of rough rice for resistance to *S. cerella*, and in a later test grew cultivars that appeared to be resistant in different geographic locations and tested the seeds from those cultivars for resistance (Cogburn *et al*., 1980). Some cultivars showed consistent results in progeny production regardless of growing location, while results for other cultivars appeared to be influenced by location. We obtained some similar results in our studies with the primary beetle pests of stored rice. Progeny production of both *R. dominica* and *S. oryzae* was greater on long-grain cultivars Cocodrie and Wells from Newport than at Hazen, but the same relationship did not hold for cultivar XP 723. However, our results with the medium-grain cultivars were more inconsistent, with a location difference for Bengal cultivar for progeny production of *R. dominica*, but not for *S. oryzae*.

Although we were able to show differences in progeny production of both *R. dominica* and *S. oryzae* with respect to cultivar and location, we could not correlate susceptibility with the kernel characteristics that were measured in our study. Moralles-Rejesus *et al*. (1982) infested different cultivars of brown rice with *S. oryzae*, *Sitophilus zeamais* (Motschulsky), the maize weevil and *Tribolium castaneum* (Herbst), the red flour beetle. They reported extensive variation in progeny production among the 15 cultivars tested in their study. Also, in some but not all cultivars, they found positive correlations with kernel length and width, and negative correlations between grain hardness, as related to susceptibility of *S. zeamais*. However, they could not correlate progeny production of *S. zeamais* with chemical properties, and there were no correlations between the physical characters and progeny of *S. oryzae* or *T. castaneum*. Similarly, McGaughey *et al*. (1990) could not correlate progeny production of *R. dominica* with the hardness of wheat kernels. In our study, kernel thickness was correlated with *R. dominica* progeny, but not progeny of *S. oryzae*. Other factors, such as variation in planting and harvest dates, have also been investigated as causes of susceptibility to stored-product insects, with negative results (Cogburn *et al*., 1983).

Since the results of the few available published studies seem to indicate that physical or chemical characteristics of the rice kernel are not important factors in conferring resistance to stored-product insects, perhaps a more promising approach is to consider how variations in the rough rice hull may present a barrier to insect attack. In studies by Breese (1960), infestations of *S. oryzae* and *R. dominica* were not found in rice grains with an intact husk and the mode of entry was assumed to be through a crack in the hulls caused either by natural means, through breakage from harvesting, or from the drying process. In a study by Takahashi and Mizuno (1982), progeny of *S. zeamais* and *S. oryzae* were not found on rough rice that was dried naturally, but progeny of both species developed in hulls with splits and cracks caused by mechanical drying. Although Cogburn *et al*. (1983) showed development of *S. cerealella* in some hulls with no visible defects, the integrity of the hull still seemed to be an important barrier to infestation. Therefore, it seems likely that the variation in progeny of stored-product insects among rice varieties may be related more to the protection afforded by the hull, which acts as a protective barrier, than with the kernel itself. This protection afforded by the hull could be further investigated to assess the level of protection among different cultivars, and how resistance through hull characteristics of individual rice cultivars could be incorporated into resistance management plans for stored-product insects.

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Note

This paper reports the results of research only. Mention of a particular rice cultivar, piece of equipment used in the study, or a trade name or proprietary product does not constitute a recommendation or endorsement by the U. S. Department of Agriculture or the University of Arkansas.

References

Arthur, F.H. (2004) Evaluation of methoprene alone and in combination with diatomaceous earth to control *Rhyzopertha dominica* (Coleoptera: Bostrichidae) on stored wheat. *Journal of Stored Products Research*, 40, 485–498.

Athanassiou, C.G., Kavallieratos, N.C., Tsaganou, F.C., Vayias, B.J., Dimizas, C.B. and Buchelos, C.Th. (2003) Effect of grain type on the insecticidal efficacy of SilicoSec against *Sitophilus oryzae* (L.) (Coleoptera: Curculionidae). *Crop Protection*, 22, 1141–1147.

Arthur, F.H. and Throne, J.E. (2003) Efficacy of diatomaceous earth (DE) to control internal infestations of rice weevil and maize weevil (Coleoptera: Curculionidae). *Journal of Economic Entomology*, 96, 510–518.

Baker, J.E., Arthur, F.H. and Bruckner, P.L. (1991) Susceptibility of twelve genotypes of triticale to the rice weevil (Coleoptera: Curculionidae) and the lesser grain borer (Coleoptera: Bostrichidae). *Journal of Entomological Science*, 26, 339–344.

Breese, M.M. (1960) The infestibility of stored paddy *Sitophilus sasakii* (Tak.) and *Rhyzopertha dominica* (F.). *Bulletin of Entomological Research*, 51, 599–630.

Cogburn, R.R. (1974) Domestic rice varieties: Apparent resistance to rice weevils, lesser grain borers, and Angoumois grain moths. *Environmental Entomology*, 3, 681–685.

Cogburn, R.R. (1977) Susceptibility of varieties of stored rough rice to losses caused by storage insects. *Journal of Stored Product Research*, 13, 29–34.

Cogburn, R.R., Bollich, C.N. and Meola, S. (1983) Factors that affect the relative resistance of rough rice to Angoumois grain moths and lesser grain borers. *Environmental Entomology*, 12, 936–942.

Cogburn, R.R., Bollich, C.N., Johnston, T.H. and Mcilrath, W.O. (1980) Environmental influence on resistance to *Sitotroga cerealella* in varieties of rough rice. *Environmental Entomology*, 9, 689–693.

Fields, P.G. (1992) The control of stored-product insects and mites with extreme temperatures. *Journal of Stored Products Research*, 28, 89–118.

Greenspan, L. (1977) Humidity fixed points of binary saturated aqueous solutions. *Journal of Research of the National Bureau of Standards, Physics and Chemistry*, 81A, 89–96.

Howe, R.W. (1965) A summary of estimates of optimal and minimal conditions for population increase of some stored products insects. *Journal of Stored Products Research*, 1, 177–184.

Howell, T.A. and Cogburn, R.R. (2004) Rough rice storage. *Rice Chemistry and Technology,* Third Edition (ed. E.T. Champagne), pp. 269–283. American Association of Cereal Chemists, St. Paul, MN, USA.

McGaughey, W.H., Speirs, R.D. and Martin, C.R. (1990) Susceptibility of classes of wheat grown in the United States to stored-grain insects. *Journal of Economic Entomology*, 68, 668–670.

Morall-Rejesus, B., Javier, P.A. and Juliano, B.O. (1982) Properties of brown rice and varietal resistance to storage insects. *Phillipine Entomologist*, 15, 227–228.

Rout, G., Senapati, B. and Ahmed, T. (1976) Studies on relative susceptibility of some high yielding varieties of rice to the rice weevil, *Sitophilus oryzae* L. (Curculionidae: Coleoptera). *Bulletin of Grain Technology*, 14, 34–38.

Takahashi, F. and Mizuno, H. (1982) Infestation of rice weevils in rice grain in relation to drying procedures after harvest and the form of the grain at different stages in the milling process. *Environmental Control in Biology*, 20, 9–16.

Throne, J.E. and Eubanks, M.W. (2002) Resistance of tripsacorn to *Sitophilus zeamais* and *Oryzaephilus surinamensis*. *Journal of Stored Products Research*, 38, 239–245.

Throne, J.E., Doehlet, D.C. and McMullen, M.S. (2003) Susceptibility of commercial oat cultivars to *Cryptolestes pusillus* and *Oryzaephilus surinamensis*. *Journal of Stored Products Research*, 39, 213–223.

Toews, M.D., Cuperus, G.W. and Phillips, T. (2000) Susceptibility of eight U.S. wheat cultivars to infestation by *Rhyzopertha dominica* (Coleoptera: Bostrichidae). *Environmental Entomology*, 29, 250–255.

USDA (1997) *Inspection Handbook for the Sampling, Inspection, Grading, and Certification of Rice*. USDA Agricultural Marketing Service, Washington, D.C., USA. HB 918–11, section 5.41.

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