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Hull characteristics as related to susceptibility of different varieties of rough rice to *Rhyzopertha dominica* (F.) (Coleoptera: Bostrichidae)☆

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Abstract

Rhyzopertha dominica (F.), an important pest of stored grains, causes economic damage to rough rice through physical damage to the kernel, resulting in reductions in grain quality. In this test, 28 varieties of commercial rough rice (10 long grain, 11 medium grain, and 7 short grain) were examined for solid, split and cracked hulls, hull thickness, and adult emergence from neonate *R. dominica* introduced on each individual variety. The percentage of solid hulls ranged from 55.5% on Koshihikari variety to 92.8% on Akita variety, and the percentages of cracked and split hulls were correlated with increased susceptibility. The Dobie index for progeny production showed Wells, Jupiter, and Pirogue varieties as the most tolerant to *R. dominica*, while Rico and Francis were the most susceptible. The hull thickness of rough rice varied among varieties, but the tolerant varieties appeared to have thicker hulls than the susceptible varieties. There was no difference among rice types (long-, medium-, or short grain) regarding tolerance or susceptibility to *R. dominica*. Results show that the characteristics of the rough rice hull are important for conferring susceptibility of individual varieties to *R. dominica*.

Keywords: *Rhyzopertha dominica*; Dobie index; Rough rice; Bioassay; Host plant resistance

1. Introduction

Since 1911, about 140 varieties of rice have been released in the United States of America (USA), with improved characteristics for agronomic production, field tolerance to insects and diseases, milling and baking quality, and industrial cooking preferences (Moldenhauer et al., 2004). Rice is categorized as long-, short-, or medium grain, and different varieties of each type have been created through demands of the milling industry and end-use consumers. There are two major rice-producing regions in the USA—the Gulf Coast region and the Sacramento Valley of California (Moldenhauer et al., 2004). More than 70% of the long grain rice is produced in the Gulf Coast region, medium grains are produced in both areas, and short grain rice is almost exclusively grown in California (Childs, 2004).

Rhyzopertha dominica (F.), the lesser grain borer, is an important pest of most stored raw grains, including rough rice. The developing larva feeds inside grain kernels, and can cause weight loss and damage to the germ and endosperm in wheat (Gundu Rao and Wilbur, 1957; Campbell and Sinha, 1976). Weight loss from individual kernels has also been reported with different varieties of triticale, a wheat-rye hybrid (Baker et al., 1991), and in rice infested with *R. dominica* (Nigam et al., 1977). Several methods have been used to assess varietal resistance of various grains to stored-product insects (Breese, 1960; Cogburn, 1977; Cogburn and Bollich, 1990; Baker et al., 1991; Toews et al., 2000; Throne et al., 2000; Watts and Dunkel, 2003), including feeding damage as measured by frass production (Baker et al., 1991), and biological

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parameters such as developmental rate, fecundity, hatch rate, and longevity of adult insects (Singh et al., 1986; Dobie and Kilminster, 1978).

Rice is generally stored as rough rice, and the hull may offer some protection from stored-product insects such as *R. dominica*. Other potential internal insect pests of rough rice include *Sitotroga cerealella* (Olivier), the Angoumois grain moth; *Sitophilus oryzae* (L.), the rice weevil; and *Sitophilus zeamais* Motschulsky, the maize weevil. Some of the properties of the rice grain, such as tightness of the hull, kernel hardness, and chemical composition of the kernel (Juliano, 1981; Breese, 1960; Cogburn, 1974; Cogburn et al., 1983) were found to confer some level of tolerance to stored-product insects. Many new varieties of rice have been developed in recent years, but there have been few assessments of varietal susceptibility or tolerance to *R. dominica*. Varietal tolerance in different stored commodities has been advocated for inclusion into management programs for insect pests (Throne et al., 2000). Therefore, the objectives of this test were to: (1) assess varieties of rough rice for susceptibility to *R. dominica* and (2) determine if specific characteristics of the rice hull confer susceptibility or tolerance to *R. dominica*.

2. Materials and methods

2.1. Classification of rice kernels

A total of 28 current commercial varieties were obtained from the University of Arkansas, Louisiana State University, the USDA in Beaumont, TX, Lundberg Family Farms, Richvale CA, and the Butte County Rice Growers Association, Richvale, CA. All rice obtained was from the 2004 crop year; however, some of these varieties were commercially grown, while others were from limited production maintained for seed stock. When rice samples arrived at the USDA-ARS Grain Marketing and Production Research Center (GMPRC) in Manhattan, KS, they were immediately placed in cold storage at about 4 °C. Before being used in tests, rice was removed from the cold room, cleaned using a #12 sieve, and tempered to 14% moisture content (m.c.).

Each variety lot was sampled to determine the number of solid, cracked, and split hulls; the procedure for this enumeration was modified from Cogburn et al. (1983). The rice hull is composed of the palea and lemma (Champagne et al., 2004), which was used to classify kernels as follows: solid hulls, with palea and lemma intact and no space between them; split hulls, with spaces in the longitudinal seam of the kernels between the palea and lemma; and cracked hulls, with the palea and lemma cracked longitudinally but not in the seam or transversely.

Twenty grams of each variety were sampled, and 100 kernels were inspected under a microscope and grains classified as having solid, split, or cracked hulls. Ten separate replicates were evaluated for each variety (10 separate 20-g lots). The number of solid, split, and cracked hulls was calculated for each variety, and the data were analyzed using the General Linear Models (GLM) procedure of the Statistical Analysis System (SAS Institute, 2001) to identify differences among varieties. The Bonferroni (Dunn) *t*-test was used to account for experiment-wise error rate and to separate means for the percentage of solid, split, and cracked hulls in each variety.

2.2. Insect bioassays

Rhyzopertha dominica adults, reared on rough rice of the long grain variety Francis at 28 °C and 68% relative humidity (r.h.), were obtained from colonies maintained at the GMPRC. Voucher specimens of *R. dominica* from these colonies were previously deposited in the Kansas State University Museum of Entomological and Prairie Arthropod Research under Lot no. 162. Two-week-old adults were obtained from these colonies, placed in a 0.95-L jar with approx. 200 g of rough rice, and held for 2 days at 28 °C and 68% r.h. Rice kernels and adults were then sieved with #12 and 35 sieves. The kernels remained on top of the #12 sieve, the adults fell through and were trapped by the #35 sieve, and eggs and frass were collected in a solid pan underneath the #35 sieve. Eggs were incubated at the same conditions until they hatched.

Four separate replicates of 20 g aliquots of each variety were placed in separate 29-mL plastic vials, and 10 neonates were added to each vial. The four replicates were established at 3-day intervals. All vials were maintained at 32 °C in plastic boxes with NaCl solution to maintain 75% r.h. (Greenspan, 1977). Temperature and r.h. were monitored during the experiment using HOBO data recorders (Onset Computer, Pocasset, MA). Adult emergence was monitored daily beginning 20 days after the initiation of a replicate by pouring the contents of the individual vials into a pan and collecting the adults. The number of adults and development time of each individual adult was recorded until emergence was complete (no emerged adults for 7 days). All emerged adults were transferred to a new vial, which contained the same variety of rice (one of the 28) on which they were reared. These vials were also maintained at 32 °C and 75% r.h. Two weeks after the first adult was placed in the vial, the rice was sifted as described previously, and eggs were collected and counted. This process was repeated at 3 and 4 weeks, and then the parental adults were killed by placing them in alcohol, and sexed by examination of male and female genitalia (Potter, 1935).

The number of emerged adults and median developmental times were averaged and mean differences determined as described for kernel analysis, using Bonferroni correction to account for experiment-wise error. The Dobie index (Dobie, 1974; Dobie and Kilminster, 1978) was also calculated for each variety as $(\log_e F)/D \times 100$, where F is the number of F_1 adults emerging from the original 10 neonates in each vial and D is the median development time of those 10 larvae. A higher Dobie index indicates a greater susceptibility to *R. dominica*. The Dobie index was used because it is an accepted means of relating the number of progeny to the intrinsic rate of increase of an insect population (Dobie, 1974; Dobie and Kilminster, 1978; Throne et al., 2000). There were some replications where there were no female parental adults, and these replications were removed from the data set before analysis.

2.3. Rice hull thickness

Five solid hulls were selected from the 1000 hulls that were collected from each variety as part of the process described in Section 2.1. Each of these hulls was cut in half transversely using a razor blade to slice the palea and lemma (Fig. 1a–c). The half of the kernel that contained the rachilla, a stem-like structure where the palea and lemma are attached, was embedded on play-dough so that the cross-sectional area with both sides of the hull (the palea and lemma) was visible. The part where the palea and lemma interlock (Hoshikawa, 1993; Champagne et al., 2004) was termed the "thick part" (Fig. 1d) of the hull while the area between the vascular bundle on the lemma next to the thick part was termed the "thin part" (Fig. 1d). The thick and thin parts have long ridges along the length of the lemma; the maximum and minimum thicknesses of these parts were determined at $10\times$ magnification. These measurements were taken using SPOT software (Diagnostics Instruments, Inc., Sterling Heights, MI, USA) to measure these four widths.

The GLM procedure and the Bonferroni (Dunn) *t*-test ($P<0.05$) in SAS were used to compare means of the top and bottom portions of the ridges of the thick and thin parts (four locations) among varieties. Correlation of solid hulls, insect response data, and hull thickness were analyzed by pooling the means of each parameter using the Correlation and Plot procedures of SAS. Stepwise regressions were run to correlate the percentage of solid hulls in each variety with each of the four parameters of hull thickness (the top and bottom ridges of the thick and the thin parts). Stepwise regressions were also utilized for progeny production, median development time, and Dobie indices.

3. Results

3.1. Classification of rice

Among 28 varieties, there were significant differences among the mean numbers of solid, split, and cracked hulls ($F = 51.4$, 26.0, and 99.0, respectively, df = 27, 252, all P values <0.01). The percentage of solid hulls ranged from 55.5 (Koshihikari variety) to 92.8 (Akita variety), the percentage of split hulls ranged from 1.1 (Jefferson and Koshihikari varieties) to 21.5 (Earl variety), and the percentage of cracked hulls ranged from 3.1 (Earl variety) to 43.7 (Koshihikari variety) (Table 1).

3.2. Insect bioassays

There were significant differences among varieties regarding the Dobie index of susceptibility, mean development time, and number of emerged adults ($F = 5.2$, 3.6, and 4.6, respectively, df = 27, 80, $P<0.01$). The Dobie index of susceptibility ranged from 1.1 for Wells to 3.8 for

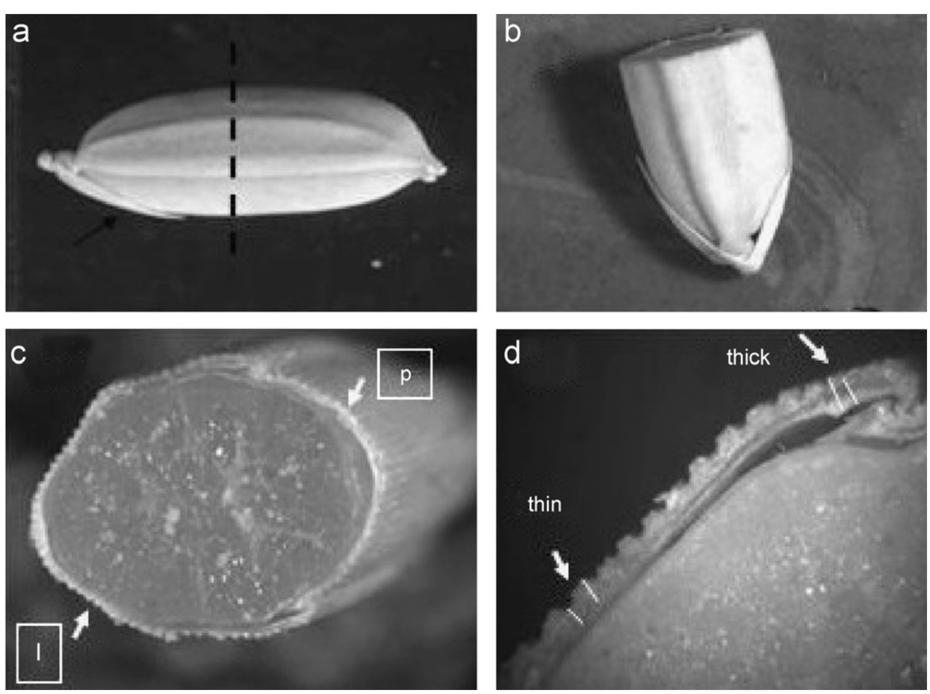

Fig. 1. (a) A medium grain rough rice kernel and (b, c) the half kernel indicating (d) the sites on the rachilla that were used to measure the thick part and thin part of the lemma; p = palea, l = lemma.

Table 1
Evaluation of 28 varieties ($n = 1000$ kernels) of commercial rough rice

Varieties	Solid hulls*	Split hulls*	Cracked hulls*
Akita (2) (S)	92.8±1.0a	2.8±0.5efghijk	4.4±0.6ghi
Jasmine (4) (L)	91.9±0.9a	2.3±0.6ghijk	5.8±0.9fghi
Black Japonica (1) (S)	91.8±1.1a	1.4±0.3ijk	6.8±1.0fghi
Jupiter (3) (M)	91.6±1.2a	3.5±0.6defghijk	5.0±0.8fghi
Wells (5) (L)	91.2±1.0a	4.9±0.8cdefghijk	8.9±0.5hi
M-202 (2) (M)	90.8±1.0a	5.9±1.0cdefghi	3.3±0.4hi
Bengal (3) (M)	90.5±0.6a	1.8±0.2ghijk	7.7±0.6fghi
Lebonnet (4) (L)	89.9±1.2a	4.9±0.8efghijk	5.2±0.8fghi
M-104 (2) (M)	89.9±1.0a	5.2±0.8cdefghijk	4.9±0.6fghi
S-102 (4) (S)	89.7±1.4a	4.8±0.8efghijk	5.5±1.0fghi
Neches (4) (L)	89.4±0.8a	6.0±0.9cdefgh	5.2±0.6fghi
Pirogue (4) (S)	88.2±1.6ab	0.9±0.3k	10.9±1.6ef
Pirogue (3) (S)	88.2±1.1ab	1.2±0.4jk	10.6±1.0efg
Cocodrie (5) (L)	88.0±1.1ab	2.6±0.4fghijk	9.4±1.0fgh
M-204 (2) (M)	87.8±1.5ab	7.7±0.8bcd	4.5±1.1ghi
M-205 (1) (M)	87.4±1.5ab	5.7±0.6cdefghi	6.9±1.1hi
Medark (4) (M)	87.1±1.0ab	5.0±1.1cdefghik	7.9±0.9fghi
M-206 (2) (M)	86.5±1.3ab	7.3±1.1bcde	6.2±0.6fghi
M-205 (2) (M)	86.0±1.4ab	9.5±1.1bc	4.3±0.7hi
Francis (5) (L)	81.4±1.5bc	11.4±1.4b	7.2±0.9fghi
Akita (1) (S)	77.3±2.5cd	6.4±1.0cdef	16.3±0.8de
Bolivar (4) (L)	76.6±1.7cd	2.5±0.8fghijk	20.9±0.8d
Rico (4) (M)	76.5±1.3cd	6.3±0.8cdefg	17.3±0.1d
Earl (4) (M)	75.4±2.2cd	21.5±2.0a	3.1±0.4i
Jefferson (5) (L)	69.8±1.9de	1.1±0.3k	29.1±1.7c
Dawn (4) (L)	62.0±2.2ef	1.6±0.4hijk	36.6±2.1b
Dellmati (4) (L)	61.4±1.0f	1.2±0.4jk	37.4±0.9b
Koshihikari (4) (S)	55.5±2.1f	1.1±0.4k	43.7±2.2a

The characters are solid hulls: palea and lemma intact and interlocked, no space between palea and lemma; split hulls: spaces between palea and lemma allowing for observation of brown rice grain (caryopsis) between them; and cracked hulls: palea and lemma cracked in any area and able to observe brown rice grain. Data are mean percentages of each hull class±SE.
(1) Lundberg Family Farms, Richvale, CA.
(2) Butte County Rice Growers, Richvale, CA.
(3) Rice Research Station, Louisiana State University, Baton Rouge, LA.
(4) Rice Research Unit, ARS-USDA, Beaumont, TX.
(5) Rice Processing Program, University of Arkansas, Fayetteville, AR
(L) = long grain, (M) = medium grain, and (S) = short grain.
*Values within one column followed by different letters are significantly different at $P<0.05$ with Bonferroni (Dunn) *t*-test.

Black Japonica, Francis, and Rico (Table 2). Long-, medium-, and short grain varieties were represented throughout the range. For example, the group that included the highest Dobie indices was the long grain varieties Francis, Dellmati, Neches, and Jefferson; the medium grain varieties Rico and M-206; and the short grain variety Black Japonica. The group with the lowest Dobie indices was the long grain variety Wells, medium grain variety Jupiter, and short grain variety Pirogue from TX.

The shortest median development time was 23.4 days for M-206 and the longest time was 27.6 days for Pirogue (TX) (Table 2). The number of emerged adults from the neonate introductions was lowest on Wells (2.0) compared to the highest of 8.8 on Rico and Jefferson.

Duplicate samples were processed for some varieties (same variety, different location), and there was a significant difference in the Dobie Index between Pirogue 3 and 4 (3.4±0.1 and 1.5±0.2, respectively); but no difference ($P\geqslant0.05$) between the duplicate samples for M-205 or Akita, nor were there any differences in median development times of *R. dominica* on these duplicate samples. However, there were significant differences between the two Pirogue samples with respect to the number of emerged adults.

The number of females among the original parental adults emerging from each variety of rice ranged from 0 to 4. However, when the 0 values were eliminated, there was no correlation between the number of females and total progeny produced on each variety ($P>0.05$); therefore total progeny was used as the analysis variable rather than mean production per female. Total progeny production of *R. dominica* was significantly different among the rice varieties ($F = 2.06$, df = 27, 69, $P<0.01$) and ranged from 6.0 to 138.2. The varieties on which *R. dominica* produced the fewest progeny were Jupiter (6.0), Wells (6.5), and Bengal (7.5) (Table 2). Varieties on which the most progeny were produced were Lebonnet (138.2) and Rico (132.5).

3.3. Rice hull thickness

Differences in the thickness of the rice hull were significant ($P<0.05$) for three of the areas of the hull measured; maximum thickness in the thick part, minimum thickness in the thick part, and maximum thickness in the thin part ($F = 3.5$, 2.6, and 2.0, respectively, df = 27, 112). In the thick part, which is on the interlocking area of lemma and palea, the maximum thickness ranged from 70.2 μm in Cocodrie to 93.6 μm in Jupiter, and the minimum thickness ranged from 54.4 in Francis to 79.0 μm in Akita (2) (Table 3). In the thin part, the maximum thickness ranged from 55.0 μm in Bolivar to 76.4 μm in Jupiter, and minimum thickness ranged from 36.8 μm in Rico to 55.0 μm in Lebonnet (Table 3). Differences in the minimum thickness of the thin part were not significant ($F = 1.4$, df = 27, 112; $P = 0.11$).

Maximum thickness of the thick part was positively correlated with progeny development time (Fig. 2), progeny production (Fig. 3), and negatively correlated with the Dobie index (Fig. 4). When all parameters of hull thickness (the maximum and minimum thickness of the thick parts; and the maximum and minimum thickness of the thin parts) were analyzed through correlations with the Dobie index using stepwise regressions, only the maximum thickness of the thick parts was significant ($F = 5.7$, df = 1, 26, $P = 0.02$). Development time ($F = 6.2$, df = 1, 26) and progeny production ($F = 9.9$, df = 1, 26) also correlated with the maximum thickness of the thick part ($P<0.05$). The percentage of solid hulls did not correlate with any of the four parameters for hull thickness nor did it correlate with the Dobie index values, development time, or progeny production ($P\geqslant0.05$).

Table 2
Dobie index of susceptibility, median development time, number of emerged adults of *R. dominica* which developed from 10 neonates released on 28 varieties of rough rice and held at 32 °C 75% r.h., and number of progeny from the surviving neonates

Varieties	Dobie index of susceptibility*,**	Median of development time (days)*	Number of emerged adults*	Number of adult progeny*
Francis (5) (L)	3.8±0.2a	23.5±0.5c	8.0±0.8a	95.5±13.0ab
Rico (4) (M)	3.8±0.2a	24.2±0.2abc	8.8±0.9a	132.5±19.5a
Black Japonica (1) (S)	3.8±0.8ab	25.3±0.6abc	6.2±0.8abc	38.3±12.2ab
Dellmati (4) (L)	3.7±0.3ab	24.4±0.7abc	8.0±0.8a	61.2±16.3ab
Neches (4) (L)	3.7±0.3ab	24.4±0.2abc	8.2±1.2a	75.0±20.7ab
Jefferson (5) (L)	3.7±0.2ab	24.5±0.3abc	8.8±0.5a	101.8±19.0ab
M-206 (2) (M)	3.6±0.2ab	23.4±0.4c	7.0±0.9ab	89.5±25.6ab
Akita (1) (S)	3.5±0.4ab	24.2±0.9abc	7.2±1.1a	72.2±24.8ab
Medark (4) (M)	3.5±0.2ab	24.6±0.2abc	7.2±0.9a	78.2±22.7ab
Lebonnet (4) (L)	3.5±0.1ab	24.5±0.5abc	7.5±0.6a	138.2±31.7a
M-205 (1) (M)	3.4±0.3ab	25.8±0.3abc	7.8±1.3a	70.5±24.3ab
Cocodrie (5) (L)	3.4±0.2ab	25.4±0.5abc	7.0±0.6ab	100.2±33.2ab
S-102 (4) (S)	3.4±0.2ab	24.4±1.0abc	6.2±0.5abc	90.25±31.8ab
Pirogue (3) (S)	3.4±0.1ab	26.2±0.2abc	7.8±0.5a	81.2±20.3ab
Earl (4) (M)	3.3±0.2ab	26.6±0.6abc	7.5±0.9a	39.0±14.2ab
M-104 (2) (M)	3.1±0.2ab	25.2±0.8abc	6.0±0.6ab	96.8±41.8ab
Jasmine (4) (L)	3.1±0.1ab	27.5±0.9a	7.0±0.0ab	79.0±30.1ab
M-204 (2) (M)	3.1±0.1ab	25.5±0.3abc	6.0±0.5abc	65.5±10.7ab
Koshihikari (4) (S)	2.9±0.6ab	25.1±0.7abc	6.2±1.6abc	63.0±19.2ab
Bolivar (4) (L)	2.9±0.3ab	25.4±0.6abc	5.8±1.1abc	39.5±10.0ab
Dawn (4) (L)	2.8±0.4ab	25.4±0.2abc	5.8±1.4abcd	32.3±1.8ab
M-202 (2) (M)	2.7±0.3abc	26.6±0.4abc	5.5±0.9abcd	100.0±39.6ab
M-205 (2) (M)	2.6±0.2abc	26.6±0.6abc	5.2±0.8abcd	46.8±12.2ab
Akita (2) (S)	2.4±0.5abcd	26.7±1.4abc	4.8±1.2abcd	48.8±10.6ab
Bengal (3) (M)	1.6±0.3abcd	26.2±0.3abc	2.8±0.5bcd	7.5±1.5b
Pirogue (4) (S)	1.5±0.2bcd	27.6±0.5a	2.8±0.5bcd	24.5±11.5ab
Jupiter (3) (M)	1.2±0.4cd	27.2±0.9ab	2.2±0.5cd	6.0±0.0b
Wells (5) (L)	1.1±0.6d	23.7±0.7bc	2.0±0.6d	6.5±5.5b

(1) Lundberg Family Farms, Richvale, CA.
(2) Butte County Rice Growers, Richvale, CA.
(3) Rice Research Station, Louisiana State University, Baton Rouge, LA.
(4) Rice Research Unit, ARS-USDA, Beaumont, TX.
(5) Rice Processing Program, University of Arkansas, Fayetteville, AR (L) = long grain, (M) = medium grain, and (S) = short grain.
*Values within one column followed by different letters are significantly different at $P<0.05$ with Bonferroni (Dunn) *t*-test.
**Dobie index of susceptibility (Dobie, 1978), $(\log_e F)/D \times 100$, where F is the number of F_1 adults emerging from the original 10 neonates in each vial and D is the median development time of those 10 larvae.

4. Discussion

Rice varieties with low Dobie indices of susceptibility of less than 2.0 (Wells, Jupiter, Pirogue, and Bengal) also had a consistently high percentage of solid hulls, ranging from 88.2% to 91.6%. Conversely, the Dobie indices in the nine varieties with a lower percentage of solid hulls ranged from 2.8% to 3.8%. This range of values, coupled with the fact that it was necessary to perform the correlations on the mean values for each variety due to the differing numbers of replicates for each parameter, could have accounted for the lack of overall correlation between the Dobie index values and the percentage of solid hulls. However, the rough rice hull offers protection from insects, molds, and moisture (Belsnio, 1988) and any break in the hull could provide an access point for stored-product beetles such as *R. dominica* and *S. oryzae* (Breese, 1960; Cogburn, 1974). The causes of breakage or splits in the hull encompass a variety of factors, including cultural practices and growing conditions (Breese 1960); however, it is also possible that other factors unique to individual varieties affect hull breakage, which could confer different levels of tolerance to *R. dominica* (Cogburn and Bollich, 1990), as seen in our test. Also, if rice is immature when harvested, the rachilla may not be attached to the lemma and palea, which can provide another access point for insects. However, this is not common compared to other splits or cracks in the rough rice hull (Breese, 1960).

Dawn variety long grain rough rice had been tested along with other varieties for susceptibility to *S. oryzae*, *S. cerealella*, and *R. dominica* in free choice tests using cylindrical screens (Cogburn, 1974). It was identified as "tolerant" compared to varieties Belle, Patna, Colusa, Bluebell, and Nato. However, Dawn in our tests had 62% solid kernels versus 38% split or cracked hulls, which rendered the variety more susceptible to *R. dominica*

Table 3
The hull thickness (μm) of 28 varieties of rice

Varieties	Thick parts (μm)		Thin parts (μm)	
	Minimum*	Minimum*	Minimum*	Minimum*
Jupiter (3) (M)	93.6±2.4a	77.4±4.4a	76.4±4.4a	46.4±3.2^{NS}
Pirogue (3)	92.4±2.6ab	77.2±4.6a	69.6±2.5ab	47.0±4.8
Earl (4) (M)	92.2±4.0ab	75.6±3.9ab	66.0±3.2ab	42.6±1.8
Bengal (3) (M)	92.2±2.5ab	74.8±1.2ab	73.0±4.2ab	50.6±3.5
Black Japonica (1) (S)	91.0±3.3abc	77.2±3.6a	69.2±4.7ab	47.3±4.1
Akita (2) (S)	90.4±3.2abc	79.0±3.9a	68.6±0.7ab	43.0±1.0
Akita (1) (S)	89.6±2.8abc	70.2±4.4ab	73.4±5.3ab	44.2±4.5
Pirougue (4) (S)	89.4±3.6abcd	74.8±5.4ab	69.8±3.6ab	42.4±2.2
S-102 (4) (S)	88.6±3.4abcd	76.8±3.9a	72.8±3.2ab	46.8±2.6
Dellmati (4) (L)	86.6±3.9 abcd	71.6±3.7ab	71.0±3.9ab	45.8±3.2
M-205 (1) (M)	86.4±3.5abcd	69.6±3.5ab	67.2±2.9ab	45.4±4.2
Wells (5) (L)	86.2±1.4abcd	67.2±2.8ab	64.0±3.5ab	42.8±3.5
Jasmine (4) (L)	84.8±3.8abcd	70.4±3.9ab	73.8±3.8ab	48.2±3.4
M-202 (2) (M)	83.6±5.3abcd	69.8±5.0ab	64.6±3.2ab	41.6±2.3
Dawn (4) (L)	83.0±4.7abcd	68.0±5.8ab	70.2±2.2ab	50.8±3.1
Medark (4) (M)	82.6±3.6abcd	67.6±1.7ab	68.4±2.3ab	39.6±2.7
M-206 (2) (M)	81.2±3.6abcd	64.0±2.8ab	61.8±2.1ab	44.8±2.8
Lebonnet (4) (M)	81.0±6.3abcd	73.4±7.7ab	69.8±4.7ab	55.0±7.6
Rico (4) (M)	81.0±3.3abcd	65.4±3.2ab	63.4±5.4ab	36.8±2.1
Neches (4) (L)	80.8±2.0abcd	72.0±1.8ab	63.6±2.7ab	47.2±3.7
M-205 (2) (M)	79.6±1.7abcd	62.4±2.5ab	62.4±3.0ab	40.2±2.6
M-204 (2) (M)	78.8±3.4abcd	63.8±2.4ab	66.8±2.9ab	40.2±2.8
M-104 (2) (M)	78.8±2.7abcd	68.4±3.6ab	60.4±4.3ab	42.0±2.6
Jefferson (5) (L)	78.6±7.9abcd	63.6±1.8ab	69.4±2.1ab	47.6±4.0
Bolivar (4) (L)	75.2±2.1abcd	60.8±3.0ab	55.0±3.5b	37.0±2.8
Francis (5) (L)	74.2±5.2bcd	54.4±4.7b	64.6±3.7ab	41.8±5.3
Koshihikari (4) (S)	72.4±3.0cd	64.0±3.6ab	65.8±2.8ab	43.2±3.8
Cocodrie (5) (L)	70.2±1.0d	60.4±1.1ab	59.8±2.1ab	41.2±1.7

The thick part has ridges along the length of the lemma, and the maximum thickness of this part was recorded at 10× magnification at the tallest portion of the top of the ridge while the minimum thickness was taken at the same magnification at the shortest portion of the bottom of the ridge. The maximum and minimum thinness in the thin part (Fig. 1c) were measured in the same manner. These measurements were taken using a microscope and SPOT software (Diagnostics Instruments, Inc., Sterling Heights, MI, USA).
^{NS}Non significant.
(1) Lundberg Family Farms, Richvale, CA.
(2) Butte County Rice Growers, Richvale, CA.
(3) Rice Research Station, Louisiana State University, Baton Rouge, LA.
(4) Rice Research Unit, ARS-USDA, Beaumont, TX.
(5) Rice Processing Program, University of Arkansas, Fayetteville, AR.
(L) = long grain, (M) = medium grain, and (S) = short grain.
*Values within a column followed by different letters are significantly different at $P<0.05$ with Bonferroni (Dunn) *t*-test.

neonates. In our tests, other newer varieties were more tolerant to *R. dominica* than Dawn, which is an older variety of long grain rice.

Solid hulls may not be a preferred oviposition site for *R. dominica* since these sound kernels do not have crevices or ridges which may be attractive to females (Breese, 1960). Conversely, Prakash et al. (1986) reported that oviposition preferences were not related to hull texture. In our test, neonates were released onto rice kernels to try and isolate the preferences of the neonates. The tolerant varieties Jupiter, Pirogue, and Wells had smooth glabrous hulls, while some of the more susceptible varieties (Black Japonica, Dellmati) had trichomes, or hair-like structures, on the hulls. The presence of these trichomes may be a preferred oviposition site for female *R. dominica*, and the hairs may provide an attachment point for neonate dispersal.

With the exception of the Wells variety, *R. dominica* generally took 2–3 days longer to develop to the adult stage on the varieties with low Dobie indices compared to the more susceptible varieties. Similar results were obtained with rice varieties considered to be tolerant or susceptible to *S. cerealella* (Russell and Cogburn, 1977). In our test, we released neonates to reduce the variation that would occur if these tests were conducted with adult females. As an example, Singh et al. (1986) released five pairs of adult *R. dominica* into wheat varieties, which was higher than the number of females in our tests, and their Dobie indices ranged from 6 to 10. Our method of using only neonates produced a clear separation between tolerant and susceptible rice varieties.

Hull thickness may be an important character, which confers tolerance to stored-product beetles. Earlier studies

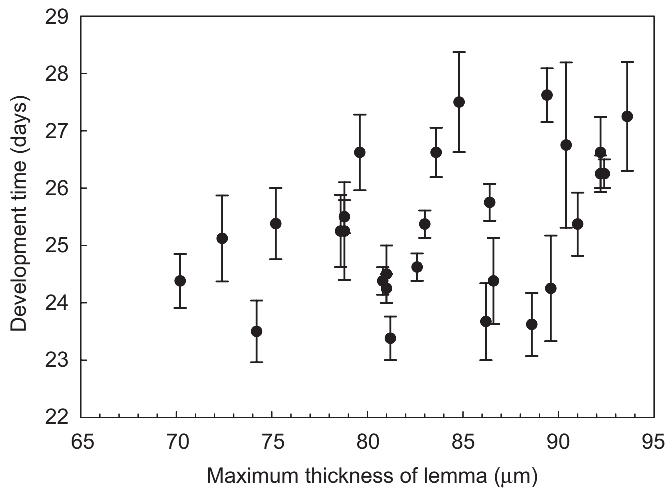

Fig. 2. Correlation between the maximum thickness of the thick part of the lemma of rough rice hulls and *R. dominica* developmental time in rough rice, which began with neonates which were released on 28 varieties and developed on the kernels until reaching the adult stage (32 °C and 75% r.h.). Pearson correlation coefficient between maximum thickness of lemma and development time = 0.42, $P = 0.03$, $N = 28$.

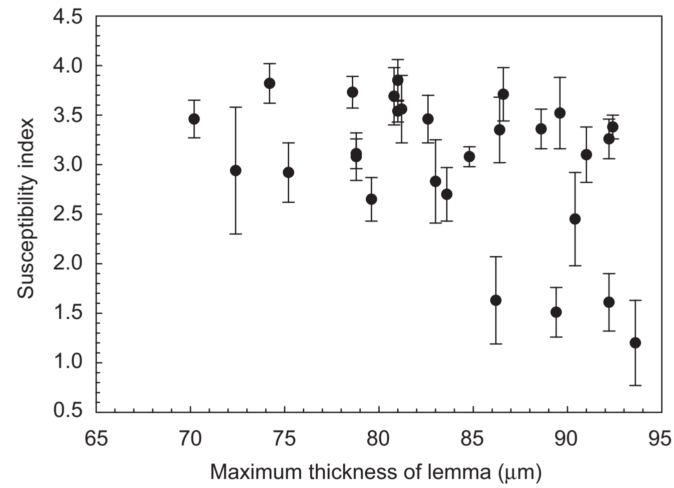

Fig. 4. Correlation between the maximum thickness of the thick part of the lemma of rough rice hulls and the Dobie index for *R. dominica* from 28 varieties of rough rice (32 °C and 75% r.h.). Pearson correlation coefficient between maximum thickness of lemma and number of progeny produced = −0.42, $P = 0.02$, $N = 28$.

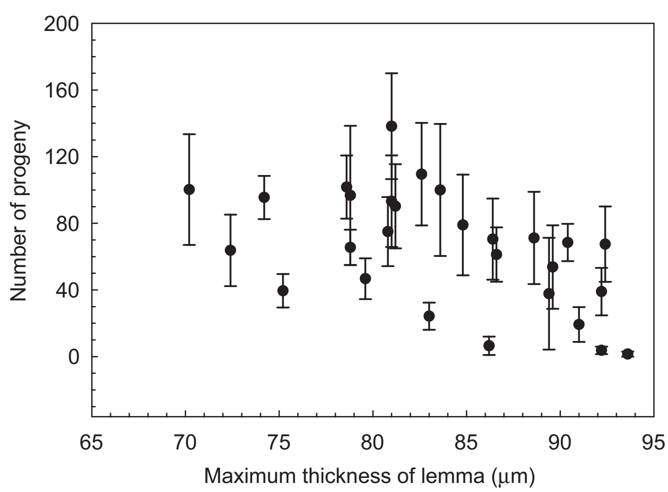

Fig. 3. Correlation between the maximum thickness of the thick part of the lemma of rough rice hulls and *R. dominica* adult progeny from 28 varieties of rough rice (32 °C and 75% r.h.). Pearson correlation coefficient between maximum thickness of lemma and the number of progeny = −0.52, $P<0.01$, $N = 28$.

had described insect infestations as related to hull defects (Breese, 1960; Cogburn, 1974). We could find no accepted standard for measuring hull thickness; hence, we measured four locations to establish differences between tolerant and susceptible rice varieties. In our analysis, the varieties with low susceptibility had a greater maximum thickness of the thick part of the hull (refer to earlier descriptions of these characters). Visual observations indicated that the kernels cracked along the parallel lines of the thin parts, which would allow access for neonate larvae.

There was no correlation between the percentage of solid hulls and emergence of adult progeny, possibly because of the greater number of solid hulls in a given sample compared to split or cracked hulls. For example, the number of kernels in 20 g of long-, medium-, and short grain rice is about 900, 800, and 600, respectively. If only 10% of the hulls are split and cracked, only 90, 80, and 60 of the total kernels are available for successful completion of development from egg to adult. However, we have clearly established the relationship between the split and cracked hulls and progeny production. These split hulls may serve as the dispersal points as insect infestations begin to develop in rough rice.

Cogburn et al. (1980) found that resistant characters against *S. cerealella* of the same rice variety varied among production sites of Louisiana, Arkansas, and Texas. They noted that environmental factors more strongly influenced susceptible varieties than resistant varieties; moreover, harvest conditions influenced kernel moisture and rice maturity (Cogburn et al., 1980). In our test, Akita from Lundberg Family Farms, CA and Butte County Rice Growers, CA had different percentages of solid hulls (77% and 92%), which translated into differences in the Dobie index of 3.5 and 2.4, respectively.

In conclusion, we were able to distinguish susceptible and tolerant rice varieties using the Dobie index, a relatively simple measure of progeny production. The Dobie index can also be used to estimate the number of progeny or population density as it is related to the intrinsic rate of population increase (Dobie, 1974; Throne et al., 2000). The standard formula of $N_t = N_0 e^{rt}$, where N_0 is the initial number of insects, N_t is the number of insects at time t, e = base of the natural logarithm = 2.7183, and r is the intrinsic rate of increase, can be used by substituting the Dobie index multiplied by a constant for r (Throne et al., 2000). Splits and cracks in the rice hull, which provide access to neonate *R. dominica*, may be related to the thickness of the hull. Although growing conditions and drying methods contribute to hull breakage, intrinsic varietal characteristics may be responsible for the degree of breakage that occurs in a given situation. The samples of rice varieties used in our tests came from various production sites in California, Arkansas, Texas, and Louisiana. All samples were from the 2004 crop, yet a wide range of susceptibility to *R. dominica* was found. Results warrant further testing of the susceptible and resistant varieties from a wide range of locations, drying conditions, and crop years to further define the degree of susceptibility to *R. dominica* and other stored-product insects.

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