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Experimental evaluation of the potential of tropical germplasm for temperate maize improvement

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Abstract Commercial maize (*Zea mays* L.) in the USA has a restricted genetic base as newer hybrids are largely produced from crosses among elite inbred lines representing a small sample (predominantly about 6- to 8-base inbreds) of the Stiff stalk and Lancaster genetic backgrounds. Thus, expansion of genetic diversity in maize has been a continuous challenge to breeders. Tropical germplasm has been viewed as a useable source of diversity, although the integration of tropical germplasm into existing inbred line and hybrid development is laborious. The present study is an evaluation of the potential of tropical germplasm for temperate maize improvement. All possible single-, three-way-, and double-cross hybrids among three largely temperate and three temperate-adapted, all-tropical inbred lines were evaluated in yield-trial tests. Single-cross hybrids containing as much as 50–60% tropical germplasm produced 8.0 t ha^{-1} of grain yield, equivalent to the mean yield of the commercial check hybrids. On the other hand, three-way and double-cross hybrids with the highest mean yield contained lower amounts of tropical germplasm, 10–19% and 34–44%, respectively. Overall, hybrids containing 10–60% tropical germplasm yielded within the range of the commercial hybrid checks. Hybrids with more than 60% tropical germplasm had significantly lower yields, and 100% tropical hybrids yielded the least among all hybrids evaluated. The results indicate that inbred lines containing tropical germplasm are not only a useful source to expand the genetic diversity of commercial maize hybrids, but they, also are competitive in crosses with temperate materials, producing high-yielding hybrids. These experimental hybrids exhibited good standability (comparable to the commercial check hybrids) but contained 1–2% higher grain moisture, leading to delayed maturity. Recurrent selection procedures are being conducted on derivatives of these materials to extract lines with superior yield, good standability, and reduced grain moisture which can be used for commercial exploitation.

Key words *Zea mays* L. · Genetic diversity · Tropical germplasm · Temperate inbreds · Combining ability

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Introduction

The rate of yield increase of hybrid maize in the last 60 years in the USA is unparalleled among all food crops. Yield increases from approximately 1 t ha^{-1} in the 1930s to approximately 8 t ha^{-1} in the 1990s have been achieved, largely from the combination of improved genotypes of parental lines, breeding methods and cultural practices (Duvick 1992; Troyer 1996). Paradoxically, the pedigrees of most popularly grown hybrids trace back primarily to derivatives of about six to eight inbred lines (Goodman et al. 1988; Smith 1988; Goodman 1992). Although the derivatives of these lines have provided farmers with high-yielding hybrids, the narrow genetic base of maize poses a threat to currently unforeseen problems. Consequently, the expansion of the germplasm base remains a continuous challenge to maize breeders.

Exotic germplasm, particularly tropical germplasm, has been suggested as a source to widen the existing genetic diversity of U.S. corn breeding programs (Gerrish 1983; Goodman 1985; Stuber 1978). It is especially regarded as a possible fount of insect and disease resistance (Brewbaker et al. 1989). Non-adaptation to temperate regions and poor standability have been the major drawbacks for the widespread utilization of tropical germplasm for breeding in the USA. In spite of several efforts involving both private and public research programs, little tropical germplasm has reached the farmer's fields. Goodman (1998) estimated that the percentage of exotic germplasm, including both temperate and tropical, in the U.S. hybrid corn market is about 2.9, but the percentage of tropical germplasm is only a tenth of the total exotic germplasm used.

Although integration of tropical germplasm into existing inbred line and hybrid development is laborious, Iowa State University and North Carolina State University (NCSU) have released 12 inbred lines containing all-tropical germplasm. In general, the use of lines developed in the public sector in the tropics for breeding in the U.S. is almost non-existent. Most of these lines per se have undesirable agronomic characteristics such as weak roots, susceptibility to smut and barrenness when grown in temperate regions. The lack of convincing yield trial data for public tropical line testcrosses has been the other major limitation to their use in temperate hybrid development programs. Thus, agronomic evaluation of temperate and tropical inbred line crosses could provide useful information to combine these two sources for the genetic improvement of hybrid maize. The study presented here was conducted with the objectives to (1) evaluate performance in yield trials of a set of single-, double-, and three-way cross hybrids among selected largely temperate and temperate-adapted, all-tropical inbred lines, and (2) demonstrate the potential contribution of temperate-adapted lines of mostly tropical germplasm for hybrid maize improvement.

Materials and methods

Six inbred lines, consisting of three largely temperate lines and three temperate-adapted, all-tropical lines developed at NCSU (Table 1) were chosen as parental lines based on previous performance. For detailed pedigree information and how the all-tropical lines were derived, the reader is referred to Goodman (1993) and Uhr and Goodman (1995). All possible single-, double-, and three-way crosses, excluding reciprocals, were made among the six inbred lines. In all, a total of 15 single-, 45 double-, and 60 three-way-cross hybrids were tested for yield and other agronomic characteristics. Hybrids from the 15 single crosses were evaluated at Clayton, Lewiston, and Plymouth, North Carolina during 1994–1996. The 45 double-cross hybrids were evaluated during 1996 and 1997 at the same three locations. Hybrids from the 60 three-way crosses were tested at the three locations in 1995 and 1996, but the data from Plymouth in 1996 were not analyzed because of extensive damage caused by hurricane Fran.

The experimental design was a triple lattice with three replications at each location. The entries were planted in 2-row plots 4.86 m long including a 1-m alley at the end of the plot. Inter-row spacing was 0.97 m at Clayton and Plymouth, and 0.91 m at Lewiston. Plant density averaged about 43,000 plants per hectare in Clayton and Plymouth, and 45,000 plants per hectare in Lewiston. These plant densities are consistent with the commercial farm plant stands in North Carolina. Four single-cross commercial hybrids, DeKalb 689, LH132 × LH51, Pioneer 3165, and Pioneer 3245, were included as checks in the three studies. At the time this study was initiated, DeKalb 689 and Pioneer 3165 were very popular hybrids among the commercial growers in North Carolina; they are still being widely grown. Both are considered defensive hybrids as they yield well even under unfavorable conditions such as drought. Pioneer 3245 is a widely grown hybrid in North Carolina and is considered to have a high-yield potential under optimal conditions. LH132 × LH51 is a single-cross hybrid from Holden's Foundation Seed Company and is marketed under several brand names. It represents the basic B73 × Mo17 heterotic pattern and is grown commercially in North Carolina. Additionally, (B73*Ht* × Mo17*Ht*) × NC296 was also included as a check in the single-cross study. This is a three-way hybrid that was produced for use as a check in gray leaf spot small plot trials and a strip plot experiment.

Grain yield (t ha^{-1}), grain moisture (%), and erect plants (%) were recorded for each plot at all locations. Flowering data (days from planting to 50% pollen shed) were recorded at Clayton only. The general and specific combining abilities of lines were estimated separately from the different sets of crosses. General and specific combining abilities of lines from single-cross data were estimated according to Falconer and Mackay (1996). The genetic effects of lines from double- and three-way crosses were calculated according to Singh and Chaudhary (1977); however, only the effects of lines

Table 1 Pedigrees of the parental inbred lines

Inbred line	Pedigree[a]	Category
NC258	TZ^2 × [NC248 × NC246] × C103	Temperate (100%)
NC260	$Mo44^4$ × Mo17	Temperate[b] (65%)
NC268	$B73^2$ × NC250	Temperate (94%)
NC296	H5 × Pioneer × 105A	Tropical (100%)
NC298	Agroceres 155 × (H5 × Pioneer X105A)	Tropical (100%)
NC300	Pioneer X105A × [(Pioneer X306B × H5)]	Tropical (100%)

[a] TZ was a McNair sister line hybrid based on McNair 14 × 16. These lines themselves were derived from Coker 811A × $C103^4$. Coker 811A was a modified double-cross of (C1 × C7) × [(C3R × C8R) × C4]. C1 was from Doufitts Prolific, C7 was from Lathams Double, C3R was from Biggs Two-Ear, C8R was from a cross of lines from Florida White and Huffman and C4 was from Florida White. C103 is a first-generation inbred line of Lancaster origin. NC250 contains 25% of Nigeria Composite AR b, so that NC268 has about 6% tropical germplasm

[b] Mo44 was derived from Mo22 × Pioneer Mexican Composite 17. Mo22 was derived from the open-pollinated Laguna population, which originally came from Mexico, and was grown in the U.S. for several years, but no records were available as to how this population was collected or maintained (M. S. Zuber, personal communication). The Pioneer Mexican Composite was itself 50% Mexican (tropical). Thus, NC260 could be as much as 70% tropical, but due to a lack of accurate data on the Laguna population, we have arbitrarily assigned NC260 as 35% tropical

from the single crosses are reported in this paper. Because the different sets of crosses evaluated in this study were all originally derived from a fixed set of six inbred lines, any inferences from the genetic effects should be considered appropriate only for these six lines and their crosses evaluated in this study.

Results and discussion

The data in this study came from several replicated experiments, each with crosses involving different degrees of tropical germplasm. As a result, one of our goals was to identify the highest yielding crosses within the different experiments with varying amounts of tropical germplasm. In the single-cross study, hybrids with 50–60% tropical germplasm produced a mean yield of 8.0 t ha^{-1}, equivalent to the mean yield of the commercial hybrid checks (Table 2). Among the three-way crosses, hybrids with tropical germplasm ranging from 21% to 60% produced 6.8 t ha^{-1}. However, three-way hybrids containing tropical germplasm in the range of 10% to 19% had the highest mean yield of 7.1 t ha^{-1} (Table 2). In the double-cross study, 34–44%-tropical crosses averaged 7.0 t ha^{-1}, followed by 6.8 t ha^{-1} for the 50–60%-tropical crosses. Although no distinct relationship was observed with respect to the degree of tropical germplasm and yield among all three types of hybrids evaluated, generally, hybrids containing tropical germplasm in the range of 10% to 60% yielded within the range of the commercial hybrids used as checks. The hybrids with more than 60% tropical germplasm had significantly lower yields than did the commercial checks. Hybrids containing 100% tropical germplasm yielded least. Pioneer hybrid 3245 had the highest yields in the single- (8.7 t ha^{-1}), three-way- (7.9 t ha^{-1}) and double-cross (8.0 t ha^{-1}) experiments. These results demonstrate that hybrids containing 10–60% tropical germplasm are competitive in yield potential with popular commercial hybrids. In 1996, the three experimental locations were affected by a tropical storm, Bertha, on July 12th, and a major hurricane, Fran, on September 4th and 5th. Thus, the percentages of erect plants are lower than normal in the hybrids as well as in the checks evaluated in this study.

Single-cross hybrids

Among the nine single crosses between largely temperate and all-tropical lines averaged over three locations and 3 years, NC258 × NC296 had the best yield, 8.6 t ha^{-1}, while the highest yielding check was Pioneer 3245 with 8.7 t ha^{-1} (Table 3). Four of the six single-cross hybrids with 50–53% tropical germplasm averaged 8.0 t ha^{-1} or higher. The lowest yielding single-cross hybrid (with 68% tropical germplasm), NC260 × NC298, averaged 7.0 t ha^{-1} (Table 3). Mean yield of single-cross hybrids among the largely temperate lines ranged from 7.1 to 8.1 t ha^{-1}, whereas that among the all-tropical lines ranged from 4.8 to 6.2 t ha^{-1}. A ranking of the experimental single-cross hybrids from the individual environments over the 3-year period and from the combined analysis (3 years × 3 locations) showed that NC258 × NC296 ranked 1 and 2 in eight out of ten cases (data not shown). NC268 × NC296 ranked in the top 3 seven out of ten times. Although the hybrids involving NC296 with the three largely temperate lines yielded 8 t ha^{-1} or higher over the 3-year period (Table 3), NC260 × NC296, containing the highest amount of tropical germplasm (68%), yielded least among the three hybrids.

The highest yielding experimental single-cross hybrid, NC258 × NC296, had a grain moisture of 20.9%, with 80% erect plants. Percent grain moisture ranged from 17.1 to 19.4 among the checks. The highest yielding check, Pioneer 3245, with 85% erect plants, had an average grain moisture of 17.6% (Table 3). In our experience, under irrigated conditions this hybrid has performed better than all other checks used in this study. The percentages of erect plants and grain moisture are within the acceptable limits under North Carolina growing conditions. The all-tropical single-cross hybrids averaged 20.4% grain moisture, whereas the largely temperate, single-cross hybrids had a mean grain moisture of 18.8%. The single crosses among the largely temperate and tropical lines averaged about 20% grain moisture, usually about 1–2% higher than the crosses among the largely temperate lines or the commercial hybrids.

The general combining abilities of lines (Table 4) indicated that the largely temperate lines showed

Table 2 Mean yield (t ha^{-1}) in different types of crosses containing various percentages of tropical germplasm and in checks. Number of hybrids in each group is given in parentheses

Type of Cross	Percentage tropical germplasm							Checks
	3	10–19	21–28	34–44	50–60	68–84	100	
Single	8.1 (1)	7.1 (1)	7.5 (1)	–	8.0 (6)	7.5 (3)	5.6 (3)	8.0 (5)
Three-way	–	7.1 (3)	6.7 (6)	6.8 (12)	6.8 (15)	6.1 (21)	4.9 (3)	7.2 (4)
Double	–	–	–	7.0 (9)	6.8 (27)	6.2 (9)	–	7.6 (4)

Table 3 Agronomic performance of single-cross hybrids at three locations and 3 years in North Carolina. Specific combining ability effects of pairs of lines are in parentheses

Cross	Mean yield (t ha^{-1})	Percentage moisture	Percentage EP[a]	GLS[b]	So. Rust[c]	Percentage tropical germplasm[d]
NC258 × NC296	8.6(1.0)	20.9(0.3)	80(1.0)	7.2(0.1)	7.7(− 0.5)	50
NC268 × NC296	8.3(0.5)	18.1(− 0.1)	83(0.4)	6.7(0.5)	8.7(0.7)	53
NC258 × NC268	8.1(− 0.6)	18.8(− 0.3)	78(− 4.0)	6.8(− 0.2)	7.0(0.1)	3
NC268 × NC300	8.0(0.2)	18.7(− 0.2)	86(3.9)	5.9(− 0.1)	8.3(− 0.1)	53
NC260 × NC296	8.0(0.9)	19.5(0.4)	84(1.6)	7.1(0.2)	8.3(0.02)	68
NC268 × NC298	7.9(0.6)	19.1(0.4)	85(0.4)	6.6(0.1)	6.7(− 0.3)	53
NC258 × NC300	7.7(0.2)	21.9(0.5)	78(0.5)	7.3(0.3)	8.7(0.1)	50
NC260 × NC268	7.5(− 0.7)	17.9(0.3)	85(− 0.5)	6.4(− 0.3)	6.7(− 0.4)	21
NC260 × NC300	7.5(0.4)	19.7(− 0.1)	81(− 0.2)	6.9(0.2)	9.0(0.3)	68
NC258 × NC298	7.3(0.3)	20.9(− 0.2)	83(2.4)	7.2(0.1)	7.0(− 0.2)	50
NC258 × NC260	7.1(− 0.9)	19.6(− 0.4)	82(0.2)	7.3(− 0.3)	7.7(0.4)	18
NC260 × NC298	7.0(0.4)	19.3(− 0.3)	84(− 1.1)	6.9(0.1)	7.0(− 0.3)	68
NC298 × NC300	6.2(0.1)	21.2(0.3)	79(− 1.4)	6.2(0.1)	9.0(0.4)	100
NC296 × NC300	5.7(− 1.0)	20.0(− 0.5)	76(− 2.7)	5.7(− 0.5)	9.0(− 0.7)	100
NC296 × NC298	4.8(− 1.4)	20.0(− 0.2)	82(− 0.2)	6.0(− 0.3)	8.7(0.4)	100
Mean	7.3	19.7	81.7	6.7	7.9	
		Checks				
Pioneer Hybrid 3245	8.7	17.6	85	4.5	4.7	
Pioneer Hybrid 3165	8.0	19.4	80	4.6	5.0	
(B73*Ht* × Mo17*Ht*) × NC296	7.9	18.0	76	5.6	8.0	
DeKalb Hybrid 689	7.8	17.8	81	7.0	6.3	
LH132 × LH51	7.5	17.1	82	4.6	5.0	
LSD.05	0.7	0.8	7.0	1.9	1.0	
C.V. %	10.0	5.0	9.0	17.9	8.0	
SE[s(i, j)][e]	0.2	0.2	2.0	0.3	0.3	

[a] %EP = Percentage of erect plants at harvest
[b] GLS = Gray leaf spot score on a 9 = no disease, 1 = dead basis (3 years and two locations)
[c] So. Rust = Southern rust score on a 9 = no disease, 1 = dead basis (1 year and one location)
[d] Treating NC260 as 35% tropical
[e] Standard error of specific combining ability between any pair of lines

Table 4 General combining ability effects for grain yield, grain moisture, erect plants, gray leaf spot-, and southern rust resistance of six parental inbred lines in single crosses

Inbred line	Yield (t ha^{-1})	Percentage moisture	Percentage EP[a]	GLS[b]	So. Rust[c]
NC258	0.6	0.9	− 2.2	0.6	− 0.4
NC260	0.1	− 0.6	1.9	0.3	− 0.3
NC268	0.8	− 1.5	2.2	− 0.3	− 0.6
NC296	− 0.3	− 0.1	− 0.9	− 0.1	0.6
NC298	− 0.9	0.5	1.1	− 0.2	− 0.4
NC300	− 0.4	0.8	− 2.1	− 0.3	1.1
Hybrid mean	7.3	19.7	81.7	6.7	7.9
SE[g (i)][d]	0.1	0.1	1.0	0.2	0.2
SE[g (i) − g (j)][e]	0.1	0.2	2.0	0.2	0.2

[a] %EP = Percentage of erect plants at harvest
[b] GLS = Gray leaf spot score on a 9 = no disease, 1 = dead basis (3 years and two locations)
[c] So. Rust = Southern rust score on a 9 = no disease, 1 = dead basis (1 year and one location)
[d] Standard error of general combining ability of any 1 line
[e] Standard error of general combining ability difference between any pair of lines

positive effects for grain yield; negative effects were associated with the tropical lines. However, in the crosses involving only the largely temperate lines, the specific combining ability effects (Table 3) were negative and resulted in lower grain yields than would be expected from the general combining abilities of the lines. Although negative general combining effects were observed for the tropical lines, average yields from temperate × tropical line crosses resulted in higher yields than would be expected from the general combining abilities. Considering the fixed nature of the lines evaluated in this study, it can be inferred that the tropical lines interacted positively for yield with selected temperate line genetic backgrounds and thus represent a useful source for temperate maize improvement.

One of the reasons for advocating the use of tropical germplasm for temperate maize improvement has been to transfer pest and disease resistance genes into elite lines. In 1995, at the Clayton location, single-cross hybrids were rated for southern rust (*Puccinia polysora* Schw.) on a 1 (100% diseased) to 9 (no disease) visual scale. The all-tropical, single-cross hybrids had an average score of 8.9, with the lowest score of 8.7 in NC296 × NC298 (Table 3). On the other hand, the four commercial check hybrids averaged a score of 5.3 and ranged from 4.7 in Pioneer 3245 to 6.3 in DeKalb 689. The remaining experimental check hybrid (B73*Ht* × Mo17*Ht*) × NC296 had a score of 8. Among the other single-cross hybrids, NC260 × NC300 had an average score of 9.0, followed by 8.7 in each of the two hybrids, NC258 × NC300 and NC268 × NC296. The lowest score was 6.7 in NC260 × NC268 and NC268 × NC298.

Gray leaf spot (*Cercospora zeae-maydis* Tehon and Daniels) is the other disease for which scores on a similar scale (1 = 100% diseased; 9 = no disease) were recorded at about 10-day intervals on single-cross hybrids at Andrews and Laurel Springs in North Carolina (Table 3). Disease scores were recorded on three different dates in 1994 from two replications at Laurel Springs, from one replication at Andrews (two dates); two replications in Laurel Springs (four dates) during 1995, and from two replications in Laurel Springs (two dates) in 1996. The all-tropical, single-cross hybrids averaged a score of 6.0 with the range from 5.7 in NC296 × NC300 to 6.2 in NC298 × NC300 (Table 3). The most susceptible commercial hybrid was Pioneer 3245, with an average score of 4.5. Of the four commercial check hybrids, DeKalb 689 exhibited the best resistance with a mean score of 7.0. Among the experimental single-cross hybrids, NC258 × NC300 and NC258 × NC260, each exhibited the highest average score of 7.3, and NC268 × NC300 was the most susceptible with an average score of 5.9 (Table 3).

Neither of these diseases, nor any others, were factors for yield in the experiments reported here. The yield trials were not disease-free, but any disease present appeared very late in the growing season after yield potential had been determined.

The average plant and ear height in the all-tropical, single-cross hybrids were 266 cm and 120 cm, respectively (data not shown). Among the commercial check hybrids, plant height ranged from 274 cm in Pioneer 3245 to 262 cm in LH132 × LH51 and ear height from 103 cm in Pioneer 3245 to 116 cm in DeKalb 689. The mean plant and ear height in hybrids of NC296 × temperate lines was 284 cm and 127 cm, respectively. Crosses of NC298 had an average plant and ear height of 269 cm and 118 cm, whereas the NC300 crosses averaged about 284 cm and 120 cm, respectively (data not shown). While it is possible that higher plant heights for tropical × temperate crosses may have given these hybrids an advantage in yield trials, the experimental check hybrid (B73*Ht* × Mo17*Ht*) × NC296 (with average plant and ear heights of 288 cm and 129 cm, respectively) outyielded all commercial checks, including Pioneer 3245, in strip trials conducted by Pioneer Hi-Bred International at Andrews in North Carolina, suggesting that shading is not the sole reason for better yield performance in the tropical × temperate line hybrids.

Three-way cross hybrids

Of 60 three-way crosses evaluated, 19 yielded at least 6.8 t ha^{-1}, as much as the lowest yielding single-cross check hybrid, DeKalb 689 (Table 5). Of these 19, 3 were crosses among the largely temperate lines, with the hybrids carrying tropical germplasm only in the range of 10% to 19%. Of the remaining 16, 8 had 27–44% and the other 8 had 59–68% tropical germplasm. Of these 16 high-yielding, three-way-cross hybrids, 9 had NC296 as one of the three parents. Grain moisture ranged from 18.4% to 21.1% in the 19 high-yielding experimental, three-way-cross hybrids and from 17.0% in LH132 × LH51 to 19.4% in Pioneer hybrid 3165 (Table 5) among the checks. Erect plants in the 19 three-way crosses ranged from 81% in (NC260 × NC296) × NC268 to 92% in (NC258 × NC260) × NC268 and from 79% to 94% in the checks.

Double-cross hybrids

Of the 45 double-cross hybrids evaluated, 12 yielded at least 7.0 t ha^{-1}. Of these 12, 6 had 35%, 1 had 52%, and 5 had 59–60% tropical germplasm (data not shown). Overall, 9 of the 45 experimental double-cross hybrids yielded at least 7.1 t ha^{-1}, comparable to the lowest yielding single-cross check hybrid, DeKalb 689 (Table 6). Of the 9 highest yielding, double-cross hybrids, 6 contained between 52% and 60% tropical germplasm, and the remaining 3 had 35% tropical germplasm (Table 6). The highest yielding, double-cross hybrid, (NC258 × NC268) × (NC298 × NC296), with 52% tropical germplasm, yielded 7.4 t ha^{-1} (Table 6); the moisture content of kernels was 19.0% at harvest with 73% erect plants. The percent erect plants in the checks ranged from 70 to 81. The average grain moisture in the 9 highest yielding hybrids was 18.5%. The lowest yield was 5.6 t ha^{-1} in the double-cross hybrid (NC298 × NC300) × (NC268 × NC296) with 77% tropical germplasm (data not shown). Yields of the commercial checks ranged from 7.1 t ha^{-1} in DeKalb 689 to 8.0 t ha^{-1} in Pioneer hybrid 3245.

Table 5 Agronomic performance of 19 highest-yielding three-way cross hybrids during 2 years in North Carolina

Cross	Mean yield ($t\,ha^{-1}$)	Percentage moisture	Percentage EP[a]	Perentage tropical germplasm[b]
(NC260 × NC296) × NC258	7.4	20.4	84	34
(NC258 × NC260) × NC296	7.3	19.9	85	59
(NC258 × NC268) × NC260	7.2	19.0	90	19
(NC260 × NC268) × NC258	7.2	19.5	88	10
(NC298 × NC296) × NC260	7.1	19.8	89	68
(NC300 × NC296) × NC260	7.1	19.7	90	68
(NC268 × NC296) × NC260	7.1	18.5	89	44
(NC258 × NC260) × NC300	7.1	21.1	87	59
(NC260 × NC268) × NC300	7.1	19.4	87	60
(NC268 × NC296) × NC258	7.0	19.8	84	27
(NC298 × NC260) × NC258	7.0	20.8	82	34
(NC260 × NC296) × NC268	7.0	18.4	81	37
(NC260 × NC268) × NC296	7.0	18.7	86	60
(NC260 × NC268) × NC298	6.9	19.7	90	60
(NC258 × NC260) × NC268	6.9	18.5	92	12
(NC258 × NC296) × NC260	6.9	19.8	89	43
(NC300 × NC268) × NC260	6.8	18.9	87	44
(NC298 × NC258) × NC268	6.8	19.7	88	28
(NC258 × NC260) × NC298	6.8	20.7	83	59
	Checks			
Pioneer Hybrid 3245	7.9	17.7	92	
LH132 × LH51	7.0	17.0	94	
Pioneer Hybrid 3165	7.0	19.4	79	
DeKalb Hybrid 689	6.8	17.8	86	
LSD.05	0.7	0.9	9.0	
C.V. %	8.0	4.0	8.0	

[a] %EP = Percentage of erect plants at harvest
[b] Treating NC260 as 35% tropical

Table 6 Agronomic performance of 9 highest yielding double-cross hybrids during 2 years in North Carolina

Cross	Mean yield ($t\,ha^{-1}$)	Percentage moisture	Percentage EP[a]	Percentage tropical germplasm[b]
(NC258 × NC268) × (NC298 × NC296)	7.4	19.0	73	52
(NC258 × NC260) × (NC300 × NC296)	7.4	19.6	71	59
(NC258 × NC268) × (NC260 × NC296)	7.3	18.2	71	35
(NC268 × NC298) × (NC258 × NC260)	7.3	18.4	69	35
(NC258 × NC260) × (NC298 × NC296)	7.3	19.3	75	59
(NC260 × NC268) × (NC300 × NC296)	7.2	18.0	80	60
(NC260 × NC268) × (NC298 × NC296)	7.2	17.8	74	60
(NC258 × NC268) × (NC300 × NC260)	7.2	18.3	71	35
(NC300 × NC260) × (NC268 × NC298)	7.1	18.2	78	60
	Checks			
Pioneer Hybrid 3245	8.0	16.3	77	
LH132 × LH51	7.6	15.7	81	
Pioneer Hybrid 3165	7.5	18.6	71	
DeKalb Hybrid 689	7.1	16.7	70	
LSD.05	0.5	0.6	10.0	
C.V. %	6.0	3.0	12.0	

[a] %EP = Percentage of erect plants at harvest
[b] Treating NC260 as 35% tropical

Grain moisture content ranged from 15.7% to 18.6% in the checks.

The results presented from all the experiments show that the tropical inbred lines have the potential to contribute genes for increased yield in crosses with temperate-adapted lines. This observation re-emphasizes the fact that the use of tropical germplasm for maize improvement is practical and that judicious selection of the parental materials is the most important component in hybrid maize breeding. Further, it also supports the view expressed by Goodman et al. (1990) that U.S. maize has no monopoly on high yield when compared with elite tropical materials. On the other hand, crosses involving tropical lines contained 1–2% higher grain moisture than the commercial checks. This represents about a 1-week difference in maturity, approximately the difference represented by DeKalb 689 (mid-maturity) and Pioneer 3165 (late-maturity). Recurrent selection among derivatives of these crosses is being conducted to extract lines that can contribute high yield and lower grain moisture to hybrids so that they can be exploited for commercial breeding purposes.

Although the integration of tropical germplasm into temperate breeding programs has been viewed with optimism, the proportion of tropical germplasm to incorporate into existing commercial germplasm remains unclear and ambiguous. In all the experiments with varying amounts of tropical germplasm investigated in the present study, hybrids containing 10–60% tropical germplasm gave higher yields and better overall performance than hybrids with more than 60% tropical germplasm. Based on a summary of existing literature, Echandi and Hallauer (1996) indicated that populations containing 25–50% exotic germplasm yield comparably to adapted sources. The observations from this study support this conclusion.

Goodman (1992) reported that NC296A, a sister line of NC296, consistently produced high-yielding topcrosses and indicated that it contained favorable alleles distinct from other U.S. breeding lines. Thus, it is no surprise that single crosses involving NC296 outyielded crosses with all other lines studied. This positive response could be exploited not only for hybrid development but also for wide adaptation and expansion of the genetic base of existing maize germplasm. It appears that NC296 contains beneficial factors for yield enhancement. It was also emphasized by Goodman (1992) and Eberhart et al. (1995) that the use of elite exotic germplasm with higher yield potential, coupled with resistance to diseases and insects, is a good strategy for the integration of genetic diversity into maize breeding programs. NC296, an all-tropical inbred line, is certainly a promising candidate to expand the genetic base of existing commercial germplasm. Although the different types of hybrids in this study containing various amounts of tropical germplasm yielded competitively with commercial check hybrids, the temperate-adapted, all-tropical lines, as reported by Uhr and Goodman (1995), are not expected to meet the standards as parental inbred lines for commercial hybrid production. It is evident from the multi-location topcross data of single-cross hybrids evaluated in this study that the all-tropical lines contained genomic regions different from the temperate germplasm pool for yield. As a result, we suggest that these lines are a potential source for new yield genes and can be used as germplasm lines in temperate maize breeding programs. We also expect that by using molecular marker techniques, these genomic regions can be monitored in hybrids, and methods can be developed for efficient integration of these regions into elite temperate line genetic backgrounds for commercial exploitation.

Duvick (1992) concluded that the genetics of the lines combined to produce hybrids is the single most important input to achieve significant future yield increases. He also indicated that genetic inputs may eventually reach a yield plateau and that even to maintain a 1% annual genetic gain maize breeders need new genotypes for wider adaptation. In a recent report, Widstrom et al. (1996) reported that hybrids containing tropical germplasm perform well in the southeastern USA under late-planting conditions. In light of these observations, it seems reasonable that temperate-adapted, tropical inbred lines, such as NC296, NC298, and NC300, can contribute to the expansion of the genetic base and to wider adaptation of U.S. commercial corn germplasm.

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