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Susceptibility of Classes of Wheat Grown in the United States to Stored-Grain Insects

W. H. McGAUGHEY, R. D. SPEIRS, AND C. R. MARTIN

U.S. Grain Marketing Research Laboratory, USDA-ARS, 1515 College Avenue, Manhattan, Kansas 66502

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ABSTRACT Comparative studies were done on the reproductive rates of *Sitophilus oryzae* (L.) and *Rhyzopertha dominica* (F.) in relation to physical properties of the predominant U.S. varieties of hard red winter, soft red winter, hard red spring, white, and durum wheats. Reproductive rates of both species differed significantly among the classes, and quantitative data were obtained that may be useful in modeling population growth on the different classes. White wheats were most susceptible to both species, but the ranking of the other classes differed between the two species. Within the classes of wheat, virtually no significant differences between varieties in reproductive rates of either species were apparent. Variation between production sites exceeded that between varieties. Kernel size and density were not suitable criteria for distinguishing between the classes and did not correlate well with reproduction by either species. Kernel hardness differed among the classes and correlated well with *S. oryzae* reproduction but not with *R. dominica*. *S. oryzae* appeared to be sensitive to kernel hardness only when differences were quite large, such as between classes. Small differences in hardness between or within varieties within a class had little effect on *S. oryzae* reproduction.

KEY WORDS Insecta, stored grain, host plant resistance, stored-product insects

MAJOR WHEATS produced in the United States are classified by species, color, functional (end use) properties, or time of planting into five classes: hard red winter, soft red winter, hard red spring, white, and durum (Parker et al. 1982). Differences in the extent of insect infestation among these classes of wheats have been suspected for many years, but it has never been clear whether the differences were classwide, resulting from consistent differences in the physical or chemical properties of all varieties of each class, or if they were a result of differences between individual varieties or a function of the climatic conditions under which they are produced, stored, and processed. Effects of relative humidity and temperature, climatic factors that differ markedly among the wheat-growing regions of the United States, on reproductive and developmental rates of storage insects are well known and can be predicted with reasonable certainty (Hagstrum & Heid 1988, Hagstrum & Throne 1989).

Under conditions of constant temperature and moisture, differences in insect reproductive and developmental rates on different varieties, cultivars, and samples of many species of grains, including wheat, have been observed by numerous investigators (Mills 1976, Russell & Cogburn 1976, Horber 1983, Dobie in press). These differences have been attributed to many different structural and compositional properties, including kernel hardness, characteristics of the pericarp, chemical composition of the endosperm, damage before or during harvesting and handling, and other factors (Breese 1960, Dobie 1974, Gomez et al. 1983, Horber 1983, Mills 1976, Pradhan 1972, Russell & Cogburn 1976, Sinha & Voisey 1978, Sinha et al. 1988, Van Schoonhoven et al. 1975). In wheats, kernel hardness is one of the most obvious differences between varieties and one that is closely related to the different functional properties of the various classes of U.S. wheats (Pomeranz et al. 1988a). The relationship between hardness and insect susceptibility has been studied in a number of wheat varieties (Amos et al. 1986, Pradhan 1972, Sinha & Voisey 1978, Sinha et al. 1988), but we are not aware of any studies that relate kernel hardness or other characteristics associated with classwide differences in functional properties to insect susceptibility.

Our study was done to determine whether consistent differences in insect susceptibility occur among the different classes of wheat and, if so, whether they can be attributed to readily measurable physical properties of the kernels. The tests were done under constant moisture and temperature conditions to eliminate climatic effects in storage, and samples from many different production sites were tested to include variability that might be due to different cultural conditions. Major varieties of each class being produced in the United States were tested so that the results would provide quantitative information that would be of practical

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Table 1. Production location for the samples of each variety and class tested

Class	Production site	Variety[a]
Western white	Marion Co., Oreg.	B
	St. Paul, Oreg.	E
	Wasco City, Oreg.	BEF
	Coulee City, Wash.	ABCDEF
	Cunningham, Wash.	ABCDEF
	Lind, Wash.	BCDEF
	Pomeroy, Wash.	ABCDEF
	Pullman, Wash.	ABCDEF
	Ritzville, Wash.	ABCDEF
	Walla Walla, Wash.	ABCDEF
Soft red winter	Bay, Ark.	ABCDEFG
	Griffin, Ga.	DE
	Plains, Ga.	D
	Quency, Fla.	BCDEF
	Lafayette, Ind.	AB
	Riley Co., Kans.	G
	Stafford Co., Kans.	G
	Lexington, Ky.	BDEG
	Bertrand, Mo.	ABCFG
	Lamar, Mo.	ABCFG
	Mt. Vernon, Mo.	ABCFG
	Novelty, Mo.	ABCEFG
	Spickard, Mo.	ABCFG
	Yellow Springs, Ohio	B
	Overton, Tex.	DE
Hard red winter	Akron, Colo.	CG
	Berthoud, Colo.	C
	Julesburg, Colo.	CG
	Brown Co., Kans.	A
	Finney Co., Kans.	BDG
	Greely Co., Kans.	ADEFG
	Harvey Co., Kans.	AB
	Reno Co., Kans.	ACDEF
	Riley Co., Kans.	ACDEFH
	Stafford Co., Kans.	ACDEFH
	Thomas Co., Kans.	ADF
	Goodwell, Okla.	B[b]E
	Lahoma, Okla.	B
	Stillwater, Okla.	BEFH
	Brookings, S.D.	G
	Bushland, Tex.	C[b]G[b]H[b]
	Stinnett, Tex.	CGH
Hard red spring	Bozeman, Mont.	CE[b]
	Crookston, Mont.	DF
	Huntley, Mont.	E
	Kalispel, Mont.	E
	Moccasin, Mont.	E
	Morris, Mont.	DF
	Shonkin, Mont.	E
	Carrington, N.D.	ABCDFG
	Dickinson, N.D.	ACDG
	Langdon, N.D.	ABCDFG
	Minot, N.D.	ABCDFG
	Williston, N.D.	ABCDFG
	Day Co., S.D.	ABCF
	Groton, S.D.	BF
Durum	Carrington, N.D.	ABCDE
	Dickinson, N.D.	ABCDE
	Fargo, N.D.	ABCDE
	Langdon, N.D.	ABCDE
	Minot, N.D.	ABCDE
	Williston, N.D.	ABCDE

[a] For western white, A, 'Daws'; B, 'Hill 81'; C, 'Lewjain'; D, 'Moro'; E, 'Stevens'; and F, 'Tres.'
For soft red winter, A, 'Arthur 71'; B, 'Caldwell'; C, Coker 747'; D, 'Coker 916'; E, 'Florida 302'; F, 'McNair 1003'; and G, 'Pike.'
For hard red winter, A, 'Arkan'; B, 'Chisholm'; C, 'Hawk'; D, 'Larned'; E, Mustang'; F, 'Newton'; G, 'Scout 66'; and H, 'TAM 105.'
For hard red spring, A, 'Alex'; B, 'Butte 86'; C, 'Len'; D, 'Marshall'; E, 'Newana'; F, 'Pioneer 2369'; and G, 'Stoa.'
←
For durum, A, 'Lloyd'; B, 'Monroe'; C, 'Rugby'; D, 'Vic'; and E, 'Ward.'
[b] Two samples of this variety from this area.

value in models to predict rates of insect population increase in the different classes of wheat.

Materials and Methods

Samples of wheat were obtained from wheat-breeding programs at state agricultural experiment stations, universities, and seed companies at various locations in the wheat-producing areas of the United States. The varieties of each class that were included in the tests were initially selected from those planted to the largest acreage in the United States in the 1984 crop year (Siegenthaler et al. 1986). The list of varieties was modified to reflect changes in plantings since that year as information was obtained verbally from suppliers of the samples. Samples from six or more locations were tested for each variety, and five to eight varieties were included from each class (Table 1). Five classes of wheat—hard red winter, soft red winter, hard red spring, western white, and durum—were tested. Samples were from the 1987 crop year.

Upon receipt, the samples were cleaned with a Hart-Carter Dockage Tester (Model XT2; Simon-Carter Company, Minneapolis, Minn.) to remove most of the foreign material and broken kernels and thus reduce variation due to differing amounts of dockage. The moisture content of the samples was adjusted by adding water or by ambient air drying, or both, and by tempering in a room at 60% RH to a range of 12–13%. Moisture content was measured using an electronic grain analysis computer (Model GAC II; Dickey-John Corporation, Auburn, Ill.). Samples were frozen for 7 d to eliminate any possibility of infestation present when they were received.

Biological Tests. As soon as the samples were equilibrated to the desired moisture content, 200-g subsamples were placed in Mason jars (0.473 liter) and infested with 25 3- to 14-d-old adults of the rice weevil, *Sitophilus oryzae* (L.), or the lesser grain borer, *Rhyzopertha dominica* (F.), from laboratory colonies reared on wheat. The jars were capped with filter paper and held at 25 ± 1°C and 60 ± 5% RH. After 7 d, parent adults were removed by sieving. Two replicate subsamples of each wheat sample were infested with lesser grain borers. The F_1 insects were removed by sieving and counted after 15 wk. Four replicate subsamples were infested with rice weevils. The F_1 in two of these subsamples were removed by sieving and counted after 10 wk. Jars containing the other two replicates were examined at regular intervals. When progeny began to emerge, the jars were sieved three times per week to provide data on developmental time as well as total numbers of progeny. The number of days from initial infestation until 50% of the progeny had emerged was used to compare developmental times among the wheats. A seventh subsample of about 400 g of each sample was stored also with the infested samples, and its moisture content was checked periodically to ensure that the moisture level in the samples remained constant through the test period.

Physical Tests. All physical measurements were made on samples that had been cleaned to remove foreign material and broken kernels and equilibrated to 12–13% moisture content. Number of kernels per 40 g was used as a measurement of kernel size. Samples were weighed and the kernels were counted on an electronic kernel counter (Model 2080; Agricultural Specialty Company, Beltsville, Md.). Density of the kernels in the samples was estimated by measuring the volume of 12-g samples with a gas pycnometer (Model SPY2; Quantachrome Corporation, Syosset, N.Y.) as described by Chang (1988), except that we used compressed air instead of helium. The hardness of individual kernels in each sample was measured with an instrument currently being developed at the U.S. Grain Marketing Research Laboratory, Manhattan, Kansas (C.R.M., unpublished data). The instrument measures the force required to crush kernels and is similar to the method used by Pomeranz et al. (1988b). The hardness score obtained is a numerical value that relates the hardness of test kernels to reference samples maintained by the U.S. Federal Grain Inspection Service. Samples that are classified functionally as hard wheats have a score of 75 and soft wheats, 25.

Subsequent experiments were done on a few samples to determine more clearly whether the insects could discriminate among kernels in a sample based upon their hardness. In the first, 100 rice weevils were introduced into a 200-g sample of hard red winter wheat, 'Hawk,' and allowed to lay eggs for 3 d. Progeny were allowed to develop in the sample for 4 wk, and the kernels were x-rayed and sorted into infested and noninfested lots. Approximately 19% of the kernels were infested. The hardness of the noninfested kernels was measured and compared with the hardness of kernels in a reference sample that was not exposed to insects. The second experiment was done in the same way, except that a composite sample containing approximately equal numbers of kernels (1,000) of one variety each of durum ('Lloyd'), white ('Lewjain'), and hard red winter ('Larned') wheat were used. Approximate weights of 1,000 kernels of these varieties were 48.5, 26.5, and 37.5 g, respectively. Two hundred rice weevils were allowed to lay eggs on this sample for 4 d, which resulted in 13.4% of the kernels infested. The purpose of this experiment was to provide a wider range of hardness for the insects.

Statistical comparisons of means for numbers of progeny, developmental time, and physical measurements on kernels were made by least squares means ($P = 0.05$) in an effort to adjust the data for differences due to production location. Such an adjustment was necessary because all varieties of a class were not grown at every (or even most) production location. Pearson's correlation coefficients were calculated to measure the relationships between insect development and physical characteristics of the wheats. All analyses were done with commercial software (SAS Institute 1982).

Results and Discussion

Reproductive rates of both rice weevils and lesser grain borers differed significantly among the five classes of wheat (Table 2). Both species produced the largest number of progeny on the western white wheats (about 21% more compared with the average of the other classes). However, suitability of the other four classes for reproduction differed depending upon the insect species. For rice weevils, soft red winter and hard red winter wheats produced more progeny than durum and hard red spring wheats; for lesser grain borers, hard red winter and durum wheats produced more progeny than soft red winter and hard red spring wheats.

Differences in insect reproductive rates between varieties within each class were relatively small compared with the differences between the classes. Comparison of the variance components indicated that 30–32% of the variance for both insect species was due to class differences and <1% was due to variety differences (Table 3). Variation among samples (production locations) exceeded that among varieties. Neither rice weevil nor lesser grain borer reproduction varied significantly among the varieties of the western white wheats or the durum wheats. Rice weevil reproduction did not differ among the varieties of hard red winter or hard red spring wheats. For lesser grain borers, differences in reproductive rates among varieties of hard red winter and hard red spring wheat were subtle. In general, the only differences large enough to be significant at $P = 0.05$ were between the highest ranking variety and the one or two lowest ranking varieties of each class (Table 4). Among the soft red winter wheats, 'McNair 1003' produced the largest number of progeny of rice weevils and 'Coker 916' produced the largest number of lesser grain borers (Table 5). However, for both insect species, the only differences large enough to be significant at $P = 0.05$ were between the highest ranking variety and the three or four lowest ranking ones. 'Arthur 71' and 'Pike' were the only varieties among the seven soft winter wheats tested that ranked low in progeny production for both insect species.

Developmental times for the progeny, which we measured only for the rice weevils, differed little among the classes of wheat; however, the rates were quite consistent and differences between most of the classes were significant (Table 2). Western white wheats, which produced the largest number of progeny, also provided for fastest rice weevil de-

Table 2. Comparison of numbers of progeny ($\bar{x}$ ± SEM), time to 50% progeny emergence ($\bar{x}$ ± SEM), hardness score, density, and kernels per 40 g for each class of wheat

Class	*n*	No.		Days to 50% rice weevil emergence	Hardness[a]	Density g/cc	Kernels per 40 g
		Rice weevil	Lesser grain borer				
Western white	46	434.4a ± 17.1	536.8a ± 36.4	45.40d ± 0.35	30.1d	1.405c	1,066.1c
Soft red winter	53	397.0b ± 18.3	406.3d ± 38.0	48.44a ± 0.36	9.6e	1.395d	1,401.3a
Hard red winter	55	375.3b ± 12.9	475.1bc ± 25.5	46.24c ± 0.22	62.5c	1.409c	1,425.8a
Hard red spring	45	319.4c ± 19.9	408.5cd ± 37.7	46.76b ± 0.29	78.1b	1.430a	1,200.9b
Durum	30	342.3c ± 16.3	482.7ab ± 35.0	46.68b ± 0.34	109.4a	1.422b	993.1d

Within a column, means followed by the same letter do not differ significantly ($P > 0.05$; least significant differences [SAS Institute 1982]).

[a] Wheats classified functionally as hard wheats have an average hardness value of 75 and soft wheats, 25.

velopment. However, developmental rates in the other four classes did not correspond with their rank in numbers of progeny. Because of this, time to 50% emergence was only weakly correlated with total numbers of rice weevil progeny ($r = -0.28845$, $P = 0.0001$).

We measured three physical characteristics of the kernels in each of the wheat samples to find easily-measured factors that might be predictive of insect susceptibility. These factors were kernel size, density, and hardness. Some significant differences between mean densities and sizes of kernels in wheats of the different classes were observed, but neither factor separated all of the classes (Table 2). Kernel size was not significantly correlated with reproduction by either rice weevils ($r = -0.04084$, $P = 0.5386$) or lesser grain borers ($r = -0.10754$, $P = 0.1045$). This lack of correlation occurred because the most susceptible (western white) and one of the least susceptible classes (durum) had very large kernels. Kernel density correlated well with reproduction by rice weevils ($r = -0.32026$, $P = 0.0001$) but not lesser grain borers ($r = -0.07556$, $P = 0.2548$).

Kernel hardness seems to be a better criterion for separating wheats into different functional groups or classes (Pomeranz et al. 1988a). The hardness measurements we used clearly distinguished between the classes (Table 2). Mean hardness values for the samples of each class differed significantly from the means for all the other classes ($P \leq 0.05$). Hardness correlated well with reproduction by rice weevils ($r = -0.41719$, $P = 0.0001$) but not lesser grain borers ($r = 0.01568$, $P = 0.8134$). However, the relationship between hardness and rice weevil reproduction occurred only between classes, where the hardness values differed considerably. Within classes, where hardness value differences were small, few differences in rice weevil reproduction occurred, and thus there was no correlation with hardness.

Developmental times for rice weevils did not correlate as well as progeny numbers with physical characteristics of the kernels. Virtually no correlation with kernel density was observed ($r = -0.02079$, $P = 0.7543$). For kernel hardness versus developmental time, the overall correlation coefficient (r) was -0.15680 ($P = 0.0176$). Developmental time was best correlated with kernel size, but reasons for this relationship are unknown ($r =$

Table 3. Variance components from analysis of variance of rice weevil and lesser grain borer progeny emerging from all samples based on least squares means

Source	Rice weevil	Lesser grain borer
Wheat classes	2,059 (32%)	6,478 (30%)
Varieties within classes	0	224 (1%)
Production locations	849 (13%)	3,940 (18%)
Error	3,459	10,857

Table 4. Numbers of lesser grain borer progeny for the varieties of hard red winter and hard red spring wheat

Variety	*n*	Mean
Hard red winter		
Arkan	7	469.8ab
Chisholm	6	504.6ab
Hawk	10	502.1ab
Larned	6	446.4ab
Mustang	6	429.3b
Newton	6	412.4b
Scout 66	8	466.9ab
TAM 105	6	569.0a
Hard red spring		
Alex	6	360.3b
Butte 86	6	442.4ab
Len	7	376.7b
Marshall	7	471.0ab
Newana	6	316.9b
Pioneer 2369	8	496.1a
Stoa	5	395.9ab

Within a class, means followed by the same letter do not differ significantly ($P > 0.05$; least significant differences [SAS Institute 1982]).

Table 5. Numbers of progeny for the varieties of soft red winter wheat

Variety	n	Rice weevil	Lesser grain borer
Arthur 71	7	356.5b	332.1b
Caldwell	10	364.3b	398.0ab
Coker 747	7	369.2b	407.1ab
Coker 916	6	409.4ab	508.8a
Florida 302	6	409.6ab	349.8b
McNair 1003	7	448.8a	418.6ab
Pike	9	362.6b	348.5b

Within a column, means followed by the same letter do not differ significantly ($P > 0.05$; least significant differences [SAS Institute 1982]).

Table 6. Percentage of kernels and hardness of kernels of each class infested by rice weevils when exposed to the insects in a uniform mixture containing equal numbers of kernels of each class

Class	% Infested kernels in each class[a]	Mean hardness[b]		
		Original sample	Non-infested kernels[c]	P value[d]
Hard red winter	14	72.5	68.8	0.0001
Durum	18	94.4	91.7	0.0001
Western white	68	25.4	23.0	0.0025
Mixed sample		64.1	61.1	0.0001

Means for two trials done at different times.
[a] 13.4% of total kernels were infested.
[b] Least squares means.
[c] Hardness could not be measured for infested kernels because infestation alters the hardness score.
[d] Observed significance level based on t test.

0.38634, $P = 0.0001$). Development was fastest on the western white wheats that had quite large kernels, but durum wheats also had large kernels, and rice weevil development was slower on them (Table 2).

These experiments measured only the ability of insects to infest and use kernels of a sample for reproduction. This is a valid, often-used measure of susceptibility of a grain sample. However, different results are sometimes obtained when ovipositing females are allowed free choice among several different samples or kernels. In two subsequent experiments, we found that rice weevils select the softer kernels in a sample for oviposition. In a sample of hard red winter wheat, 'Hawk,' we found that kernels not infested by rice weevils were significantly harder (mean 73.0) than kernels of a reference sample not exposed to insects (mean 70.2) ($P = 0.0052$). We could not measure the hardness of the infested kernels because insect infestation drastically altered the hardness values. In composite samples containing one variety each of durum, white, and hard red winter wheat, rice weevils also selected kernels of the softer class (white) by a wide margin (Table 6). However, within the classes they did not exhibit the same degree of preference for softer kernels, possibly because of the much narrower range of hardness. In fact, in this mixture, there was a slight but statistically significant tendency for the rice weevils to select the harder kernels within a class. We also measured kernel size in this experiment, but no consistent trends were identified.

Several conclusions can be drawn from the results of this study. First, lesser grain borers and rice weevils exhibit different reproductive potentials on different classes of wheat. Reproductive rates were about 21% higher on western white wheats for both insect species. The ranking of the other classes differs between the two insects. Second, hardness, which is a very good indicator of functional properties and wheat class, correlates well with rice weevil reproductive potential but not with lesser grain borer reproduction. This relationship is true when large differences in hardness, such as those between classes of wheat, are compared. Small differences in hardness, such as those within classes, did not correlate with rice weevil reproduction, confirming the results of earlier studies by Pradhan (1972), Amos et al. (1986), and Sinha et al. (1988). Third, rice weevil generation time, although quite consistent within each class, does not differ much between classes and is not particularly well correlated with numbers of progeny. Fourth, when allowed free choice, rice weevils will select softer kernels in a sample for oviposition if the range of hardness is large as in a mixed lot. If the range of hardness is small as in a single variety, rice weevils may exhibit little preference or even choose the harder kernels. Fifth, although knowledge of kernel size, hardness, and wheat class will allow some predictions to be made regarding the rate and extent of insect development on different lots of wheat, other factors not elucidated by this study also must be involved in determining the suitability of wheats, particularly individual varieties within a class, for insect reproduction. This was more apparent for lesser grain borers than for rice weevils. Finally, as one might expect from their similar end use properties, wheat varieties within each class were quite uniform in their susceptibility to insect infestation. Variation due to different cultural conditions and production sites greatly exceeded that due to varietal characteristics.

These conclusions are based upon results obtained under constant storage environment conditions. The difference in susceptibility of western white wheat was large enough that it would probably be apparent under a range of different storage environments. However, differences among the other classes were small. Environmental conditions in different regions of the United States where the various classes are produced and stored probably would have a much greater effect on storage insect infestation and subsequent damage than would relative susceptibility.

Although causes of differences in rice weevil and lesser grain borer reproductive rates on the different classes of wheat have not been completely elucidated by this study, the quantitative data obtained (means and standard errors) should prove useful in population growth models to estimate relative rates of increase of populations of these two species on different classes of wheat.

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