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Seed Quality of Maize Inbred Lines with Different Composition and Genetic Backgrounds

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ABSTRACT

By introgressing exotic germplasm into elite maize in the USA, breeders have developed lines with wider variability for seed oil and protein contents than in U.S. adapted lines. Seed quality of these introgressed lines has not been evaluated. The objectives of the study were (i) to characterize introgressed inbred lines for seed quality, (ii) to assess the effects of oil and protein contents on seed quality, and (iii) to determine whether the interaction between genetic background and production location was significant. The lines used in the study were developed by crossing elite lines of Stiff Stalk and non-Stiff Stalk heterotic background with St. Croix and Argentina germplasm. They were grown at four locations of the U.S. Corn Belt. Seed quality was measured by standard germination test, a series of vigor tests, and an inbred quality index. Genotype × location interactions were significant. Genotypic differences were observed for all the traits measured within each location. Seed composition and genetic background did not affect germination, however production location did. Standard germination ranged from 56 to 93% in Iowa, 48 to 89% in Missouri, 53 to 91% in Illinois, and 52 to 89% in Nebraska. High protein inbred lines had a saturated cold test of 64%, averaged across locations, while the low protein line averaged 49%. Inbred lines with St. Croix background and lines produced in colder locations (Iowa and Nebraska) had high cold test percentage. Inbred lines with St. Croix background, all having low oil contents, had the lowest accelerated aging test results (49%), whereas inbred lines with Argentina background had the highest (65%). The low protein inbred line had low accelerated aging results (49%), whereas high protein inbred lines averaged 62%. Because seed composition affects seed quality of the inbred, it is important that breeders evaluate new germplasm for seed quality early in the breeding program.

The demand for more nutritious and abundant food and feed is leading breeders to search for desirable characteristics in a wide range of exotic germplasm (Vasal and McLean, 1994). It is important to look at exotic germplasm because there is not much variability for these nutritional traits in elite U.S. germplasm (Dunlap et al., 1995; Pollak, 2002; Salhuana et al., 1998). Maize breeders have evaluated exotic germplasm for desirable agronomic and quality traits (Brun and Dudley, 1989; Pollak, 1993; Salhuana et al., 1998). However, seed quality is usually not one of the selection criteria.

Seed scientists are concerned that breeders do not evaluate seed quality characteristics in their breeding programs (Burris, 2000). It is essential for producers that the improvement of the nutritional value of maize is not done at the expense of seed quality. Seed quality is one of the most important factors affecting early performance and productivity of most agricultural crops. Exotic germplasm may have seed quality traits that differ from locally adapted germplasm. The Germplasm Enhancement of Maize project (GEM), a cooperative breeding project between the public and private corn breeding sectors led by USDA-ARS (Pollak, 2002), is introgressing exotic germplasm into commercial breeding materials, so it may be important to test these lines for seed quality before a problem arises that would negatively affect GEM. The objectives of this study were to characterize 10 inbred lines derived from GEM breeding crosses for physiological seed quality, to assess the effects of oil and protein contents on seed quality, and to determine whether the interaction between genetic background and production location was significant.

MATERIALS AND METHODS

Seed Production

The inbred lines used in this study are listed in Table 1. Eight inbred lines were developed by crossing elite lines of Stiff Stalk or non-Stiff Stalk heterotic pattern with Argentina (representing temperate) or St. Croix (representing tropical) germplasm. Two additional lines were public inbred checks, B73 and Mo17. Seeds were planted at four locations during the 2001 growing season in a randomized complete block design with two replications. Locations were the Agronomy and Agricultural Engineering farm, Iowa State University, near Ames, and farms located near Columbia, MO, Clinton, IL, and Hooper, NE. Soils at the Ames location are Clarion and Webster loam. Clarion is a mesic Typic Haplusdoll and Webster a mesic Typic Endoaquoll, formed in loamy glacial till and glacial sediments, moderately drained and permeable. Soils at the Columbia location are Freeburg silt loam, a mesic Aquic Hapludalf formed in silty alluvial sediments, very deep, somewhat poorly drained and moderately permeable. The Clinton farm has two closely related soils, Ipava silty loam (43%) and Sable silty clay loam (68%). Ipava is a mesic Aquic Argiudoll, a very deep, somewhat poorly drained and moderately permeable soil formed in loess upland. Sable is a mesic Typic Endoaquoll, a very deep, poorly drained and moderately permeable soil formed in loess on nearly leveled summits of moraines and stream terraces. Soil at Hooper is a Moody silty clay, a mesic Udic Haplustoll, very deep, well drained soil formed in loess uplands. Seeds were produced under normal seed production practices of cultivation, insect and soil fertility management. Precipitation and growing degree days (GDD) data are in Table 2. Growing degree days were calculated by the formula GDD = [(minimum temperature + maximum temperature) $\times 2^{-1}$] – 10°C. If maximum temperature >30°C, then maximum temperature = 30°C. If minimum temperature <10°C, then minimum temperature = 10°C. Plants were self-pollinated to maintain genetic integrity. In all locations, seeds were bulked because of limited seed supply.

Seeds were harvested at a seed moisture concentration of

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about 300 g kg^{-1}, which was approximately physiological maturity as determined by black layer formation. Husks were then removed and ears were dried with ambient forced air. At 130 g kg^{-1} moisture content, ears were shelled with a laboratory sheller (model LS91, Custom Seed Equipment, Altoona, IA). Seeds were stored 30 to 90 d in a cold room at 10°C and 50% RH until laboratory analyses were performed.

Seed Quality Determination

Several tests were conducted to assess seed quality. The seed industry uses the standard germination test (AOSA, 2002) for labeling. It estimates germination under ideal growing conditions. Five additional tests were used to assess seed vigor. These tests were also used to calculate the Inbred Quality Index (IQI) as described below (Hoegemeyer and Gutormsen, 2000).

Standard Germination Test

Seeds were placed on moistened crepe cellular paper and incubated at 20/30°C, with 16 h of darkness and 8 h of light, for 7 d. Seedlings were classified as normal, abnormal, or dead (AOSA, 2002).

Saturated Cold Test

A plastic grid rack of 60 by 40 cm was placed in a 61- by 41- by 5-cm tray. A single germination paper towel of 60 by 30 cm was wrapped over the plastic grid rack and two additional paper towels were placed on top. One liter of tap water was poured on the paper towels and allowed to soak through into the tray. Excess water was sufficient to keep the paper towels and soil saturated throughout the test. Sandy loam soil sifted through a 70-mm sieve was sprinkled over the paper towels to form a thin layer. Seeds were planted on top of the soil with their embryos oriented down. Tests were conducted in a dark cold room at 10°C for 7 d, and then moved to 25°C for 3 d with continuous light. Seedlings were evaluated following AOSA rules (2002).

Accelerated Aging (AA) Test

Seeds were placed on top of the screen inside AA boxes, each 10 by 10 by 4 cm, and 40 mL of tap water were added. Boxes were covered and placed in an AA chamber at 42°C for 96 h. Seeds were weighed before and after being placed in the chamber to calculate seed moisture increase during aging. Seeds were planted in crepe cellulose paper and covered with sand. Seedlings were evaluated after 7 d according to AOSA rules (2002).

Table 1. Entry number, seed composition, and genotype description of the inbred lines used in the study.

Entry	Seed composition†	Genotype‡
1	HP-LO	SCR01:N1310-378-11-1-1-7-3-B
2	HP-LO	SCR01:N1310-378-11-1-1-4-4-B
3	HP-LO	AR16035:S02-235-1-1-6-4-7-B
4	HP-LO	AR16035:S02-235-1-1-6-6-11-B
5	LP-LO	SCR01:N1310-338-31-6-2-1-6-B
6	HP-HO	AR16035:S02-235-1-1-6-6-3-B
7	HP-HO	AR16035:S02-235-1-1-6-3-13-B
8	HP-LO	AR16035:S02-235-1-1-6-3-9-B
Check§		B73
Check		Mo17

† The following values (dry matter basis) for the lines are selection criteria during line development: LP, low protein (90–110 mg g^{-1}); HP, high protein (158–170 mg g^{-1}); LO, low oil (25–30 mg g^{-1}); HO, high oil (58–70 mg g^{-1}).

‡ SCR01, St. Croix 1 (population collected from St. Croix denoted as '1'); AR16035, ARZM 16035 (population collected from Argentina denoted as '16035'); S denotes that AR16035 was crossed to a line of the Stiff Stalk heterotic pattern from a company coded as '02'; N denotes that SCR01 was crossed to two lines of the non-Stiff Stalk heterotic pattern from companies coded as '13' and '10'.

§ The following mean values (dry matter basis) for the check lines are from seed grown in the same nurseries as above: B73 protein (125 mg g^{-1}), oil (37 mg g^{-1}); Mo17 protein (120 mg g^{-1}), oil (37 mg g^{-1}).

Soak Test

Seeds were soaked in 25 mL of tap water for 24 h. Then seeds were planted in a standard germination test (AOSA, 2002).

Electrical Conductivity (EC)

Electrical conductivity was measured with the Individual Seed Analyzer, Genesis-2000 (Wavefront, Inc., Ann Arbor, MI). Mean conductivity of three replicates of 25 seeds each was used to calculate IQI. Individual seeds were soaked in 3.75 mL deionized water at 23°C. Electrical conductivity of

Table 2. Precipitation and growing degree days (GDD) for the four experimental locations.

		Month						
Location	Parameter	May	June	July	August	September	October	Total
Ames, IA	Precip. (mm)†	174	42	43	64	134	57	514
	GDD_{10}‡	196	323	425	374	204	107	1629
	Temp. Max. (°C)§	21	27	30	28	22	16	
	Temp. Min. (°C)¶	11	15	19	17	10	4	
Columbia, MO	Precip. (mm)	162	133	59	82	77	103	616
	GDD_{10}	268	348	459	433	278	114	1900
	Temp. Max. (°C)	24	27	32	31	25	16	
	Temp. Min. (°C)	13	16	20	19	13	6	
Clinton, IL	Precip. (mm)	100	80	27	143	72	165	587
	GDD_{10}	252	338	427	371	231	146	1765
	Temp. Max. (°C)	24	27	30	30	25	17	
	Temp. Min. (°C)	11	15	18	18	12	6	
Hooper, NE	Precip. (mm)	264	109	177	67	93	22	732
	GDD_{10}	228	333	450	402	243	131	1787
	Temp. Max. (°C)	23	26	31	30	24	18	
	Temp. Min. (°C)	12	15	20	18	11	4	

† Precip. (mm): precipitation in millimeters

‡ GDD_{10}: growing degree days in degrees Celsius = [(minimum temperature + maximum temperature) $\times 2^{-1}$] − 10°C. If maximum temperature is >30°C, then maximum temperature = 30°C. If minimum temperature is <10°C, then minimum temperature = 10°C.

§ Temp. Max. (°C): average maximum temperature in °C.

¶ Temp. Min. (°C): average minimum temperature in °C.

the water was measured after 6 and 24 h. Conductivity was recorded in microsiemens per centimeter ($\mu S\ cm^{-1}$)(AOSA, 1983).

Fast Green Test

Seeds were submerged in fast green solution for 15 to 30 s, rinsed under running tap water, and air-dried. Staining patterns were used to classify seed damage (Koehler, 1957). The percentage seeds with no or very light damage was used to calculate IQI.

Inbred Quality Index

The inbred quality index (Hoegemeyer and Gutormsen, 2000) for each line was calculated as

$$IQI = SC + AA + FGN + Soak + [200 - (EC6h + EC24h)]\ 60^{-1},$$

where SC = saturated cold test, %; AA = accelerated aging test, %; FGN = seeds with light or no damage in the fast green test, %; Soak = soak test, %; EC6h = electrical conductivity at 6 h $\mu S\ cm^{-1}\ g^{-1}$ seed; and EC24h = Electrical conductivity at 24 h, $\mu S\ cm^{-1}\ g^{-1}$ seed. The IQI values range from 1 (worst) to 10 (best) (Hoegemeyer and Gutormsen, 2000).

Statistical Analysis

Laboratory tests were conducted in a completely random design. Data were analyzed as a two-way factorial with location and genotype as factors. Tests were repeated three times. Analysis of variance was determined by general linear model procedures in Statistical Analysis System (SAS Institute, Inc., 1990). Genotype × location effects were highly significant for all seed quality measurements. Mean separation was conducted within location using LSD. Inbred lines used in this experiment were partially selected for differences in oil and protein contents during their development. Initial oil and protein contents of these lines at planting were used to subdivide inbred lines into groups of high and low protein and oil. Because genotype × location interaction was significant at the 0.05 probability level for protein content but not for oil content, lines were grouped by composition and genotype, and calculated contrasts determined by least significant difference were used to differentiate among seed composition and genotype.

RESULTS AND DISCUSSION

Standard Germination

Location of seed production interacted significantly with inbred lines, thus results are presented by location (Table 3). Growing locations were chosen to provide very different environments, because factors such as soil, temperature, and moisture could affect seed quality. Germination of B73 was highest when seed were produced in locations with cooler climates (IA, IL, and NE), whereas germination of Mo17 was highest in the warmest location (MO). Germination of Mo17 seed produced in IL was also high, although average minimum temperatures during seed development and maturation in IL were similar to those in IA and NE. Burris (1977) reported that differences in growing season, such as temperature and moisture affected seed quality. The reduction in quality observed was attributed to an interaction between seed maturation and environment. Genotypes that are not adapted to the growing environment might reach critical physiological stages during unfavorable environmental conditions. Seeds of the same genotypes produced at different locations germinated differently. Our findings support earlier reports that cultivars respond differently to environment of production (TeKrony and Hunter, 1995). For example, Inbred 4 had the highest germination in IA, but had one of the lowest in MO. Not all inbred lines responded this way; Inbred 1 had the best germination in IL, but did not significantly differ from the highest germinating line at the other locations. Although both Inbred Lines 1 and 4 were classified as high protein and low oil, seed composition did not significantly affect seed germination according to contrasts between groups of lines with different protein and oil composition (Table 4).

Table 3. Mean standard germination for seeds of 10 inbred lines produced at four locations.

Inbred	Locations			
	IA	MO	IL	NE
	%			
1 HP-LO SC	88	77	91	81
2 HP-LO SC	69	87	89	77
3 HP-LO AR	85	48	88	73
4 HP-LO AR	93	48	75	87
5 LP-LO SC	72	75	89	52
6 HP-HO AR	85	71	53	69
7 HP-HO AR	71	52	83	77
8 HP-LO AR	80	64	77	71
B73	88	69	83	89
Mo17	56	89	84	59
LSD (0.05)	17	18	16	15

We expected genotypic differences within locations because of differences in areas of adaptation for the inbred lines. Our lines included Corn Belt lines (B73 and Mo17), lines introgressed with exotic temperate germplasm from Argentina, and lines introgressed with tropical germplasm from the Caribbean. Inbred 1 germinated well at all locations, but this apparent stability could not be attributed to its St. Croix germplasm because other St. Croix lines performed poorly in IA (Inbred 2) and NE (Inbred 5). Rather, the apparent stability of Inbred 1 seems to come from the ability of St. Croix lines to germinate well in the cooler climates as well as MO. Therefore, it appears that lines with tropical St. Croix germplasm germinate better in the most southern location, which is where we would expect these lines to have better adaptation, but Inbred 1 evidently also gained genetic contribution from its Corn Belt parents to germinate well in the more northern locations. We are also concerned with potential germination problems in the Corn Belt arising from the exotic component of the line, but the Corn Belt Line Mo17 had the lowest germination in seeds produced in IA in our experiment.

Overall, seed produced in IL germinated best. This result could be attributed to abundant precipitation in August, which coincided with seed development, and cooler and drier conditions in September, during seed maturation. Seed produced in MO germinated least. High temperatures during seed development and maturation could have diminished seed quality (Burris, 1977).

Table 4. Statistical significance of contrasts of inbred lines grouped by seed composition and genotype for the following seed quality tests: Standard Germination (Std germ), Saturated Cold Test (Cold Test), Accelerated Aging (AA), Electrical Conductivity (EC), Soak Test (Soak), and Seed Weight (Wt).

Contrasts†	Std germ	Cold Test	AA	EC	Soak	Wt
HPAR vs. HPSC	ns	ns	ns	ns	ns	***
HO vs. LO	ns	ns	ns	ns	**	ns
HOAR vs. LOSC	ns	**	*	ns	***	**
LP vs. HP	ns	*	*	ns	***	***
Mo17 vs. HPSC	ns	ns	*	**	ns	ns
Mo17 vs. LOSC	ns	ns	**	*	***	ns
B73 vs. HPAR	ns	ns	ns	*	ns	ns
B73 vs. HOAR	*	ns	ns	ns	*	ns
Mo17 vs. B73	ns	ns	ns	ns	ns	**

* Significant at $P = 0.05$.
** Significant at $P = 0.01$.
*** Significant at $P = 0.001$.
Nonsignificant (ns) at $P = 0.05$.
† HP, high protein; LP, low protein; HO, high oil; LO, low oil; AR, Argentina background; SC, St. Croix background.

Fenner (1991) reported that timing of any unfavorable temperature regime during the parent's life cycle affects seed germinability of the progeny. High temperature during seed maturation accelerates development at the expense of seed quality (de Carvalho et al., 1999; Miedema, 1982; Pahlavanian and Silk, 1988).

Saturated Cold Test

The concept of seed vigor was developed on the basis of the observation that two seed lots or genotypes with similar viability performed differently under stressful field conditions (Delouche and Baskin, 1973). A vigorous seed lot maintains a rapid and uniform emergence under a broad range of environmental conditions. Several vigor tests were used in this study to evaluate seed quality among genotypes with similar germination percentage.

Significant differences among genotypes were observed for the cold test in each location, but LSDs were large in IA; thus, few significant differences were observed there (Table 5). Illinois had the highest germination values and a number of significant differences among genotypes. For example, three introgressed lines had significantly lower cold test values than B73, and three introgressed lines had significantly greater cold test values than Mo17. Inbred Line 2 had the highest cold test value in all locations except for seeds produced in IA, but still not significantly different from B73, the Corn Belt check with greater cold test values in each location. Although there were no introgressed lines that were significantly higher than B73 at any location, Inbred 2 had greater values than B73 in each location except for IA where it was still not significantly different from B73. Inbred 2, with introgressed tropical St. Croix germplasm, could be useful in breeding for cold tolerance.

Saturated cold test contrasts between different groups of inbred lines differing in seed composition and genetic background showed significant differences between high oil inbred lines containing Argentina germplasm and low oil containing St. Croix germplasm (Table 4). Low oil inbred lines with St. Croix germplasm had germination of 60%, while high oil with Argentina germplasm lines had an average of 65% (data not shown). High protein inbred lines had an average germination of 64%, whereas the low protein line had an average of 49%. In summary, inbred lines with Argentina germplasm and lines with high protein content had high vigor as determined by saturated cold test. Seeds produced in cooler IA and NE also had a greater average cold test than seed produced in warmer MO and IL.

Accelerated Aging

Significant differences among genotypes were observed at all locations except IA (Table 6). Accelerated aging (AA) has been used to predict seed storability (Delouche and Baskin, 1973) and has been widely adopted as a vigor test. Inbred lines with St. Croix germplasm usually had smaller AA values than inbred lines with Argentine background. These results were unexpected because St. Croix has a tropical climate and because we had expected that inbred lines containing tropical germplasm would be better adapted to hot, humid conditions. In the AA test, membrane degradation occurs as a consequence of the oxidation of unsaturated fatty acids (Navari-Izzo and Rascio, 1999). Basavarajappa et al. (1991) associated lipid peroxidation in aged maize seeds with membrane damage. However, differences observed between the groups of inbred lines for accelerated aging may not be explained by differences

Table 5. Means of saturated cold test results for 10 inbred lines produced at four locations.

	Locations			
Inbred†	IA	MO	IL	NE
	%			
1 HP-LO SC	60	37	73	61
2 HP-LO SC	52	73	84	80
3 HP-LO AR	69	55	52	80
4 HP-LO AR	77	53	52	68
5 LP-LO SC	57	37	65	36
6 HP-HO AR	88	43	39	77
7 HP-HO AR	75	51	77	71
8 HP-LO AR	81	59	60	80
B73	71	57	77	59
Mo17	57	65	40	48
LSD(0.05)	32	22	23	24

† HP, high protein; LP, low protein; HO, high oil; LO, low oil; AR, Argentina background; SC, St. Croix background.

Table 6. Accelerated aging means for 10 inbred lines produced at four locations.

	Locations			
Inbred†	IA	MO	IL	NE
	%			
1 HP-LO SC	37	51	77	51
2 HP-LO SC	41	75	67	60
3 HP-LO AR	48	64	93	48
4 HP-LO AR	65	63	56	88
5 LP-LO SC	43	41	77	35
6 HP-HO AR	57	63	63	76
7 HP-HO AR	43	47	87	84
8 HP-LO AR	45	59	67	53
B73	45	68	53	64
Mo17	56	81	89	61
LSD(0.05)	32	22	24	26

† HP, high protein; LP, low protein; HO, high oil; LO, low oil; AR, Argentina background; SC, St. Croix background.

in fatty acid composition of their membranes. Dunlap et al. (1995) evaluated fatty acid composition of oil from exotic maize breeding materials. They reported that oils from exotic maize were slightly more saturated than those of U.S. origin. Leibovitz and Ruckenstein (1983) also reported that maize oil from warmer regions had a greater proportion of saturated fatty acids than those from cooler areas.

Accelerated Aging contrasts between groups of inbred lines showed significant differences (Table 4). Inbred lines with initial low oil content and St. Croix germplasm had the lowest vigor for AA (55%), whereas inbred lines with high oil content of Argentina background had greater vigor (65%). The line with low protein content had low AA of 49%, whereas high protein inbred lines had an average of 62%.

Soak Test

Germination of seeds soaked for 24 h in water correlated directly with maize inbred line sensitivity to flooding (Khosravi and Anderson, 1990). Significant differences between genotypes were observed within locations as determined by LSD (Table 7). Inbred 5 germinated least in all locations. Soak test germination of Inbred 2 was high (72–89%) in all locations. Both Inbreds 2 and 5 are introgressed with St. Croix germplasm, showing that assumptions about seed quality based on the origin of its exotic component should be avoided. Interestingly, of all tested inbred lines, Mo17 germinated best in MO and IL, whereas B73 germinated best in IA and NE. These results could be associated with climatic conditions during seed development and maturation. As mentioned earlier, MO and IL had the highest number of days with temperatures above 30°C (33 and 31 d, respectively) during seed development and maturation. Mo17 is adapted to these warmer conditions and probably attained maximum seed vigor (Knittle and Burris, 1976).

Contrasting groups of lines classified as high and low oil differed significantly (Table 4). Seed from lines with low oil content germinated well in the soak test (76%), whereas high-oil lines did not (57%). Statistical differences between low oil inbred lines from St. Croix and high oil from Argentina were observed. High oil inbred lines from Argentina germinated 66%, whereas seed with low oil from St. Croix germinated only 38%.

Contrasts between high and low protein groups of lines had highly significant differences. The low protein inbred line had the lowest germination of 38%, while high protein inbred lines germinated 75%. Contrasts were made between B73 and the group of inbred lines from Argentina and between Mo17 and the group of inbred lines with St. Croix background (Table 4). Check B73 germinated better than high oil inbred lines with Argentina background, whereas Mo17 germinated better than high oil inbred lines with St. Croix background. The contrast between B73 and high oil inbred lines of Argentina background was significantly different, with 83 and 66%, respectively. Contrasts between Mo17 and low oil inbred lines from St. Croix background also showed highly significant differences. Mo17 had a germination of 79% while low oil lines from St. Croix germinated 66%.

These soak test results confirm the findings of Khosravi and Anderson (1990), who reported that inbred lines were affected differently by soaking. Previous studies also demonstrated that anaerobic conditions during soaking could produce lethal toxicity (Khosvari and Anderson, 1990) and carbon dioxide accumulation (Cerwick et al., 1995; Martin et al., 1988), thus reducing germination of maize inbred lines sensitive to flooding.

Electrical Conductivity

During initial stages of imbibition most seeds leak ions, amino acids, and sugars. Weaker seeds, that is, those with poor cell membrane structure or slow restoration of cell membrane function during rehydration, tend to leak more. Seed leakage can be quantified by the increase in the EC of the soak water (Black and Bewley, 2000). The higher the EC value, the lower the seed quality.

Genotypes showed many significant differences for EC in all locations (Table 8). Seeds produced in IA and MO had the greatest seed leachate EC, and seeds from IL had the least. Inbred 2 had high EC in IA, significantly greater than any other line in that location, but in other locations, it was not significantly different from the two Corn Belt checks except for B73 in NE. How-

Table 7. Soak test means for 10 inbred lines produced at four locations.

	Locations			
Inbred†	IA	MO	IL	NE
	%			
1 HP-LO SC	64	67	92	77
2 HP-LO SC	72	79	89	83
3 HP-LO AR	61	55	85	75
4 HP-LO AR	84	67	80	84
5 LP-LO SC	20	45	53	35
6 HP-HO AR	76	52	57	71
7 HP-HO AR	57	47	92	79
8 HP-LO AR	75	55	91	83
B73	95	73	79	85
Mo17	72	91	93	60
LSD(0.05)	20	18	18	18

† HP, high protein; LP, low protein; HO, high oil; LO, low oil; AR, Argentina background; SC, St. Croix background.

Table 8. Electrical conductivity for seed of 10 inbred lines produced at four locations.

	Locations			
Inbred†	IA	MO	IL	NE
	$\mu S\ cm^{-1}\ g^{-1}$			
1 HP-LO SC	5.0	7.3	4.6	7.1
2 HP-LO SC	7.0	3.5	4.5	4.9
3 HP-LO AR	4.5	4.6	3.0	4.3
4 HP-LO AR	3.6	5.0	6.5	3.4
5 LP-LO SC	5.3	3.9	2.1	9.5
6 HP-HO AR	4.5	3.7	4.2	4.1
7 HP-HO AR	4.8	3.7	4.0	3.7
8 HP-LO AR	4.5	5.2	4.2	4.8
B73	3.9	2.0	2.3	2.4
Mo17	3.7	2.6	3.0	4.2
LSD(0.05)	1.5	2.1	2.0	2.3

† HP, high protein; LP, low protein; HO, high oil; LO, low oil; AR, Argentina background; SC, St. Croix background.

ever, the highest EC of all locations was recorded for Inbred 5 from seeds produced in NE (9.5 $\mu S\ cm^{-1}\ g^{-1}$). Seed leachate of this inbred line produced in other locations had low conductivity, and the lowest of all lines in IL. Inbred 1 had the highest EC in MO, thus all three St. Croix introgressed lines had high EC in some locations. In general, tested lines introgressed with tropical germplasm did not show stability of EC values.

Seed composition did not affect seed leachate in most of the groups that were compared (Table 4). However, high oil inbred lines with St. Croix germplasm had greater seed leachate EC than the elite check, Mo17. Similarly, comparisons between B73 and high protein inbred lines with Argentinean germplasm, showed that B73 had significantly less seed leachate.

Differences in EC between genotypes were similar to those reported by previous investigators (Abdul-Baki and Anderson, 1972; Basavarajappa et al., 1991; Santipracha et al., 1997). Seed produced in IL had the highest overall quality as shown by the vigor tests. The two checks included in this study were more vigorous than all the new inbred lines, and inbred 5 had the most variable EC, with both the lowest (IL) and the highest (NE) EC values (Table 8).

In general, seed vigor measured by saturated cold test, AA, and EC showed genotypic differences within and among locations. High protein inbred lines had higher vigor than low protein inbred lines. Similar results have been reported for other crops. Schweize and Ries (1969) reported that oats seeds high in protein content tend to show greater vigor. Also, wheat with high protein content germinated faster and developed into larger seedlings (Lopez and Grabe, 1973).

Inbred Quality Index

There were differences in IQI among the inbred lines within locations (Table 9). Exotic inbred lines tested had IQI values from 1.6 to 8.9, and both of these extreme values were found in the same line, Inbred 5. Differences in IQI values suggest that some inbred lines were better adapted to cool environments and others to warm environments. Inbred 4 had a greater IQI when produced in IA and NE, and Mo17 had among the highest IQI when produced in MO and IL. Most IQI values for the exotic inbred lines were above 5, which indicates good seed quality. Seed composition and genetic background did not affect IQI of inbred lines (Table 4). Seed of B73 and Mo17 had superior quality to all the other lines because of their consistently high IQI values across locations. However, MO was the only location where B73 had a significantly greater IQI than the majority of the introgressed lines. Further investigations are needed to determine why introgressed lines have inconsistent IQI values across locations. If the relative IQI score of an inbred proves to be unstable across seed production environments, breeders and seed producers need to be aware of the strong interaction between these two factors when evaluating inbred lines for seed quality characteristics.

Table 9. Mean inbred quality index (IQI) values for 10 inbred lines produced at four locations.

	Locations			
Inbred†	IA	MO	IL	NE
	IQI			
3 HP-LO AR	5.7	4.4	7.1	5.0
4 HP-LO AR	4.2	7.1	7.2	6.4
5 LP-LO SC	6.2	5.2	8.0	6.3
6 HP-HO AR	8.1	5.0	4.5	7.5
7 HP-HO AR	4.1	5.4	8.9	1.6
8 HP-LO AR	7.1	6.5	4.8	6.7
3 HP-LO AR	5.7	5.4	7.9	7.3
4 HP-LO AR	6.0	4.4	6.9	6.2
B73	7.0	7.9	8.1	8.0
Mo17	6.6	8.4	8.1	6.0
LSD(0.05)	1.5	1.8	2.1	2.6

† HP, high protein; LP, low protein; HO, high oil; LO, low oil; AR, Argentina background; SC, St. Croix background.

Seed germination and vigor differences were evident among the inbred lines. Inbreds achieved maximum seed quality levels according to their adaptation to the environmental conditions in which seed developed. Overall, seeds produced in IL had the highest quality. This can be attributed to optimal rainfall and GDD during the critical physiological stages of seed development and maturation. Seeds produced in IA had the highest overall cold test values, an indication of high vigor. The low protein inbred line had low vigor compared with high protein inbred lines. When protein content was high, seed quality was high regardless of the oil content. The inbred line with low seed protein had lower seed quality and greater levels of mechanical damage (data not shown). Our results indicate that selection for higher oil content in seed could adversely affect seed quality. Further studies are needed to evaluate how change in oil composition, that is, degree of fatty acid saturation, is affected by selection, and the relationship of oil composition with seed quality and production environment. Inbred lines with germplasm from Argentina had better seed quality compared with those from St. Croix. Our results suggest that it is important to evaluate seed quality attributes of inbred lines early in the selection process, especially when introgressing exotic germplasm.

Breeders who are developing new inbred lines from materials introgressed with exotic germplasm need to be aware of these seed quality issues. They should cooperate with seed scientists to be sure that advanced lines do not show unexpected and detrimental quality problems in locations where they may be increased or used to make hybrids, or that potential seed quality problems are not expressed in the hybrid.

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