International Journal of Tropical Insect Science Vol. 27, No. 2, pp. 114–121, 2007 DOI: 10.1017/S1742758407814676

Evaluation of quality protein maize genotypes for resistance to stored grain weevil *Sitophilus oryzae* (Coleoptera: Curculionidae)

Firoz Hossain[1], Prasanna M. Boddupalli[1]*, Rakesh K. Sharma[2], Pradyumn Kumar[3] and Bir Bahadur Singh[1]

[1]Division of Genetics, Indian Agricultural Research Institute, New Delhi 110012, India: [2]Division of Entomology, Indian Agricultural Research Institute, New Delhi 110012, India: [3]Directorate of Maize Research, Indian Agricultural Research Institute, New Delhi 110012, India

(Accepted 13 July 2007)

Abstract. The stored grain weevil, *Sitophilus oryzae* (Linnaeus), causes significant losses to maize grains in tropical countries. Despite the nutritional superiority of the quality protein maize (QPM), an important concern is the possible vulnerability of QPM genotypes to stored grain weevil infestation. In the present study, the responses of 24 QPM inbred lines, along with several non-QPM inbred lines and hybrids, were evaluated against *S. oryzae* under laboratory conditions. Two attributes, namely (i) % weight loss in the grains after a fixed period of incubation with the insect and (ii) the number of progeny insects (insect multiplication) generated from six pairs of adult insects, were considered. A cumulative resistance index was computed for each genotype giving equal weight to both attributes. The study revealed DMRQPM-60 and CML167 as the most resistant entries. Shaktiman-1, the released QPM hybrid in India, showed moderate resistance against the grain weevil. However, most of the elite QPM inbred lines as well as some non-QPM inbred lines and hybrids were found to be highly susceptible to the weevil infestation. To explore the possible relationship between enhanced protein quality and varying degree of kernel vitreousness and vulnerability to the grain weevil infestation, both the QPM and the non-QPM genotypes were analysed. The correlations between kernel quality traits and kernel texture with % kernel weight loss due to weevil infestation and insect multiplication were found to be non-significant, indicating possible influence of other factors, including pericarp thickness and endosperm composition, in determining the susceptibility of the QPM genotypes to *S. oryzae*. The study indicates that QPM genotypes are not necessarily susceptible to the stored grain weevil and identifies promising QPM genotypes with resistance to *S. oryzae*.

Key words: genetic variability, QPM, inbred lines, tryptophan content, cumulative resistance index, *Sitophilus oryzae*, *Zea mays*

*E-mail: bmprasanna@gmail.com

Introduction

Maize occupies an important position in the world economy and trade as food and feed, and as an industrial crop par excellence. It serves as a vital source of proteins, calories (in the form of carbohydrates and fats), and some of the important vitamins and minerals to billions of people worldwide, particularly in Africa, South America and Asia, and has been considered a 'poor man's nutricereal' (Prasanna *et al.*, 2001). Stored grain weevils represent one of the major factors responsible for the post-harvest losses of maize worldwide.

Sitophilus spp. are important post-harvest pests in maize, especially in the tropics (Mookherjee *et al.*, 1968; Vaidya *et al.*, 2001). *Sitophilus zeamais* Motschulsky is chiefly prevalent in Latin America, Europe and Africa, and *Sitophilus oryzae* (Linnaeus) (Coleoptera: Curculionidae) causes substantial losses in India and other Asian countries. *Sitophilus oryzae* is a major stored grain pest of rice and wheat, but because of its polyphagous nature, it also infects maize grain. Both the adults and the larvae of the weevils are internal feeders and can cause great losses to the grains, both quantitatively and qualitatively. Grain loss between 12 and 20% is common (Golob, 1984; Giga *et al.*, 1991), but up to 80% has been reported in the untreated kernels (Mutiro *et al.*, 1992; Pingali and Pandey, 2001). Weevils not only cause direct damage to the stored grains to be used as food, but also affect their viability and successful planting by small farmers particularly in the case of open-pollinated varieties/composites.

Unlike in the developed countries where maize grain is stored in silos with controlled moisture and chemical treatment, maize grain in developing countries like India is often traditionally stored in bags made of jute fibre. This results in a significant increase in moisture and humidity especially during the rainy season, thus leading to conditions highly conducive to infestation by the grain weevil as well as by pathogens such as *Aspergillus flavus*.

Although insecticide treatment is recommended for weevil control, resource-poor farmers in developing countries cannot afford such a practice. More importantly, chemically treated grains may not be usable for human or animal consumption. In addition, use of such chemicals may raise environmental concerns due to residual toxicity. There are also reports of the development of resistance to insecticides among weevil populations (Perez-Mendoza, 1999). Therefore, genetic resistance against weevil infestation is considered more preferable, at least in the long term. Painter (1968) first elaborated the mechanism of resistance by plant systems against insect pests, and classified resistance into three categories: non-preference (for oviposition, food or shelter), antibiosis (adverse effect of plant on the biology of insects) and resistance (repair, recovery or active ability to withstand infestation).

Genotypic variability for resistance to grain weevil infestation was earlier reported in non-QPM genotypes. Sinaloa-35 and Yucatan-7 among the Mexican landraces (Arnason *et al.*, 1994) and Kilima among the open-pollinated maize varieties (Derera *et al.*, 1999) were found to be resistant. Among the tropical inbred lines, Hi41, Hi34, Ku1409, Hi39 and ICA L221 (Kim *et al.*, 1988), and among the temperate inbred lines, B37, B68, R805 and T220 (Tipping *et al.*, 1988) showed resistance to the grain weevil infestation. Kurdikeri *et al.* (1993) studied the effect of *S. oryzae* on kernel damage and found Ganga Safed-2 to be the most resistant hybrid in India while many other released hybrids were highly susceptible. Sharma (2000) studied the relative resistance of some maize varieties to *S. oryzae*. Maximum % loss in grain weight was recorded in the sweet corn variety Madhuri (22%) and the least in the composites Surya (2%) and Ageti-76 (2%). The remaining varieties registered weight loss ranging from 9 to 19%. Based on different criteria (% weight loss, total progeny count and % kernel infestation), Surya was considered moderately resistant to *S. oryzae*, followed by Ageti-76 and Dhawal, during a storage period of 50 days. Among the CIMMYT (International Maize and Wheat Improvement Center) non-QPM inbred lines, CML387 was found to have the most promising level of resistance to grain weevil infestation and expressing a positive GCA (General Combining Ability) for grain yield (Dhliwayo *et al.*, 2005).

The discovery of the nutritional advantage of the *opaque2* (*o2*) mutation in maize, which enhances lysine and tryptophan contents in the endosperm, offered new opportunities for the use of this maize in human nutrition. However, the softness of the endosperm was one of the factors attributed to the high susceptibility of the *opaque2* maize to the stored grain pest (Ortega *et al.*, 1975; Bjarnason and Vasal, 1992). The kernel vitreousness or texture of the *o2* maize was later improved by introgression of genetic endosperm modifiers, leading to the development of 'quality protein maize', popularly known as QPM (Bjarnason and Vasal, 1992; Prasanna *et al.*, 2001). The QPM genotypes were reported to be as resistant to the stored grain weevil *S. zeamais* as the best checks (Bjarnason and Vasal, 1992). Santos *et al.* (1996) analysed the genetic variability in QPM lines developed in Brazil for resistance to the stored grain weevil *S. zeamais*, and identified 8 QPM inbred lines out of 31 maize entries, with performance comparable to that of the resistant check, Cateto-SL.

Although some studies were carried out on the responses of maize genotypes, including QPM, to *S. zeamais*, there are no published reports on the genetic variability in elite QPM germplasm for resistance to *S. oryzae*. The present study was undertaken to evaluate the performance of the Indian and CIMMYT QPM inbred lines to infestation by *S. oryzae*, relative to selected non-QPM inbred lines and hybrids in the public domain. We also compared grain quality (protein and tryptophan contents) and kernel texture with susceptibility of maize genotypes to grain weevil infestation to identify if there is any relationship between these traits.

Materials and methods

Genetic materials

To analyse the genetic variability in QPM genotypes for their responses to the stored grain weevil *S. oryzae*, a set of 14 QPM inbred lines developed and maintained in India, and 10 QPM lines developed at CIMMYT, Mexico were selected on the basis of kernel colour (yellow), texture and flint type. In addition, two popular QPM hybrids in India, Shaktiman-1 and Shaktiman-2, were also selected for the study (Table 1). To compare the performance of the QPM genotypes with

Table 1. Pedigree and grain type of the QPM and non-QPM genotypes analysed in the study

Genotypes	Pedigree	Grain type
QPM inbred lines		
DMRQPM-17-1	28 full sib families (MS) 6 HECC Bulk-1	YF
DMRQPM-17-4	28 full sib families (MS) 6 HECC Bulk-4	YF
DMRQPM-28-3	Shakti (SO) HE 25 # CC Bulk 50% f-#-⊗-1-3-4 ⊗ BB-3	YF
DMRQPM-28-5	Shakti (SO) HE 25 # CC Bulk 50% f-#-⊗-1-3-4 ⊗ BB-5	YF
DMRQPM-45	Rattan SOHS 47 # SO # SN CC 25%-f-###	YF
DMRQPM-56	SN Comp. Bulk SN5 CC Bulk ⊗-12-1-BB	YF
DMRQPM-58	SN Comp. Bulk 2 Bulk SN5 CC Bulk ⊗-16-4-BB	YF
DMRQPM-60	28 full sib families (MS) 6 HECC Bulk ⊗-15-1-BB	YF
DMRQPM-65	SO/SN Comp. Category 'O' ⊗-1-1-B-B	YF
DMRQPM-401	28 full sib families (MS) 6 HECC Bulk ⊗-1-4-BBBB	YF
DMRQPM-402	28 full sib families (MS) 6 HECC Bulk 2 ⊗-16-4-BBBB	YF
DMRQPM-403	Shakti SO/SN HE 25 # CC Bulk 50% f-#-#-10-3-B-1-B	YF
DMRQPM-404	SO/SN Comp Bulk 2 Bulk SN5 CC Bulk 2⊗-16-4-BBBB	YF
Tuxpeno Carrib.	Tuxpeno Carrib HE/o2 -f-#-#-⊗-4-⊗	YF
CML142	Pob62c5HC93-5-6-1-3-B-B-B-7-B-B-#	WF
CML150	G24QMH169-2-1-B-3-1-1-B-B-3-B-#-#-B	WF
CML166	Pob66c1HC215-4-1-2-B-B-2-B-B-B	YF
CML167	G25QSINT-37-3-2-2-B-B	YF
CML169	G26Qc22MH7-1-1-1-1-B-B	YF
CML171	G25QS4B-MH13-5-B-1-1-2-B-1-B-B-B	YF
CML172	G25QS4B-MH35-2-B-1-1-2-B-4-B-B-B-B	YF
CML176	(P63-12-2-1/P67-5-1-1)-1-2-B-B	WF
CML186	Pob67C2HC26-1-2-1-B-B	WF
CML189	G34QMH17-2-1-1-B	YF
Non-QPM inbred lines		
CM139	(Tarun × MS 1)-Y63	YF
CM140	J 617-61	YF
LM5	Tux. Pool C2 I C2	YF
LM6	MS Pool C2 I C2-5	YF
QPM hybrids		
Shaktiman-1	(CML142 × CML150) × CML186	WF
Shaktiman-2	CML176 × CML186	WF
Non-QPM hybrids		
PEHM1	CM135 × CM136	YF
PEHM2	CM137 × CM138	YF
PEHM3	CM213 × CM143	YF
Checks		
Surya (resistant)	Composite	YF
Basi local (susceptible)	Landrace from Rajasthan state in India	YF

Y, yellow; W, white; F, flint.

the non-QPM genotypes, four non-QPM inbred lines developed by the national maize breeding programme, namely LM5 and LM6 (parental lines of a single-cross hybrid Paras), and CM139 and CM140 (parental lines of a single-cross hybrid Parkash) and three popular early-maturing non-QPM hybrids (PEHM-1, PEHM-2 and PEHM-3) were also evaluated. Basi local, a maize landrace from Rajasthan state in India, and Surya (composite) were included in the study as the susceptible and resistant checks, respectively. Seeds of the test genotypes under the present study were generated by controlled pollinations during *kharif* (rainy season) 2003 at the Indian Agricultural Research Institute (IARI) Experimental Farm, New Delhi. The resultant seeds of the inbred lines, the F_2 generation seeds harvested from the F_1 plants of the commercial hybrids, along with the checks (Basi local and Surya) were tested for grain weevil resistance as well as for grain quality and kernel texture.

Screening for grain weevil resistance

The experiment was undertaken in the Maize Entomology Laboratory, Directorate of Maize Research, New Delhi, in a completely randomized design with three replications. Twenty chemically untreated sound grains (for each replication for each entry) were sterilized at 60 °C in a hot air oven for 4 h. After cooling, the grains were wrapped in a muslin cloth (fine cotton cloth) and kept in desiccators with a relative humidity of 70 ± 2%, maintained by using potassium hydroxide solution for 15 days (Solomon, 1951) to bring grain moisture content down to ≥14%.

The initial weight of the conditioned kernels of each entry was noted, and the kernels were transferred to individual plastic Petri plates with four holes in the upper lid to allow ventilation. A stock culture of *S. oryzae* was maintained on Basi local (susceptible check). Seven-day-old adult insects were examined under the microscope to identify male and female insects, as per the procedure given by Halstead (1963). Six pairs of the adult *S. oryzae* were released in each Petri plate containing the maize grains of the test entry, and were allowed to mate. After 7 days of incubation, the released parental insect pairs were carefully taken out and transferred to a BOD incubator maintained at 29 ± 1 °C and 70 ± 2% RH. After 45 days of incubation, the number of visible insect progenies were counted and removed from each Petri plate on every alternate day for a period of 30 days. After this period, the cleaned infested kernels were again weighed to estimate the kernel weight loss due to insect infestation. The total number of insect progeny per entry was determined, and the kernel weight loss was calculated by deducting the final weight of the infected kernels from the initial weight of the conditioned kernels.

Analyses of endosperm protein quality and kernel texture

To ascertain the possible influence of better endosperm protein quality (higher lysine and tryptophan content) in the QPM genotypes on the level of resistance/susceptibility of the QPM grains to *S. oryzae*, the endosperm protein content was estimated using the Micro-Kjeldahl Procedure (AOAC, 1965) and the tryptophan content in the endosperm protein was estimated by colorimetric method (Hernandez and Bates, 1969).

Kernel modification (more appropriately, endosperm modification) of the QPM genotypes was rated in the present study using a procedure suggested by Bjarnason and Vasal (1992). Backlit kernels were rated on a scale of 1–5, with 1 indicating 100% normal (vitreous), 2 indicating 25% opaque, 3 indicating 50% opaque, 4 indicating 75% opaque and 5 indicating 100% opaque. Mean kernel modification scores were derived based on evaluation of 100 randomly selected kernels from the ears of each genotype obtained through controlled pollination (bulk sibbing).

Statistical analyses

Angular transformation of % kernel weight loss values was carried out as per the procedure given by Bliss (1937). ANOVA was carried out to determine the significance of differences among the genotypes for each of the characters under study. Least Significant Difference (LSD) was used to compare the mean values and for ranking the genotypes based on the level of resistance/susceptibility using SAS statistical package.

Cumulative resistance indices (CRI) for the genotypes were computed using LSD ranks for the two attributes (% kernel weight loss and insect multiplication) in accordance with procedure reported by Arunachalam and Bandopadhyay (1984). This method allows a comparison of genotypes using cumulative indices based on simultaneous consideration of a set of characters. If K_1 was the number of groups for character 1 in case of '*n*' characters, the genotypes in the highest ranked group were given a score of K_1/K_1, those in the second ranked group were given a score of $(K_1 - 1)/K_1$ and those in the last ranked group were given a score of $1/K_1$. For the nth character, group scoring would be K_n/K_n, $(K_{n-1})/K_n$,..., $1/K_n$, respectively. The individual scores thus obtained for the two characters (% weight loss and insect multiplication) were added to provide a CRI for each genotype.

Correlation coefficients among various attributes, namely endosperm protein content, % tryptophan in endosperm protein, kernel modification, % kernel weight loss (due to weevil infestation) and insect multiplication per entry, were computed and tested for their significance following standard statistical procedure (Gomez and Gomez, 1984).

Results and Discussion

ANOVA on the data of the 24 QPM lines revealed significant variation among the QPM lines for both % kernel weight loss and the number of insect progeny after a fixed period (45 days) of incubation with *S. oryzae*. Among the Indian QPM inbred lines, DMRQPM-60 was found to be the most promising in terms of resistance to the stored grain weevil, with a relatively low kernel weight loss (11.0%), an insect multiplication factor of 5.7 and a highest CRI of 2.00 (Table 2). Among the CIMMYT QPM lines, CML167 showed the highest CRI (1.96; Table 2) with a kernel weight loss of 12.7% and insect multiplication value of 8.7. Both DMRQPM-60 and CML167 exhibited higher CRI values than the resistant check, Surya (non-QPM composite) (Fig. 1). The popular QPM hybrids in India, Shaktiman-1 and Shaktiman-2, were also found to be resistant to grain weevil infestation with CRI comparable to the resistant check. Moderate resistance was exhibited by DMRQPM-28-3, CML189 and CML176 (Table 2). These observations indicate that some QPM genotypes carry gene(s) for resistance to the grain weevil *S. oryzae*, in addition to their enhanced protein quality. However, as many as five QPM lines (DMRQPM-56, DMRQPM-58, Tuxpeno Carribb., CML150 and CML186) were found to be highly susceptible to *S. oryzae* infestation, with CRI values approaching that of the susceptible check, Basi local (Fig. 1).

The resistance of Shaktiman-1 [(CML142 × CML150) × CML186] to *S. oryzae* was also reported recently by Bajracharya and Sharma (2004). Interestingly, the parental lines of the Shaktiman-1 hybrid were found to be susceptible to the weevil infestation with very low CRI values. Shaktiman-2 (CML176 × CML186) also displayed resistance with relatively lower % kernel weight loss and insect multiplication values. CML176, one of the two parental lines of Shaktiman-2, exhibited moderate resistance, while the other parental line, CML186, was found to be highly susceptible. Therefore, the resistance profiles of Shaktiman-1 and Shaktiman-2 may be attributed to the accumulation of favourable genes and/or gene complementation imparting resistance to grain weevil infestation. Although there are some reports of maternal influence on grain weevil resistance in maize (Widstrom *et al.*, 1975; Kang *et al.*, 1995; Derera *et al.*, 2001), this aspect could not be analysed in this study, as the genetic materials used were not experimental hybrids generated from reciprocal crosses.

Eden (1952) found that weevil infestation decreased with an increase in kernel hardness. Ortega *et al.* (1975) and Santos *et al.* (1996) reported severe susceptibility of *opaque2* genotypes to the stored grain weevil attack due to their soft and chalky kernel texture. The QPM lines with their hard kernel texture were reported to be less

Table 2. Mean values for parameters of grain weevil resistance/susceptibility, kernel texture and quality traits in the maize genotypes under study

Genotypes	%KWL	NIP	CRI	KMI	%PrE	%TrPr
DMRQPM-17-1	23.6	29.7	0.95	3.16	11.40	0.79
DMRQPM-17-4	21.6	28.0	1.20	3.22	9.65	0.83
DMRQPM-28-3	19.4	17.0	1.59	1.63	9.75	0.72
DMRQPM-28-5	23.0	29.0	1.04	3.61	9.55	0.94
DMRQPM-45	24.7	24.3	1.05	3.04	10.20	0.69
DMRQPM-56	30.3	43.7	0.35	1.45	8.75	0.80
DMRQPM-58	47.3	30.0	0.29	2.63	11.40	0.79
DMRQPM-60	11.0	5.7	2.00	2.95	9.10	0.77
DMRQPM-65	24.3	22.0	1.23	1.38	9.65	0.83
DMRQPM-401	28.8	32.7	0.55	3.12	7.90	0.89
DMRQPM-402	28.3	37.7	0.52	3.27	10.55	0.85
DMRQPM-403	21.6	24.7	1.28	1.39	10.40	0.77
DMRQPM-404	28.9	36.0	0.51	3.25	9.65	0.73
Tuxpeno Carrib.	31.4	32.0	0.50	1.45	9.60	0.83
CML142	24.4	20.7	1.27	1.17	10.40	0.96
CML150	42.2	28.3	0.46	1.41	8.70	0.92
CML166	28.6	23.7	0.89	1.34	10.65	0.75
CML167	12.7	8.7	1.96	1.20	10.85	0.74
CML169	27.6	20.3	1.12	1.08	9.50	0.84
CML171	26.1	26.7	0.96	1.50	10.70	0.84
CML172	22.4	22.3	1.35	1.23	10.80	0.83
CML176	19.7	15.7	1.62	1.19	7.30	0.96
CML186	31.9	41.3	0.34	1.31	8.20	0.98
CML189	22.9	13.3	1.61	1.30	10.40	0.96
CM139	33.1	40.3	0.30	1.00	9.33	0.32
CM140	31.5	29.0	0.61	1.00	9.23	0.33
LM5	25.5	28.3	0.94	1.00	9.44	0.42
LM6	27.5	21.0	1.13	1.00	9.36	0.32
Shaktiman-1	13.6	11.7	1.88	1.20	9.60	0.94
Shaktiman-2	18.9	14.3	1.71	1.31	9.30	0.97
PEHM1	31.1	28.0	0.68	1.00	9.77	0.31
PEHM2	25.9	28.7	0.90	1.00	9.75	0.41
PEHM3	33.5	23.0	0.59	1.00	9.10	0.33
Surya	18.7	10.7	1.87	1.00	9.50	0.32
Basi local	41.0	59.3	0.12	1.00	9.87	0.41

LSD values: %KWL = 4.27; NIP = 6.10; KMI = 0.11; %PrE = 0.29 and %TrPr = 0.02.

% KWL, % kernel weight loss; NIP, number of insect progeny; CRI, cumulative resistance index; KMI, kernel modification index; %PrE, % protein in endosperm; %TrPr, % tryptophan in endosperm protein.

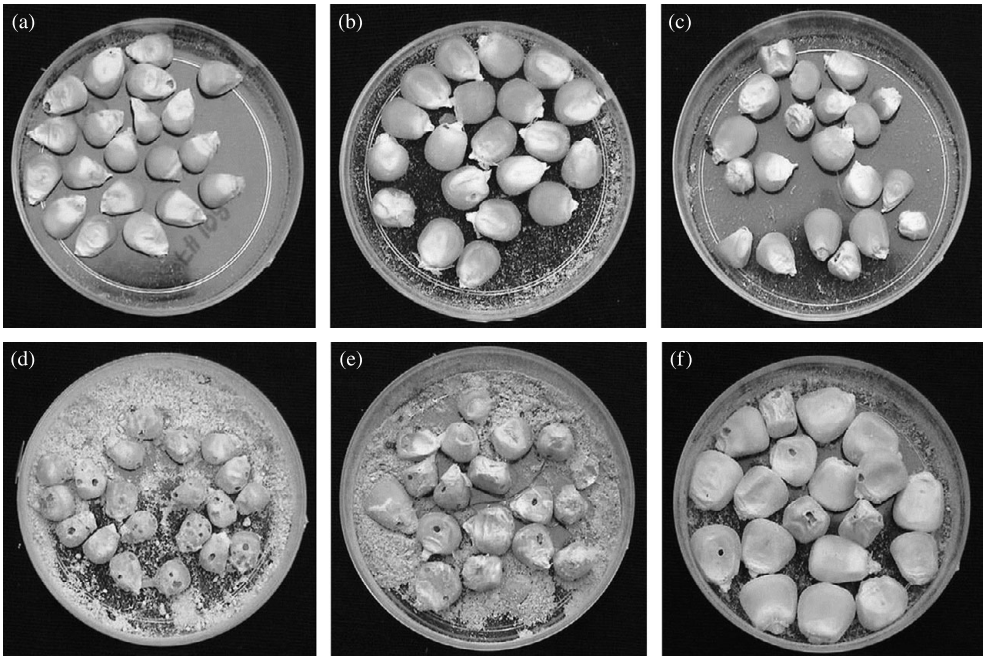

Fig. 1. Differential responses of the maize genotypes to the stored grain weevil (*Sitophilus oryzae*) infestation (a) DMRQPM-60; (b) CML167; (c) Surya (resistant check); (d) DMRQPM-58; (e) Basi local (susceptible check) and (f) Shaktiman-1

preferred by the stored grain weevil than those with only the *o2* gene. Being internal feeders, both larvae and adult insects consume the soft endosperm more quickly than the hard endosperm. Due to the segregation of endosperm modifier genes, many of the QPM genotypes under study showed variable degree of endosperm softness/hardness. Therefore, if kernel hardness *per se* contributes to the resistance to stored grain weevil infestation, the non-QPM genotypes with 100% hard endosperm should show resistance. Interestingly, the non-QPM hybrids (PEHM-1, PEHM-2 and PEHM-3) as well as the non-QPM inbred lines (CM140, CM139, LM5 and LM6) analysed in this study were found to be as vulnerable to stored grain weevil infestation as the QPM genotypes (Table 2).

Among the QPM inbred lines, DMRQPM-56 showed very low kernel modification index or KMI (1.45) indicating high kernel vitreousness; however, the genotype was found to be extremely susceptible to weevil infestation, with a very low CRI (0.35) comparable to that of the susceptible check, Basi local. In contrast, DMRQPM-28-5 showed a moderate CRI (1.04) although the genotype displayed a higher degree of kernel opaqueness (KMI = 3.61) when compared with DMRQPM-56 (Table 2). Among the QPM lines analysed, CML167 revealed a high CRI (1.96) coupled with good kernel texture (KMI = 1.20). The kernel vitreousness in case of DMRQPM-60 was moderate (KMI = 2.95), although the genotype was highly resistant to weevil infestation, with a CRI of 2.00. Furthermore, the correlations of kernel modification with % kernel weight loss due to weevil infestation ($r = -0.06$) and insect multiplication ($r = 0.11$) were both found to be non-significant (Table 3). This clearly suggests that kernel texture *per se* is not the sole factor influencing the susceptibility of a QPM genotype to grain weevil infestation. Arnason *et al.* (1993) and Santos *et al.* (1996) also concluded that the QPM genotypes were not necessarily more or less susceptible to *S. zeamais* damage than normal maize. The results obtained in this study highlight the need for genetic enhancement of

Table 3. Pearson correlation coefficients of kernel modification index, % endosperm protein and % tryptophan in endosperm protein with % weight loss and insect multiplication

	%KWL	NIP
KMI	− 0.06	0.11
%PrE	− 0.01	− 0.08
%TrPr	− 0.23	− 0.18

% KWL, % kernel weight loss; NIP, number of insect progeny; KMI, kernel modification index; %PrE, % protein in endosperm; %TrPr, % tryptophan in endosperm protein.

resistance to stored grain weevil in QPM as well as the non-QPM germplasm.

The endosperm protein content in some of the QPM inbred lines, namely DMRQPM-17-1 (11.40%), DMRQPM-45 (10.20%), DMRQPM-58 (11.40%), DMRQPM-402 (10.55%), DMRQPM-403 (10.40%), CML166 (10.65%), CML167 (10.85%), CML171 (10.70%), CML172 (10.80%) and CML189 (10.40%) was higher than other QPM/non-QPM genotypes under study. However, *t*-test revealed that the difference in endosperm protein content among the QPM genotypes, in general, as compared with the non-QPM genotypes, was non-significant. The correlation of endosperm protein with kernel weight loss due to weevil infestation ($r = -0.01$) and insect multiplication ($r = -0.08$) was non-significant (Table 3). Likewise, there were no significant positive correlations between tryptophan in endosperm protein with kernel weight loss ($r = -0.23$) and insect multiplication ($r = -0.18$) (Table 3). These observations, therefore, discount the possibility of endosperm protein content or its quality being key factors influencing the susceptibility/resistance of the QPM genotypes to the weevil.

A combination of several other factors may be responsible for the susceptibility of maize genotypes to weevil infestation. During kernel infestation, the weevils scoop out a portion of the pericarp and lay eggs beneath it. Thus, the thickness of the pericarp, a maternal tissue, was suggested as an important factor influencing the resistance of maize genotypes to grain weevils (Schoonhoven *et al.*, 1972; Tipping *et al.*, 1988; Lara *et al.*, 2004). Another possible factor contributing to the resistance could be the presence of certain metabolites in the endosperm, which might hinder weevil growth and multiplication. Singh and McCain (1963) analysed kernels of 10 maize hybrids (ranging from susceptible to resistant to weevils) for sugar, starch, fat and protein, along with kernel hardness, and concluded that sugar content and kernel hardness were important factors for resistance to the weevil after removal of the husk. Singh *et al.* (1973) suggested that the levels of uric acid and free fatty acids were directly correlated with the infestation, with the susceptible varieties containing more uric acid than the resistant ones. Lara *et al.* (2004) suggested that phenolics in the kernels might play an important role in imparting resistance to the stored grain insect pests. Thus, there is a distinct need for empirical data gathering and intensive analysis on the biochemical basis of resistance to stored grain insect pests.

Widstrom *et al.* (1975) studied the inheritance of resistance to the maize weevil *S. zeamais* and reported that the dominance effects of maternal and endosperm genotypes were important, while the cytoplasmic effects were non-significant. The resistant QPM inbred lines, DMRQPM-60 and CML167, identified in the present study could aid in undertaking systematic genetic analyses of resistance to the stored grain weevil *S. oryzae*.

Conclusions

The present study highlights the need for further genetic enhancement of QPM (as well as non-QPM germplasm) for resistance to stored grain weevil *S. oryzae*. It may be possible to accomplish this through selection procedures, since this trait was not selected during the normal QPM breeding activities. Identification of QPM lines resistant to *S. oryzae* in the present study offers an opportunity to breed for resistance to this weevil in these genotypes.

Acknowledgements

The authors are grateful to Drs N. N. Singh and S. B. Singh (DMR, New Delhi), Dr Ganesan Srinivasan (former Associate Director, Maize Program, CIMMYT, Mexico) and Dr Ashish Srivastava (CIMMYT-India Maize Program) for providing the seed materials of DMRQPM and CIMMYT QPM lines, respectively, and to Dr Rajesh Kumar (Division of Genetics, IARI) for his technical assistance.

References

AOAC (1965) *Official Methods of Analysis of the Association of Official Agricultural Chemists*. 10th edn. 868 pp.

Arnason J. T., Baum B., Gale J., Lambert J. D. H., Bergvinson D., Philogene B. J. R., Serratos J. A., Mihm J. and Jewell D. C. (1994) Variation in resistance of Mexican landraces of maize to maize weevil *Sitophilus zeamais* in relation to taxonomic and biochemical parameters. *Euphytica* 74, 227–236.

Arnason J. T., Lambert J. D. H., Gale J., Mihm J., Bjarnason M., Jewell D. C., Serratos J. A., Fregeau-Reid J. and Pietrzak L. (1993) Is quality protein maize more susceptible than the normal lines to attack by maize weevil, *Sitophilus zeamais*? *Postharvest Biology and Technology* 2, 349–358.

Arunachalam V. and Bandopadhyay A. (1984) A method to take decisions jointly on a number of different characters. *Indian Journal of Genetics and Plant Breeding* 43, 419–424.

Bajracharya A. S. R. and Sharma R. K. (2004) Interspecific competition for losses and population build-up of *Sitophilus oryzae* (L.) and *Rhyzopertha dominica* (F.) in stored maize, pp. 310–313. In *Proceedings of the 1st KMITL International Conference on Integration of Science and Technology for Sustainable Development*, vol. 2, King Mongkut Institute of Technology, Ladkrabang, Thailand.

Bjarnason M. and Vasal S. K. (1992) Breeding of quality protein maize (QPM). *Plant Breeding Reviews* 9, 181–216.

Bliss C. I. (1937) Analysis of field experimental data expressed in percentage. *Plant Protection* 12, 67–77.

Derera J., Pixley K. V. and Giga D. P. (1999) Inheritance of maize weevil resistance in maize hybrids among maize lines from southern Africa, Mexico and CIMMYT-Zimbabwe, pp. 24–27. In *Maize Technologies for the Future: Challenges and Opportunities.* Proceedings of the 6th Eastern and Southern Africa Regional Maize Conference, Addis Ababa, Ethiopia, 21–25 September 1998. CIMMYT, Harare, Zimbabwe.

Derera J., Pixley K. V. and Giga D. P. (2001) Resistance of maize to the maize weevil. I. Antibiosis. *African Crop Science Journal* 9, 431–440.

Dhliwayo T., Pixley K. V. and Kazembe V. (2005) Combining ability for resistance to maize weevil among 14 southern African maize inbred lines. *Crop Science* 45, 662–667.

Eden W. G. (1952) Effect of kernel characteristics and components of husk cover on rice weevil damage to corn. *Journal of Economic Entomology* 45, 1084–1085.

Giga D. P., Mutemererwa S., Moyo G. and Neeley D. (1991) Assessment and control of losses caused by insect pests in small farmers' stores in Zimbabwe. *Crop Protection* 10, 287–292.

Golob P. (1984) Improvement in maize storage for the smallholder farmer. *Tropical Stored Products Information* 50, 14–19.

Gomez K. A. and Gomez A. A. (1984) *Statistical Methods for Agricultural Research*. John Wiley and Sons, New York, 680 pp.

Halstead D. G. (1963) External sex differences in stored product Coleoptera. *Bulletin of Entomological Research* 54, 199–210.

Hernandez H. H. and Bates L. S. (1969) A modified method for rapid tryptophan analysis of maize. *CIMMYT Research Bulletin* No. 13, CIMMYT, Mexico.

Kang M. S., Zhang Y. and Magari R. (1995) Combining ability for maize weevil preference of maize grain. *Crop Science* 35, 1556–1559.

Kim S. K., Brewbaker J. L. and Hallauer A. R. (1988) Insect and disease resistance from tropical maize for use in temperate zone hybrids, pp. 194–226. In *Proceedings of the 43rd Annual Corn/Sorghum Research Conference*, American Seed Trade Association, Washington DC, USA.

Kurdikeri M. B., Aswathaiah S., Rajendraprasad S., Katgal R. D. and Aswathanarayana S. C. (1993) Studies on relative kernel damage, loss in weight and loss of viability caused by *Sitophilus oryzae* (Linn.) and *Rhyzopertha dominica* (Fabr.) in maize hybrids. *Seed Research* 21, 72–77.

Lara S. G., Bergvinson D. J., Burt A. J., Ramputh A. I., Pontones D. M. D. and Arnason J. T. (2004) The role of pericarp cell wall components in maize weevil resistance. *Crop Science* 44, 1546–1552.

Mookherjee M. G., Jotwani M. G., Sircar P. and Yadav T. D. (1968) Studies on the incidence and extent of damage due to insect pests in stored seeds. *Indian Journal of Entomology* 30, 61–65.

Mutiro C. F., Giga D. P. and Chetsanga P. (1992) Post-harvest damage in small farmers' stores. *Zimbabwe Journal of Agricultural Research* 30, 49–59.

Ortega A., De Leon C., Granados G. and Vasal S. K. (1975) Disease-insect interactions in quality protein maize, pp. 173–192. In *High Quality Protein Maize* (Edited by L. F. Bauman). Hutchinson Ross Publishing Co., Stroudsburg, PA, USA.

Painter R. H. (1968) *Insect Resistance in Crop Plants*. The University Press of Kansas, Lawrence, USA.

Perez-Mendoza J. (1999) Survey of insecticide resistance in Mexican populations of maize weevil *Sitophilus zeamais* Motschulsky (Coleoptera: Curculionidae). *Journal of Stored Product Research* 34, 107–115.

Pingali P. L. and Pandey S. (2001) Meeting world maize needs: Technology opportunities and priorities for the public sector, In *CIMMYT (1999–2000). World Maize Facts and Trends* (Edited by P. L. Pingali). CIMMYT, Mexico.

Prasanna B. M., Vasal S. K., Kassahun B. and Singh N. N. (2001) Quality protein maize. *Current Science* 81, 1308–1319.

Santos J. P., Guimaraes P. E. O., Waquil J. M. and Foster J. E. (1996) Resistance to maize weevil in quality protein maize lines and commercial corn hybrids. *Resistant Pest Management* 8, 52–54.

Schoonhoven A. V., Horber E., Mills R. B. and Wassom C. E. (1972) Resistance in corn kernels to the maize weevil *Sitophilus zeamais* Motsch. *Proceedings of the North Central Branch of the Entomological Society of America* 27, 108–110.

Sharma R. K. (2000) Studies on relative resistance of some maize varieties to *Sitophilus oryzae*. *Annals of Agricultural Research* 21, 145–147.

Singh D. N. and McCain F. S. (1963) The relationship of some nutritional properties of the corn kernel to rice weevil infestation. *Crop Science* 3, 259–261.

Singh K., Agrawal N. S. and Girish G. K. (1973) Studies on the susceptibility of high-yielding varieties of maize to *Sitophilus oryzae* (Linn.) (Coleoptera: Curculionidae) and *Trogoderma granarium* Everts (Coleoptera: Dermestidae). *Bulletin of Grain Technology* 11, 198–202.

Solomon M. E. (1951) Control of humidity with potassium hydroxide, sulphuric acid or other solutions. *Bulletin of Entomological Research* 42, 543–554.

Tipping P. W., Rodriguez J. G., Poneleit C. G. and Legg D. E. (1988) Resistance of dent corn inbreds to oviposition by the maize weevil. *Journal of the Kansas Entomological Society* 61, 131–134.

Vaidya D. N., Ramesh L. and Lal R. (2001) Seasonal infestation of maize grain stores in District Kangra (Himachal Pradesh). *Insect Environment* 7, 33–34.

Widstrom N. W., Hanson W. D. and Redlinger L. M. (1975) Inheritance of maize weevil resistance in maize. *Crop Science* 15, 467–470.