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Assessment of genetic gains for grain yield and components from introgression of temperate donor inbred line into tropical elite maize inbred lines: II. Performance inter se

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Abstract In maize breeding programs, temperate germplasm can be used to introgress genes from temperate inbred lines into elite tropical maize inbred lines to improve grain yield and its components across environments. This study's objective was to determine the genetic gains for grain yield and its components achieved by the introgression of temperate maize germplasm in tropical elite maize inbred lines for adaptability to South African environments. One hundred and twenty-two Introgressed inbred lines developed using the pedigree breeding method were crossed to four tropical elite inbred line testers using a line x tester mating design to obtain 488 experimental single cross hybrids. Subject to availability of adequate seed for evaluation, a panel of 444 experimental single-cross hybrids were evaluated using an augmented design in two experiments defined as populations A and B at three sites in South African environments. Grain yield and ear prolificacy had positive realized genetic gains of up to 58 and 26%, respectively, relative to the panel mean and commercial check hybrids. Secondary traits, such as anthesis and silking days, had gains ranging from 1 to 37%. Negligible gains were attained for stalk and root lodging and grain moisture content at harvest. Despite the need for further improvement, introgressed inbred lines performance *inter se* indicated significant grain yield potential improvements following one breeding cycle. The following experimental single-cross hybrids 12C22785, 12C20628, 11C1774, 12C20264, 12C20595, 11C1645 13XH349 outperformed the best commercial check hybrid PAN6Q445B, a leading hybrid on the South African market for grain yield performance potential. These seven selected single-cross hybrids also combined high grain yield potential performance with good ear prolificacy, in particular, experimental single-cross hybrids 12C20628, 11C1774 and 12C202595. Two experimental single-cross hybrids 12C2064 and 13XH349, combined high grain yield performance potential with low grain moisture content at harvest and improved standing ability relative to commercial check hybrids. Parents of these selected experimental single-cross hybrids will be advanced in the breeding program and will be the basis of future breeding for adaptation to South African environments. However, the general trend showed that many of the selected experimental single-cross hybrids did perform poorly for standability data

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depicted by plant aspects such as plant and ear height, stalk, and root lodging. Therefore, there is a need to improve these plants further to enhance the adaptability of tropical germplasm in South African environments. In conclusion, the introgression strategy effectively enhanced tropical elite inbred lines for the desired economic traits, to the extent that several of their combinations resulted in superior hybrids that are highly desired for South African markets.

Keywords Maize hybrids · Genetic gain · Grain yield · Grain yield components · Performance *inter se*

Introduction

Maize (*Zea mays*, L) is sub-Saharan Africa (SSA) most widely grown cereal and a major staple crop with high economic value as a livestock feed. It occupies more than 50% of total farmland devoted to crops in SSA. It is estimated that over 55% of the daily intake of calories is derived from maize, with an average consumption of about 85–140 kg year^{-1} person^{-1} (Setimela et al. 2017). In Southern Africa, maize is particularly important, accounting for over 30% of the total calories and protein consumed (Cairns et al. 2013). Despite the importance of maize in SSA, maize yields remain sub-optimally low at 1.5−2 t ha^{-1} (Cairns et al. 2012; Setimela et al. 2017; FAO 2020), reports that the demand for maize in SSA is projected to increase by 30% by the year 2050 due to rising population growth. Thus, indicating the need for a 2.40% annual increase in maize production and productivity to offset the projected increase in food demand.

In particular, several breeding programs in both private and public and sector, particularly CIMMYT and IITA in several countries in SSA, have active breeding programs that are developing market-oriented maize inbred lines and hybrids to address the decline in average yield. CIMMYT maize breeding program in SSA has significantly contributed to germplasm development in National Agriculture Research Systems (NARS) and private sector in several countries resulting in the release of over 150 maize hybrids and open-pollinated varieties (OPVs) by CIMMYT and partners in the region (Masuka et al., 2017a, b). Genetic gain in maize improvement within the CIMMYT sub-Saharan Africa, NARS, and private sectors has been noted in many studies. Masuka et al. (2017a) report an estimated genetic increase at 0.85 to 2.2% yr^{-1} within the CIMMYT Eastern and Southern Africa hybrid maize breeding program from 2000 to 2010 under various environmental conditions. An estimated genetic gain under optimal conditions, managed drought, random drought, low N, and MSV were recorded to have increased by 109.4, 32.5, 22.7, 20.9, and 141.3 kg ha^{-1} yr^{-1}, respectively (Masuka et al. 2017a). While in Central and Western Africa, Badu-(Badu-Apraku et al. 2020) report an annual increase in grain yield of 61 kg ha^{-1} (1.24%) associated with reduced anthesis silking interval, improved ear aspect, and increased ears per plant. Despite the effort on maize breeding programs, there remains a considerable yield gap for maize in SSA as evidenced by a continuous to decline in average yield ((M'mboyi et al. 2010; Cairns et al. 2013; Masuka et al. 2017a, b; Gedil and Menkir 2019; Mushayi et al. 2020);

The decline in average yield could be due to genetic 'bottle-necks' in maize germplasm currently being utilized in many public and private breeding programs, notably in developing countries (Mushayi et al. 2020). Consequently, a narrow genetic germplasm base is created, which results in reduced potential for long-term gains in productivity and increased susceptibility to new pathotypes of diseases (Tarter et al. 2004). Hence the need to create new genetic variation through designed crosses involving divergent germplasm resources to enhance the potential of maize yields in SSA. Designed crosses of tropical and temperate maize germplasm can be exploited to strengthen genetic gains and increase maize yield production across environments (Musundire et al. 2019). Edmeades et al. (2017) report that maize production yield and time trends (2000–2014) illustrate that temperate maize producing regions have an average yield of 7.21 t/ha and an annual increase of 74 kg/ha/year (1.02%).

In contrast, tropical maize producing regions, particularly Eastern and Southern Africa, have an average yield of 2.14 t/ha and an annual increase of 42 kg/ha/year (1.94). These divergent yield trends and the annual rate of growth noted in temperate and tropical maize germplasm provide an opportunity to improve yields and its components in global maize breeding programs, particularly SSA. Tropical germplasm, the most genetically diverse source of exotic maize, is a possible source of favourable alleles for yield for incorporation into SSA maize breeding programs. Populations developed from crosses between tropical germplasm accessions and temperate germplasm have been reported to have more significant opportunities for genetic enhancement and increase in yields across target environments than the temperate parent in test crosses evaluated in these target environments (Abadassi and Hervé 2000; Tarter et al. 2004; Nelson et al. 2006; Nelson and Goodman 2008; Wang et al. 2008; Reif et al. 2010; Prasanna 2012; Mushayi et al. 2020) However, tropical maize germplasm carries some undesirable genes namely; late flowering, excessive vegetative growth, photoperiod sensitivity, high grain moisture content at harvest, poor standability, high ear placement, and low grain yield potential relative to temperate germplasm (Musundire et al. 2019).

Mushayi et al. (2020) report that undesirable genes potentially limit achievable genetic gains during the breeding process. Therefore, over-reliance on tropical germplasm narrows genetic variation and the ability to respond to current and future production constraints in SSA. Hence, the need to introduce temperate germplasm into tropical elite inbred lines to improve these traits in a well-controlled manner for the target environments in sub-Saharan Africa, particularly South Africa. Several studies have reported significant breeding progress from introgression of temperate germplasm into tropical germplasm for target environments in sub-Saharan Africa. (Abadassi and Hervé 2000) reported the significant highest expected genetic improvement from the introduction of temperate germplasm into the elite tropical maize population. The introgression significantly increased earliness, reduced plant height, number of grains per ear, 1000 grains weight, and grain yield. (Darsana et al. 2004) reported significant quadratic response for grain yield, linear response to days to anthesis, and silking and grain moisture content for tropical germplasm introgressed with temperate germplasm in South African environments. (Mushayi et al. 2020) report that hybrids that were generated from crossing temperate and tropical inbred lines had improved agronomic potential performance, yield stability, broad and specific adaptation across selected environments in Southern Africa, in particular, South Africa and Zimbabwe.

In sub-Saharan Africa, maize is produced in a wide range of production environments. Based on agroclimatic factors and grain maturity characteristics, the CIMMYT Global Maize Program has identified eight distinct maize production environments, known as mega-environments: tropical lowlands, tropical mid-altitude zones, tropical highlands, subtropical lowlands, Subtropical mid-altitude zones, Subtropical highlands, Subtropical winter zones, and temperate-subtropical zone (M'mboyi et al. 2010). These mega-environments are defined primarily in climatic factors, including mean temperatures during the maize growing season, elevation above sea level, and day length. In the current study, germplasm created from the Introgression of temperate germplasm into tropical elite inbred lines were evaluated in South African environments, predominantly dry tropical lowlands, subtropical mid-altitude, and temperate-subtropical zones. Single-cross maize hybrids, both conventional and genetically modified maize, dominate South African environmental markets. In South Africa, maize has a commercial value that determines the region's social, economic, and political stability. According to Syngenta Foundation for Sustainable Agriculture (2020), it is predicted that the growing South African population will become increasingly dependent on maize for food, feed, and industrial usage, with an expected increase in demand for animal feed close to 6.4 million tonnes by 2030. South African maize industry is regarded as a net earner of foreign currency, rendering this market highly lucrative for tropical breeding programs operating from both inside and outside South African environments. However, tropical germplasm directly introduced into the South African environments, mainly by breeding programs operating outside the South African environments, is characterized by a lack of adaptability.

In the current study, introgressed inbred lines were developed from introgression of temperate genes into elite tropical inbred lines to exploit genetic gains for improving an increase in grain yield and its components across South African environments. Introgression of temperate genes into tropical elite inbred lines also can enhance the suppression of undesirable genes, namely, late physiological maturity, high grain moisture content at harvest, poor standability, and low grain yield potential with tropical germplasm in target environments. Single-cross hybrids were generated from resultant introgressed inbred lines were test-crossed to tropical elite inbred line testers T1, T2, T3, and T4 using line by tester mating design and were evaluated in South African environments. Hence, the current study's objective was to assess genetic gains for grain yield and its components as a basis of gaining information on the response to selection and to establish the *inter se* performance of introgressed inbred lines in single cross hybrids evaluated in South African environments. The results would devise a breeding strategy for introgressing temperate germplasm into tropical elite inbred lines to improve the adaptation of resulting hybrids in South African environments.

Material and methods

Germplasm development

Introgressed inbred lines development

Introgressed inbred lines used to generated experimental single-cross hybrids evaluated in the current study were developed from a pedigree breeding method. A single common donor maize parental inbred line (08CED6_7_B) from South Africa was used to introgress genes from temperate germplasm into 12 elite tropical inbred lines from Zimbabwe through crosses in 2008 in South Africa. Tropical maize inbred lines used were representative of the major tropical heterotic groups, mainly N3 (derived from Salisbury white), SC (Southern Cross which was derived from an open-pollinated population grown by Mr South in Zimbabwe), and P (derived from the open-pollinated variety (OPV) Potchefstroom, Pearl, South Africa). The temperate maize population was one of the major temperate heterotic groups used in South Africa (TTTT AAA BBB [TAB] population). Hand crosses were made between the tropical and temperate populations to generate F_1 seed. Due to challenges in flowering synchronization (nicking) and seed availability, a total of eight populations were generated for advancement and selection at F_2 generation. Each population was independently advanced from F_3-F_6 generation through selfing and selection of adapted segregants to produce 122 introgressed inbred lines.

Experimental single-cross hybrids development

Experimental single-cross hybrids used in the current study were generated from testcrossing 122 Introgressed inbred lines to four tropical elite inbred line testers T1, T2, T3, and T4 using line by tester mating design. The four tropical elite inbred line testers used represented maize germplasm from two tropical heterotic groups P and N. A total of 488 experimental single-cross hybrids were produced from the test crosses. Subject to availability of adequate seed for evaluation, a panel of 444 experimental single-cross hybrids were evaluated using an augmented experimental design. Due to the large number (444) of the experimental single-cross hybrids involved and for convenience of the study, the experimental single-cross hybrids were divided into two populations that were designated as populations A and B, with both populations related to heterotic groups P and N. Population A comprised 280 experimental single-cross hybrids including four commercial hybrid checks; temperate hybrids (PAN3Q740 and PAN6Q445B) and tropical hybrids (PAN67 and SC633) to give a total evaluating panel of 284 entries. Population B consisted of 164 experimental single-cross hybrids, including three commercial hybrid checks (PAN6611, PAN6Q445B, and SC633) to give a total evaluating panel of 167 entries. Commercial check hybrids used in both populations were single-cross hybrids that are predominantly used in the South African market.

Experimental design and trial management

A total of five trials were planted in three locations in South Africa environments. Table 1 presents a summary of the locations. In population A, 284 entries (experimental single-cross hybrids and commercial hybrid checks) were randomly assigned into 20 blocks; in each block, 14 experimental single-cross hybrids and two repeating checks (PAN3Q740 and PAN67) were randomly assigned to each block. Due to limited seed, commercial check hybrid entries SC633, PAN6227, and PAN6Q445B were randomly assigned into blocks as non-repeating commercial checks. In population B, 162 entries (experimental single cross hybrids and commercial checks) were randomly assigned into 16 blocks; in each block, ten experimental single-cross hybrids were included with two

Table 1 Summary of trial locations used in the study

Season data								
Location	Latitude	Longitude	Coordinates	Altitude(m)	Description (units)	A	B	Stress conditions experienced at each site
*Ukulinga	29°37′S	30°16′E	(−29.617, 20.267)	812	Av max temp (°C)	25.9	24	Heat and drought stress
					Av min temp (°C)	16	12.9	Increased cold soil temperature
					Rainfall (mm)	600.7	885	Increased frost exposure
								Grey leaf spot (GLS)
								long day length
*Cedara	26°32′S	30°16′E	(−25.533, 30.267)	1068	Av max temp (°C)	25.2	23.6	Northern Corn Leaf Spot (NCLS)
					Av min temp (°C)	13	9.6	Phaeosphaeria leaf spot (PLS)
					Rainfall (mm)	647	873	Grey leaf spot (GLS)
								long day length
*Potchefstroom	26°73′S	27°75′E	(−26.117, 28.250)	1349	Av max temp (°C)	27.7	25.7	Heat and drought stress, rain poor distributed in the season
					Av min temp (°C)	19.5	9.8	Phaeosphaeria leaf spot (PLS)
					Rainfall (mm)	708.7	703.1	Long day length

m - meters above sea level; **A**-2012–13 season data; **B**-Long term average seasonal data; Av-Average; * - Weather data provided by the Agricultural Research Council–Institute for Climate, Soil, and Water.

repeating commercial checks (PAN6611 and PAN6Q445B). Due to limited seed, non-repeating commercial check SC633 was randomly assigned into the blocks. Population A was replicated over two sites, namely Ukulinga and Cedara Research Stations. In comparison, Population B was replicated over three locations: Ukulinga, Cedara, and Potchefstroom Research Station. An augmented experimental design was used to evaluate the trial (Lin and Poushinsky 1983; Scott and Milliken 1993; Spehar 1994). Due to the limited availability of seed, all experiments across sites were each planted as single-row plots. At Ukulinga Research Station, each entry was planted to 5 m length, spaced at 0.3 m in-row and 0.75 m between row spacing to achieve a total plant population density of at least 44 000 plants ha^{-1}. At Cedara Research Station, 5 m row-plots, in-row spacing 0.3, and row spacing of 0.9 m were used to achieve a plant stand of at least 37 000 plants ha^{-1}. While at Potchefstroom Research Station, 6.6 m length, spaced at 0.25 m in-row, and 1.5 m between row spacing were employed to attain a total plant population density of at least 26 000 plants ha^{-1}. Standard cultural management practices for growing maize were carried out at all the sites. Irrigation was only applied to achieve uniform establishment and to supplement rainfall as and when necessary. Fertilizer was applied at a rate of 120 kg Nitrogen (N), 33 kg Phosphorous (P), and 44 kg Potassium (K) at Cedara, Ukulinga, and Potchefstroom Research Stations.

Measurements

Data were collected at all the sites applying standard procedures used at International Maize and Wheat Improvement Centre (CIMMYT 1985) for the following traits: days to anthesis and silking days were recorded when 50% of the plants were shedding pollen, and 50% of the plants had silks emerged, respectively; plant and ear height were measured before harvesting on five representative plants per plot; percentage stalk and root lodging was recorded as a percentage of plants per plot that had their stems broken and percentage of plants per plot which had their stems inclined at least 45°, respectively; and the number of ears per plant-ear prolificacy (EPP) was calculated as the count of the number of ears plot as a fraction of the total number of plants in the plot. All plants were hand-harvested, and shelled grain weight was measured. Grain weights were adjusted to 12.5% moisture content and 80% shelling percentage to calculate grain yield (t ha^{-1}).

Statistical analyses

Data for grain yield and other agronomic traits from individual sites and combined sites was subjected to a general analysis of variance (ANOVA) of Augmented design using PROC GLM of SAS (SAS Institute Inc 2013). Before a combined analysis of variance was carried out, tests for homogeneity of variance following Levene's test and Welch's test were conducted using SAS's GLM procedure (SAS Institute Inc 2013).

The linear statistical model for the combined data was as follows:

$$Y_{ijk} = \mu + B_i + C_j + X_k(C) + Eijk$$

where Yijk = observed inbred response; μ = overall trial mean; B_i = effect of the ith block; I = 1 …6; C_j = effect of the jth hybrid control; j = 1.2; X_k (C) = effect of the experimental hybrid within checks; k = 1… 160 (Population A) and 280 (Population B); E_{ijk} = random experimental error. The block effects were treated as random while the hybrid main effects were considered fixed.

Estimation of genetic parameters

The data measurements were used to compute and estimate genetic parameters at 10% selection intensity for grain yield and its components in Population A and B.

1. Realized genetic gain 1 (%) (RG1 %) was calculated relative to the Population mean of all experimental hybrids in each Population, using the method suggested by (Singh and Chaudhary 2004) and (Souza et al. 2009), using the equation:

$$\text{RG 1 (\%)} = (\text{Mean of a sampled population(MS)} - (\text{Mean of the total Population(MP)})/\text{MP}) * 100$$

2. Realized genetic gain 2 (%) (RG2 %) was calculated relative to the mean of the better check commercial hybrids, applying a modified method suggested by (Singh and Chaudhary 2004), using the equation:

$$\text{RG 2 (\%)} = (\text{MS} - \text{Mean of the better check (MBC)})/\text{MBC}) * 100$$

3. Realized genetic gain 3 (%) (RG3 %) was calculated relative to the mean of the two repeated check commercial hybrids, applying a modified method suggested by (Singh and Chaudhary 2004), using the equation:

$$\text{RG 3 (\%)} = ((\text{MS} - \text{Mean of all checks(MC)})/\text{MC}) * 100$$

4. Narrow sense heritability (%) h^2; was estimated using the variance ratio (Hallauer and Miranda 1988). The variance component analysis was performed using the PROC Varcomp procedure in SAS (SAS Institute Inc 2013). Therefore, heritability was estimated using the equation:

$$h^2 = \delta_g^2 / (\delta^2/re + \delta_{ge}^2/e + \delta_g^2)$$

where δ^2_g is variance entry, δ^2 is variance error, δ^2_{ge} is variance site x entry interaction, and e is the number of sites.

5. Coefficient of genotypic variation percentage (CGV %) was calculated according to (Singh and Chaudhary 2004); (Souza et al. 2009) and (Al-Tabbal and Al-Fraihat 2011), using the equation:

$$(\text{CGV \%}) = \left(\surd\left(\delta_g^2\right)/x\right) * 100$$

where: δ^2_g = genotypic variance, X = mean of selected inbred lines.

6. Coefficient of genotypic variation as a function of the coefficient of variance (GCV/CV) was calculated according to (Souza et al. 2009) using the equation:

CGV/CV

where: CV was obtained using PROC GLM of SAS (SAS Institute Inc 2013).

7. The genetic gain was calculated by applying the method suggested by (Singh and Chaudhary 2004); (Souza et al. 2009) and (Al-Tabbal and Al-Fraihat 2011) using the equation:

$$GG = i * \sigma_p * h^2$$

where GG: genetic gain; i: standardized selection differential = 1.76 at 10 % selection intensity; σ_p: is the phenotypic standard deviation; h^2: heritability in narrow sense.

8. The genetic gain percentage was calculated by applying the method suggested by using the equation (Souza et al. 2009):

$$GG\ (\%) = \left(i * \sigma_p * h^2\right) * 100$$

Results

Analysis of variance

Mean squares of grain yield and its components for maize hybrid Population A and B are presented in Table 2. Experimental single-cross hybrids were observed to have significant ($P < 0.01$) differences for all the economic traits, excluding ear height and root lodging in Population A. In Population B, experimental single cross hybrids were observed to have significant ($P < 0.01$) differences for all the economic traits. Commercial hybrid check entries had significant ($P < 0.01$) differences for all the traits apart from root lodging. In contrast, in Population B, all the economic traits had significant differences except grain moisture content at harvest. Environment effect was observed to have significant ($P < 0.01$) differences for all the economic traits, except plant height and stalk lodging in Population A for the check hybrids. Experimental single-cross hybrids had a significant environment effect observed for anthesis and silking days, root and stalk lodging, ear prolificacy, and grain yield in Population B. Mean of squares of grain yield and its components for Population B showed a significant ($P < 0.05$) environment effect on all the economic traits, excluding ear height for the check entries. A significant ($P < 0.05$) environmental effect for the experimental single-cross hybrids was observed for anthesis days and silking days, stalk and root lodging, ear prolificacy, grain moisture content at harvest, and grain yield.

Realised genetic gain for Population A

Genetic gains realized due to introgression of temperate germplasm in elite tropical inbred lines is interpreted relative to the mean of the population, mean of new experimental single-cross hybrids in each Population (A and B) relative to mean of total Population (realized genetic gain 1), the mean of the best commercial check hybrid (realized genetic gain 2) and the mean of the commercial check hybrids (realized genetic gain 3). The estimates of grain yield potential and its components the selected 10% of the hybrids were superior to the population mean and the mean of the commercial check hybrids across sites (Table 3). The selected experimental single-cross hybrids were superior in the primary trait, grain yield, relative to the best commercial check hybrid at Cedara Research Station (Table 3), but they were inferior by about 9% Ukulinga Research Station (Table 4). A similar trend was also observed for ear prolificacy.

There were also significant gains across sites for secondary traits such as anthesis and silking days, root and stalk lodging, which were reduced by 1 to 37%, respectively, with respect to the mean of total population (Table 3). However, there was only a marginal improvement over the mean of commercial check hybrids for these traits, except stalk lodging (5%). There was no improvement of plant attributes, such as plant and ear height, which were more significant than the population means (Table 3). In contrast, significant general gains ranging from 2 to 21% were observed at Cedara and Ukulinga Research Station for plant traits such as stalk lodging, plant and ear heights, anthesis and silking days, which were more significant than the population means and the mean of the commercial check hybrids (Table 4). The grain moisture content at harvest of selected hybrids was generally above the mean of the population, and the commercial check hybrids

Table 2 Mean squares for grain yield and its components for Population A and B from combined analyses

Maize hybrid population A over two sites

Source of variation	Site (n = 1)	Check (n = 2)	X(Check) (n = 279)	Site*Check (n = 2)	Site*X(Check)	DF	MS (Error)	DF
Anthesis days	111.21***	76.00***	12.04***	103.58***	9.91**	221	2.42	49
Silking days	133.16***	96.47***	12.21***	127.76***	10.47***	218	2.81	51
Plant height (m)	3.81***	0.86***	0.05**	0.07	0.04	214	0.05	55
Ear height (m)	0.48***	3.78***	0.029	0.11**	0.02	233	0.02	57
Stalk lodging (%)	11170***	1899.34***	219.21***	1539.93***	159.60***	277	56.73	57
Root lodging (%)	1791.36***	108.27	58.83	75.18	60.09**	277	41.61	57
Ears per plant (No)	0.34***	2.63***	0.09***	0.10***	0.05***	277	0.02	57
Moisture content (%)	22.21***	91.99***	1.97***	7.18***	1.17	278	0.88	57
Grain yield (t ha^{-1})	154.26***	181.09***	9.64***	40.21***	5.44**	278	2.98	57

Maize hybrid population B over three sites

Source of variation	Site (n=2)	Check (n=2)	X(Check) (n=159)	Site*Check (n=4)	Site*X(Check)	DF	MS (Error)	DF
Anthesis days	2829.25***	38.25***	13.08***	68.84***	9.43***	293	4.06	69
Silking days	2364.02***	15.26*	11.734***	47.14***	8.58***	290	3.97	70
Plant height (m)	12.34***	0.21**	0.056***	0.091*	0.03	285	0.03	65
Ear height (m)	0.53***	0.17***	0.040***	0.026	0.017	316	0.01	75
Stalk lodging (%)	2627.10***	1083.76***	223.29***	338.60*	193.41***	157	66.37	45
Root lodging (%)	295.11***	113.40***	39.26***	60.17***	38.32***	157	3.74	45
Ears per plant (No.)	3.69***	4.87***	0.13***	0.80***	0.080*	316	0.06	75
Grain moisture	927.94***	1.32	5.66***	31.13***	5.49***	316	1.6	74
Grain yield (t ha^{-1})	1375.45***	167.32***	1.87**	13.11**	1.27*	316	1.73	74

*, **, *** indicates the data is significant at respectively $P \leq 0.05$, $P \leq 0.01$, $P \leq 0.001$; "grain moisture" describes percentage grain moisture content at harvest; "X (Check)" represents experimental single-cross hybrids nested within checks; (n) indicates degrees of freedom; DF, Degrees of freedom.

Predicted genetic gain for Population A

Results indicate a predicted gain of 19.75% and 13.42% for grain yield and ear prolificacy, respectively, for selected hybrids across sites (Table 3). The levels of predicted gains were similar at the Cedara and Ukulinga Research Stations (Table 4). The gains in secondary traits such as anthesis and silking days, plant and ear heights, and stalk and root lodgings were not in the desired direction (Table 3 and Table 4). The grain moisture content at harvest of selected hybrids was generally above the mean by 6 to 9%.

Negligible genetic variation was observed for ear prolificacy and plant and ear height across sites (Table 3). The remaining traits had low genetic variation ranging from 1.97 to 17.13% for grain moisture content at harvest and stalk lodging. The coefficient of genotypic variation and heritability estimates ranged from low (2.11%) for days to anthesis to high (59.90%) for root lodging for the economic traits (Table 3). Most of the traits had a low coefficient of variation, except stalk and root lodging with a high coefficient of variation estimates, 66.78% and 210.92%, respectively. A comparable trend was also observed for the economic traits at individual sites (Table 4).

Mean performance of individual hybrids

Six experimental single-cross hybrids outperformed the top commercial check hybrids (Table 5). The six experimental single cross hybrids 12C22785 (14.89

Table 3 Estimates of realized and predicted a gain of grain yield and its components of top-performing hybrids from Population A at 10% selection intensity across two sites

Combined sites															
Realized genetic gain								Predicted genetic gain							
Traits	MS	MP	MBC	MCS	RG 1(%)	RG 2(%)	RG 3(%)	δ^2_g	CGV (%)	h^2 (%)	CV	CGV/CV	St Dev	GG	GG (%)
AD	77.87	78.68	77.60	77.16	−1.02	0.35	0.92	2.69	2.11	39.90	1.74	0.01	1.34	0.94	1.21
SD	77.83	79.11	81.31	77.62	−1.62	−4.28	0.27	3.19	2.30	43.99	5.21	0.00	1.39	1.08	1.38
PH	2.84	2.77	2.76	2.79	2.58	2.87	2.01	0.02	4.52	64.33	8.03	0.01	0.09	0.10	3.59
EH	1.39	1.34	1.30	1.26	3.78	6.26	9.84	0.08	20.21	89.15	10.96	0.02	0.08	0.13	9.05
SL	10.68	11.82	1.70	11.25	−9.59	529.22	−5.00	17.13	38.74	16.67	66.87	0.01	5.46	1.60	15.00
RL	2.61	4.13	0.33	2.58	−36.92	686.99	1.06	2.44	59.90	7.95	210.92	0.00	2.07	0.29	11.10
EPP	1.48	1.41	1.62	1.32	5.06	−8.64	11.81	0.06	16.07	86.60	9.01	0.02	0.13	0.20	13.42
MC	16.48	15.98	15.84	15.45	3.10	4.05	6.66	1.97	8.52	87.88	5.90	0.01	0.65	1.01	6.10
GY	13.04	9.53	13.77	11.39	36.85	−5.27	14.54	3.16	13.62	57.19	18.07	0.01	2.56	2.58	19.75

MS-mean of a sampled population; MP-mean of the total Population; MBC-mean of the better check; MCS-mean of all checks; RG 1-percentage realized gain 1; RG 2-percentage realized gain 2; RG 3-percentage realized gain 3; δ^2_g-genetic variance; CGV-coefficient of genotypic variation; h^2 (%)-percentage heritability; CV-coefficient of variance; St dev-standard deviation; GG-genetic gain; GG (%)-percentage genetic gain; AD-anthesis days; SD-silking days; PH-plant height (cm); EH-ear height (cm); SL-percentage stalk lodging; RL-percentage root lodging; EPP-number of ears per plant (ear prolificacy); MC-percentage grain moisture content at harvest; GYD-grain yield (t ha^{-1}).

t/ha), 12C20628 (14.78 t/ha), 11C1774 (14.67 t/ha), 12C20264 (14.03 t/ha), 12C20595 (13.81 t/ha) and 11C1645 (t/ha) displayed significantly higher yield potential than best commercial check hybrid PAN6Q4445B (13.77 t/ha) ($P \leq 0.05$). All selected top hybrids were significantly ($P \leq 0.05$) better yielding than the mean of checks (11.39 t/ha). Another important trait for the South African market is high ear prolificacy. In this regard, there was a significant improvement because, in the top ten, there were five experimental single-cross hybrids 12C20628 (1.64), 11C1774 (1.78), 12C20595 (1.68), 12C20300 (1.82), and 12C20558 (1.67) with better ear prolificacy relative to best commercial check hybrid PAN6Q4445B (1.62) at ($P \leq 0.05$). The other desirable attribute for hybrids developed for the South African market is early physiological maturity, which is reflected by days to pollen shedding and silk emergence (flowering days), and low grain moisture content at harvest. However, the selected experimental single-cross hybrids performed poorly for grain moisture content at harvest (Table 5). They exhibited higher grain moisture content at harvest than the best commercial check hybrid (PAN6Q445B). However, experimental single-cross hybrid 12C20264 was the outstanding exception because it combined high yield potential (14.03 t/ha) with low grain moisture content (15%) relative to the best commercial check hybrid (PAN6Q445B) that had a grain yield potential performance of 13.77 t/ha and 15.84% grain moisture content at harvest across sites. It displayed a similar trend for the flowering days. Plant traits such as plant and ear height and stem and root lodging are critical in South African environments. In general, plants of

Table 4 Estimates of realized gain and predicted gain of grain yield and its components of top-performing hybrids from population A at 10% selection intensity at individual sites

Realized genetic gain								Predicted genetic gain							
Traits	MS	MP	MBC	MCS	RG1 %	RG2 %	RG3 %	δ^2_g	CGV (%)	h^2 (%)	CV	CGV/CV	St Dev	GG	GG (%)
AD	77.54	77.18	79.08	77.7	0.46	−1.94	−0.21	0.25	0.65	10.50	1.51	0.00	0.97	0.18	0.23
SD	76.59	76.27	78.08	76.95	0.42	−1.9	−0.46	0.15	0.51	12.78	1.47	0.00	0.71	0.16	0.21
PH	2.52	2.72	2.69	2.69	−7.33	−6.61	−6.31	0.02	6.23	92.86	5.86	0.01	0.13	0.21	7.82
EH	1.25	1.27	1.25	1.17	−1.32	0.4	7.51	0.07	21.79	60.68	12.38	0.02	0.10	0.10	8.10
SL	17.52	17.72	5.00	22.25	−1.16	250.36	−21.27	184.90	77.62	63.13	54.64	0.01	9.17	10.19	57.49
RL	0.91	0.29	0.28	0.89	219.29	231.82	2.82	0.03	19.66	1.45	120.22	0.00	0.36	0.01	3.25
EPP	1.46	1.34	1.75	1.33	8.74	−16.4	9.43	0.05	15.19	74.05	9.01	0.02	0.15	0.20	14.55
MC	16.84	15.53	15.41	15.04	8.49	9.31	12.03	3.75	11.50	77.52	5.34	0.02	0.83	1.14	7.33
GY	12.87	9.27	12.84	10.37	38.79	0.21	24.13	8.14	22.17	71.06	14.79	0.02	1.17	1.46	15.78
Ukulinga research station															
Traits	MS	MP	MBC	MC	RG1 %	RG2 %	RG3 %	GV	CGV (%)	h2 (%)	CV	CGV/CV	St Dev	GG	GG (%)
AD	78.48	80.17	75.63	76.63	−2.11	3.77	2.42	8.58	3.73	44.96	1.92	0.02	2.36	1.87	2.33
SD	78.48	80.17	75.63	76.63	−2.11	3.77	2.42	10.74	4.18	50.27	2.96	0.01	2.36	2.09	2.6
PH	2.91	2.83	2.95	2.93	2.79	−1.4	−0.81	0.02	5	56.38	5.2	0.01	0.12	0.12	4.21
EH	1.45	1.40	1.48	1.39	3.75	−1.57	4.82	0.13	25.23	100	10.53	0.02	0.11	0.19	13.82
SL	5.06	5.21	0.13	1.50	−2.82	394.15	237.35	3.34	36.12	4.51	124.52	0	4.01	0.32	6.12
RL	6.77	5.98	4.15	6.18	13.21	63.1	9.61	6.72	38.29	6.16	151.67	0	4.23	0.46	7.67
EPP	1.56	1.47	1.63	1.34	6.63	−3.88	17.06	0.09	19.34	100	9.2	0.02	0.16	0.28	19.19
MC	16.57	16.38	15.54	15.69	1.21	6.67	5.65	1.67	7.79	100	4.43	0.02	0.87	1.53	9.35
GY	15.55	9.82	17.06	13.04	58.4	−8.83	19.27	3.86	12.63	36.41	17.38	0.01	2.07	1.33	13.51

MS - mean of a sampled population; MP- mean of the total Population; MBC-mean of the better check; MCS-mean of all checks; RG 1-percentage realized gain 1; RG 2-percentage realized gain 2; RG 3-percentage realized gain 3; δ^2_g-genetic variance; CGV-coefficient of genotypic variation; h^2 (%)-percentage heritability; CV-coefficient of variance; St dev-standard deviation; GG-genetic gain; GG (%)-percentage genetic gain. AD-anthesis days; SD-silking days; PH-plant height (cm); EH-ear height (cm); SL-percentage stalk lodging; RL-percentage root lodging; EPP-number of ears per plant (ear prolificacy); MC-percentage moisture content at harvest; GYD-grain yield (t ha^{-1}).

short stature are preferred. Although the highest yielding hybrids were taller than standard commercial check hybrids, there were a few experimental single-cross hybrids (12C20595, 11C2234, and 11C1483) that performed better than the standard checks across sites but were low yielding (Table 5).

Individual site data Tables 6 and 7 for Cedera Research Station and Ukulinga Research Station, respectively, displaying a similar trend across site data for all the traits. At Cedera Research Station (Table 6) the top eleven experimental single-cross hybrids (12C20553, 11C1623, 12C21229, 12C20558, 12C21710, 11C1633, 12C20264, 12C22785, 12C20300, 12C19377 and 12C21210) exhibited significantly higher yield potential ranging from 12.89–14.89 t/ha relative to be best commercial check hybrid PAN6Q445B (12.84 t/ha). Ukulinga Research Station data (Table 7) demonstrated that experimental single-cross hybrids 12C20628 and 11C1174 had significantly higher grain yield potential 19.55 and 17.27 t/ha, respectively, relative to best commercial check hybrid PAN6Q445B (17.27 t/ha). Ear prolificacy and grain moisture content at harvest data highlighted that at Cedera Research Station (Table 6), three experimental single-cross hybrids 12C20300, 11C2234, and 12C21229 had exceptional performance relative to the best commercial check hybrid (PAN6Q445B) that had 1.75 ear prolificacy and

Table 5 Summary of grain yield and its components of top-performing hybrids from Population A at 10% selection intensity across sites

Entry	Name	GYD	EPP	MC	AD	SD	PH	EH	SL	RL
225	12C22785	14.89^{t}	1.28^{e}	17.07^{tu}	80.35^{t}	80.03^{s}	2.95^{p}	1.44^{r}	18.26^{q}	2.88^{i}
89	12C20628	14.78st	1.64^{t}	17.76^{v}	78.73^{q}	77.93^{m}	#	1.50^{v}	6.92^{i}	4.21^{j}
246	11C1774	14.67^{s}	1.78^{x}	15.84^{h}	76.35^{c}	#	2.84^{i}	1.40^{q}	13.11^{n}	0.40^{ab}
43	12C20264	14.03^{r}	1.35^{j}	15.00^{c}	76.60^{d}	76.46^{cd}	2.93^{o}	1.32^{j}	4.69^{f}	9.24^{n}
75	12C20595	13.81^{q}	1.68^{v}	16.31^{l}	77.85^{k}	77.18^{i}	2.73^{c}	1.47^{s}	6.06^{h}	3.99^{j}
260	11C1645	13.78^{q}	1.45^{m}	16.20^{jk}	78.85^{r}	78.83^{p}	2.86^{k}	1.36^{m}	18.44^{q}	0.44^{ab}
277	SC721	13.71^{q}	1.19^{d}	16.70^{r}	77.98^{l}	78.31^{n}	2.99^{s}	1.53^{w}	1.35^{ab}	2.54^{hi}
45	12C20300	13.44^{p}	1.82^{z}	16.30^{l}	78.60^{p}	78.56^{o}	2.90^{m}	1.34^{k}	7.01^{i}	0.22^{a}
146	12C21739	13.30^{o}	1.54^{q}	17.01st	76.98^{l}	77.13^{hi}	2.91^{n}	1.49^{u}	7.27^{ij}	1.88^{fg}
61	12C20558	12.92^{m}	1.67^{u}	15.72^{g}	80.35^{t}	79.68^{r}	2.79^{h}	1.40^{q}	2.93^{d}	1.84^{efg}
41	12C20261	12.92^{m}	1.30^{g}	17.75^{v}	76.73^{e}	#	2.98^{r}	1.48^{t}	5.37^{g}	1.75^{ef}
254	11C1541	12.89^{m}	1.33^{i}	15.65^{f}	77.35^{h}	76.79^{e}	#	1.53^{w}	15.77^{p}	1.15^{cd}
137	12C21446	12.77^{l}	1.56^{r}	18.01^{w}	79.85^{s}	79.13^{q}	#	1.56^{x}	2.27^{c}	6.91^{m}
271	11C2226	12.72^{kl}	1.50^{o}	17.06^{tu}	77.73^{j}	77.03^{gh}	#	1.25^{d}	21.60^{r}	1.25^{d}
253	11C1350	12.70^{kl}	1.81^{y}	16.95^{s}	78.23^{n}	80.56^{t}	2.85^{j}	1.31^{i}	13.90^{o}	5.50^{l}
40	12C20046	12.69^{kl}	1.13^{c}	16.17^{j}	78.48^{o}	77.46^{k}	#	1.35^{l}	34.89^{u}	0.70^{bc}
138	12C21447	12.62^{jk}	1.40^{k}	18.41^{x}	81.35^{u}	81.93^{v}	2.96^{q}	1.57^{y}	3.96^{e}	9.08^{n}
14	12C19575	12.62^{jk}	1.33^{i}	15.71^{fg}	77.35^{h}	77.33^{j}	2.84^{i}	1.28^{g}	28.69^{t}	0.37^{ab}
245	11C1579	12.56^{ij}	1.33^{i}	16.26^{kl}	76.60^{d}	77.06^{h}	2.85^{j}	1.27^{f}	10.54^{k}	2.54^{hi}
256	11C1563	12.53^{hij}	1.40^{k}	15.80^{h}	76.10^{b}	#	2.74^{d}	1.35^{l}	13.83^{o}	0.37^{ab}
92	12C20684	12.45^{ghi}	1.70^{w}	15.27^{d}	77.35^{h}	76.10^{b}	2.73^{c}	1.39^{o}	4.18^{ef}	1.40^{de}
272	11C2234	12.43^{gh}	2.05^{aa}	16.40^{mn}	76.60^{d}	76.36^{c}	2.61^{b}	1.38^{n}	1.37^{ab}	1.07^{cd}
263	11C1715	12.43^{gh}	1.35^{j}	16.55^{p}	75.98^{a}	76.81^{ef}	2.78^{g}	1.17^{c}	1.57^{b}	2.54^{hi}
240	11C1483	12.40^{g}	1.51^{p}	16.41^{n}	76.73^{e}	76.03^{ab}	2.73^{c}	1.13^{b}	0.90^{a}	1.25^{d}
278	SC633	12.38^{fg}	1.29^{f}	14.81^{b}	76.35^{c}	76.56^{d}	2.87^{l}	1.42^{q}	24.93^{s}	4.91^{k}
20	12C19746	12.36^{fg}	1.00^{a}	16.52^{op}	78.10^{m}	76.92^{fg}	2.86^{k}	1.17^{c}	14.32^{o}	2.26^{gh}
29	12C19933	12.28^{ef}	1.64^{t}	16.62^{q}	78.23^{n}	77.67^{l}	2.79^{h}	1.32^{j}	7.66^{j}	0.45^{ab}
139	12C21448	12.17^{e}	1.33^{i}	17.11^{u}	78.73^{q}	77.88^{m}	2.84^{i}	1.62^{z}	7.34^{ij}	1.88^{fg}
	Mean of selected	13.04^{n}	1.48^{n}	16.48^{o}	77.87^{kl}	77.83^{m}	2.84^{i}	1.39^{o}	10.68^{k}	2.61^{hi}
	Mean population	9.53^{b}	1.41^{l}	15.98^{i}	78.68^{pq}	79.11^{q}	2.77^{f}	1.34^{k}	11.82^{m}	4.13^{j}
	Check 1 (PAN3Q740 temperate)	7.58^{a}	1.03^{b}	14.11^{a}	77.95^{kl}	76.70^{e}	2.60^{a}	0.90^{a}	2.63^{cd}	0.99^{cd}
	Check 2 (PAN67-tropical)	11.82^{d}	1.35^{j}	17.04^{t}	76.75^{e}	75.93^{a}	2.90^{m}	1.42^{q}	15.73^{p}	4.09^{j}
	Check 3 (SC633 tropical)	12.38^{fg}	1.29^{f}	14.81^{b}	76.35^{c}	76.56^{d}	2.87^{l}	1.42^{q}	24.93^{s}	4.91^{k}
	Check 4 (PAN6Q445B temperate)	13.77^{q}	1.62^{s}	15.84^{h}	77.60^{d}	81.31^{u}	2.76^{e}	1.30^{h}	1.70^{b}	0.33^{ab}
	Mean of checks	11.39^{c}	1.32^{g}	15.45^{e}	77.16^{g}	77.62^{l}	2.79^{h}	1.26^{e}	11.25^{l}	2.58^{hi}
	LSD $_{(0.05)}$	0.12	0.01	0.07	0.11	0.12	0.01	0.01	0.53	0.46
	CV (%)	18.07	9.01	5.9	1.74	5.21	8.03	10.96	66.87	210.92
	St dev	2.56	0.13	0.65	1.34	1.39	0.09	0.08	5.46	2.07
	SE	18.07	9.01	5.9	1.74	5.21	8.03	10.96	66.87	210.92

Table 5 continued

Entry	Name	GYD	EPP	MC	AD	SD	PH	EH	SL	RL
	Pr>F	**	***	**	***	***	*	NS	***	NS

AD-anthesis days; SD-silking days; PH-plant height (cm); EH-ear height (cm); SL-percentage stalk lodging; RL-percentage root lodging; EPP-number of ears per plant (ear prolificacy); MC-percentage moisture content at harvest; GYD-grain yield (t ha^{-1}); SE-standard error, NS-not significant at $P = 0.05$; *,**,***significant at 0.05; 0.01; 0.001 level, respectively. #-missing data; temperate-temperate germplasm; tropical-tropical germplasm; Means with the same superscript letter in the same column are not significantly different at 0.05.

15.41% grain moisture content at harvest. At Ukulinga Research Station (Table 7), one experimental single-cross hybrid (12C20300) that combined good ear prolificacy (1.78) and grain moisture at harvest (15.29%) relative to best commercial hybrid PAN6Q445B, 1.63 ear prolificacy and 15.54% grain moisture content at harvest.

Plant traits data for plant and ear heights and stem and root lodging at individual sites (Table 6 and 7) illustrated a similar trend across sites. Although the highest yielding experimental single-cross hybrids were taller than standard commercial check hybrids, a few experimental single-cross hybrids performed better than the standard checks. At Ukulinga Research Station, an exceptional experimental single-cross hybrid 12C20628 combined top-grain yield potential with short plant stature (Table 7). With respect to standing ability, the top-yielding hybrids were generally inferior to the commercial hybrids. Four experimental single-cross hybrids 12C20553, 12C20558, 12C20684, and 12C21710 exhibited good stalk strength compared to the mean of the population and the mean of commercial check hybrids at Cedara Research Station (Table 6). Ten experimental single-cross hybrids exhibited good root strength relative to the population mean and the mean of commercial hybrids at Ukulinga Research Station (Table 7). The top three hybrids, 12C20628, 12C20595, and 12C22785, combined high yield potential with good root strength. A generally similar trend was observed for grain moisture content at harvest and flowering days at Ukulinga Research Station (Table 7) relative to the mean of the best commercial check hybrid (PAN6Q445B). However, here experimental single-cross hybrid 11C774 exhibited exceptional low grain moisture content (14.54%) at harvest combined with high grain yield potential (17.27 t/ha) relative to the mean of the best commercial check hybrid PAN6Q445B, 15.54% grain moisture content at harvest and 17.06 t/ha grain yield, respectively.

Realized genetic gain for Population B

Results showed positive gains (25%) for grain yield of the selected hybrids over the Population mean, but there was negative gain realized relative to the commercial check hybrids (Table 8). A similar trend was observed for ear prolificacy. There was a smaller gain for grain yield and the number of ears per plant at Potchefstroom Research Station than at Cedara and Ukulinga Research Station (Table 9). The trends for secondary traits such as grain moisture content at harvest and anthesis and silking days were similar to observations in Population A. Contrary to Population A; there was a general increase in stalk and root lodging and plant and ear height in Population B.

Predicted genetic gain for Population B

Predicted genetic gains in Population B (Table 8) exhibited lower genetic gains, 11.53 and 5.06% for grain yield and number of ears per plant, respectively, compared to Population A. However, increases in predicted gains, ranging from 12 to 28%, were observed at all the individual sites (Table 9). Similar to Population A, secondary traits, anthesis

and silking days, plant and ear heights, and stalk and root lodgings had predicted gains, not in the desired direction (Table 8 and Table 9). The grain moisture content at harvest also exhibited similar trends to Population A, with selected hybrids generally showing grain moisture content at harvest above the mean.

Low genetic variation was observed for traits such as anthesis and silking days, root lodging, ear prolificacy, and grain moisture at harvest across sites (Table 8). Grain yield had a negligible genetic

Table 6 Summary of grain yield and its components of top-performing hybrids from Population A at Cedara Research Station

Cedara research station										
Entry	Name	GY	EPP	MC	AD	SD	PH	EH	SL	R.L.
60	12C20553	14.39^{t}	1.30^{g}	18.46^{y}	78.08^{h}	78.08^{j}	2.42^{e}	0.97^{c}	5.50^{e}	0.28^{b}
257	11C1623	14.09^{s}	1.03^{a}	18.36^{x}	78.08^{h}	76.08^{d}	2.27^{b}	0.76^{a}	10.50^{g}	5.28^{g}
131	12C21229	13.79^{r}	1.79^{w}	15.46^{fg}	78.08^{h}	77.08^{h}	2.68^{n}	1.18^{j}	18.50^{k}	0.28^{b}
61	12C20558	13.49^{q}	1.54^{r}	17.66^{n}	79.08^{i}	77.08^{h}	2.44^{g}	1.09^{f}	5.50^{e}	0.28^{b}
144	12C21710	13.24^{p}	1.19^{c}	17.21^{qr}	77.58^{fg}	77.08^{h}	2.58^{j}	1.31^{o}	1.50^{b}	0.28^{b}
259	11C1633	13.24^{p}	1.56^{s}	17.11^{p}	75.58^{fg}	74.58^{a}	2.37^{c}	0.97^{c}	35.00^{p}	2.73^{f}
43	12C20264	13.19^{op}	1.53^{q}	16.11^{jk}	75.58^{fg}	75.58^{c}	2.91^{w}	1.42^{u}	11.00^{gh}	0.28^{b}
225	12C22785	13.19^{op}	1.23^{d}	17.91^{v}	79.08^{i}	78.58^{i}	2.78^{s}	1.32^{p}	36.50^{q}	0.28^{b}
45	12C20300	13.14^{o}	1.86^{y}	16.56^{m}	78.08^{h}	77.08^{h}	2.78^{s}	1.07^{e}	10.50^{g}	6.28^{h}
1	12C19377	12.94^{n}	1.37^{k}	15.51^{gh}	77.58^{fg}	77.08^{h}	2.68^{n}	1.20^{k}	6.50^{f}	0.28^{b}
92	12C20684	12.89^{mn}	1.36^{j}	15.96^{i}	78.08^{h}	76.08^{d}	2.43^{f}	1.12^{g}	5.50^{e}	0.28^{b}
127	12C21210	12.84^{m}	1.75^{v}	16.06^{j}	83.58^{j}	77.58^{i}	#	1.39^{t}	22.50^{l}	0.28^{b}
135	12C21443	12.79^{lm}	1.52^{p}	16.66^{n}	78.08^{h}	77.08^{h}	2.49^{h}	1.09^{f}	13.50^{i}	0.28^{b}
137	12C21446	12.79^{lm}	1.56^{j}	18.51^{y}	77.58^{fg}	77.58^{i}	#	1.50^{x}	5.00^{de}	0.28^{b}
138	12C21447	12.74^{l}	1.17^{b}	17.86^{v}	78.08^{h}	76.58^{f}	2.76^{r}	1.39^{t}	14.00^{i}	0.28^{b}
78	12C20603	12.64^{k}	1.30^{g}	14.66^{c}	77.08^{e}	76.08^{d}	2.71^{p}	1.36^{r}	37.50^{r}	0.28^{b}
88	12C20625	12.59^{jk}	1.60^{u}	16.11^{jk}	79.08^{i}	77.58^{i}	#	1.38^{s}	0.50^{a}	0.28^{b}
272	11C2234	12.59^{jk}	1.81^{x}	16.81^{o}	76.58^{d}	76.58^{f}	2.44^{g}	1.35^{q}	0.00^{a}	0.28^{b}
37	12C20041	12.54^{ij}	1.42^{n}	18.91^{z}	75.58^{c}	75.08^{b}	#	1.29^{n}	6.50^{f}	0.28^{b}
38	12C20044	12.49^{hi}	1.59^{t}	15.11^{e}	75.58^{c}	75.58^{c}	#	1.64^{y}	88.00^{t}	0.28^{b}
75	12C20595	12.49^{hi}	1.37^{k}	16.16^{k}	78.08^{h}	77.08^{h}	2.41^{d}	1.12^{g}	11.50^{g}	0.28^{b}
260	11C1645	12.49^{hi}	1.41^{m}	16.26^{l}	77.58^{fg}	77.58^{i}	2.83^{t}	1.38^{s}	32.50^{n}	2.23^{e}
268	11C2139	12.49^{hi}	1.27^{e}	18.06^{w}	77.08^{e}	76.08^{d}	0.05^{a}	1.43^{v}	3.00^{c}	0.28^{b}
8	12C19510	12.44^{h}	1.54^{r}	17.46^{s}	74.58^{a}	75.58^{c}	2.89^{v}	1.47^{w}	33.50^{o}	0.28^{b}
39	12C20045	12.29^{g}	1.41^{m}	17.76^{u}	79.08^{i}	77.08^{h}	2.63^{m}	1.01^{d}	34.50^{p}	0.28^{b}
146	12C21739	12.19^{f}	1.38^{l}	16.71^{n}	79.08^{i}	77.58^{i}	2.61^{l}	1.17^{i}	6.50^{f}	0.28^{b}
41	12C20261	12.14^{f}	1.29^{f}	16.31^{l}	75.08^{b}	75.08^{b}	2.95^{x}	1.42^{u}	11.00^{gh}	0.28^{b}
	Mean of selected	12.87^{mn}	1.46^{o}	16.84^{o}	77.54^{f}	76.59^{f}	2.52^{i}	1.25^{l}	17.52^{j}	0.91^{d}
	Mean of population	9.27^{b}	1.34^{i}	15.53^{h}	77.18^{e}	76.27^{e}	2.72^{q}	1.27^{m}	17.72^{j}	0.29^{b}
	Check 1 (PAN3Q740 temperate)	5.88^{a}	1.03^{a}	13.58^{a}	78.05^{h}	76.90^{g}	2.58^{j}	0.91^{b}	2.75^{c}	0.00^{a}
	Check 2 (PAN67 temperate)	11.11^{d}	1.34^{i}	17.24^{r}	77.10^{e}	76.25^{e}	2.87^{u}	1.38^{s}	28.25^{m}	0.55^{e}
	Check 3 (SC633 tropical)	11.64^{e}	1.23^{d}	13.91^{b}	76.58^{d}	76.58^{f}	2.60^{k}	1.13^{h}	53.00^{s}	2.73^{f}
	Check 4 (PAN6Q455B temperate)	12.84^{m}	1.75^{v}	15.41^{f}	79.08^{i}	78.08^{j}	2.69^{o}	1.25^{l}	5.00^{de}	0.28^{b}
	Mean of checks	10.37^{c}	1.33^{h}	15.04^{d}	77.70^{g}	76.95^{g}	2.69^{o}	1.17^{i}	22.25^{l}	0.89^{d}
	LSD (0.05)	0.1	0.01	0.06	0.13	0.08	0.01	0.01	0.68	0.09
	CV	14.79	9.01	5.34	1.51	1.47	5.86	12.38	54.64	120.22
	St dev	1.17	0.15	0.83	0.97	0.71	0.13	0.1	9.17	0.36
	St error	0.08	0.01	0.05	0.11	0.07	0.01	0.01	0.58	0.07
	Pr>F	*	***	**	NS	NS	NS	NS	***	NS

AD-anthesis days; SD-silking days; PH-plant height (cm); EH-ear height (cm); SL-percentage stalk lodging; RL-percentage root lodging; EPP-number of ears per plant (ear prolificacy); MC-percentage moisture content at harvest; GYD-grain yield (t ha^{-1}), NS-not significant at $P = 0.05$; *,**,***significant at 0.05; 0.01; 0.001 level, respectively; #-missing data; temperate-temperate germplasm, tropical-tropical germplasm; Means with the same superscript letter in the same column are not significantly different at 0.05

Table 7 Summary of grain yield and its components of top-performing hybrids from Population A at 10% selection intensity at Ukulinga Research Station

Entry	Name	GYD	EPP	MC	AD	SD	PH	EH	SL	RL
89	12C20628	19.55^{x}	1.55^{m}	18.44^{z}	78.13^{h}	78.13^{h}	2.69^{d}	1.49^{q}	2.88^{de}	3.65^{c}
246	11C1774	17.27^{w}	1.75^{u}	14.54^{c}	78.63^{j}	78.63^{i}	2.96^{r}	1.45^{m}	5.88^{h}	0.65^{a}
75	12C20595	16.96^{v}	2.05^{y}	18.64^{AA}	77.13^{e}	77.13^{e}	3.03^{x}	1.86^{y}	0.63^{b}	18.65^{m}
225	12C22785	16.56^{u}	1.32^{f}	16.24^{k}	81.63^{o}	81.63^{n}	3.01^{v}	1.56^{s}	0.13^{a}	5.35^{d}
271	11C2226	16.34^{t}	1.61^{p}	16.39^{m}	76.63^{d}	76.63^{d}	2.97^{s}	1.21^{d}	7.88^{i}	2.35^{b}
256	11C1563	16.14^{s}	1.63^{q}	16.09^{j}	77.13^{e}	77.13^{e}	2.86^{k}	1.47^{o}	14.88^{m}	1.85^{b}
240	11C1483	16.01^{r}	1.63^{q}	17.29^{t}	75.63^{a}	75.63^{a}	2.79^{h}	1.26^{g}	2.88^{de}	4.85^{d}
108	12C20998	15.88^{q}	1.79^{w}	16.34^{l}	84.63^{q}	84.63^{p}	2.92^{n}	1.64^{t}	0.13^{a}	4.15^{c}
253	11C1350	15.68^{p}	1.67^{s}	18.64^{AA}	78.63^{j}	78.63^{i}	2.71^{e}	1.35^{i}	0.13^{a}	4.15^{c}
245	11C1579	15.47^{no}	1.25^{e}	17.19^{s}	76.13^{b}	76.13^{b}	3.00^{u}	1.40^{k}	2.88^{de}	4.85^{d}
263	11C1715	15.44^{no}	1.54^{l}	17.79^{w}	75.63^{a}	75.63^{a}	2.99^{t}	1.33^{h}	2.63^{d}	4.85^{d}
134	12C20261	15.41^{mn}	1.36^{h}	16.74^{p}	76.13^{b}	76.13^{b}	3.09^{z}	1.46^{n}	8.88^{j}	8.65^{h}
41	12C21439	15.41^{mn}	1.37^{i}	18.19^{y}	78.13^{h}	78.13^{h}	2.93^{o}	1.50^{r}	1.13^{c}	12.65^{j}
154	12C21790	15.38^{mn}	1.55^{m}	15.64^{g}	78.13^{h}	78.13^{h}	3.05^{y}	1.56^{s}	15.88^{n}	8.65^{h}
43	12C20264	15.3^{lm}	1.13^{b}	12.99^{b}	76.63^{d}	76.63^{d}	2.93^{o}	1.22^{e}	0.13^{a}	17.35^{l}
181	12C22169	15.22^{kl}	1.6^{o}	16.69^{o}	78.63^{j}	78.63^{i}	2.49^{a}	1.16^{c}	13.88^{l}	10.85^{i}
139	12C21448	15.17^{jk}	1.6^{o}	17.09^{r}	79.63^{l}	79.63^{k}	3.15^{AB}	1.76^{w}	2.63^{d}	4.85^{d}
146	12C21739	15.1^{j}	1.74^{t}	17.39^{u}	76.63^{d}	76.63^{d}	2.94^{p}	1.70^{u}	2.88^{de}	4.85^{d}
114	12C21008	14.92^{i}	1.23^{d}	16.09^{j}	80.63^{n}	80.63^{m}	2.61^{b}	1.25^{f}	7.88^{i}	14.85^{k}
251	11C2245	14.89^{i}	1.43^{j}	16.69^{o}	76.63^{d}	76.63^{d}	2.94^{p}	1.41^{l}	2.88^{de}	4.85^{d}
267	11C1966	14.85^{i}	1.63^{q}	12.74^{a}	82.63^{p}	82.63^{o}	2.67^{c}	1.05^{b}	12.88^{k}	0.65^{a}
123	12C21197	14.73^{i}	1.66^{r}	17.19^{s}	82.63^{p}	82.63^{o}	2.72^{f}	1.26^{g}	2.88^{de}	10.85^{i}
61	12C20558	14.58^{h}	1.86^{x}	14.59^{d}	82.63^{p}	82.63^{o}	3.11^{AA}	1.72^{v}	4.38^{f}	4.85^{d}
28	12C19853	14.57^{h}	1.66^{r}	17.74^{v}	76.63^{d}	76.63^{d}	3.24^{AC}	1.79^{x}	5.88^{h}	4.85^{d}
45	12C20300	14.5^{h}	1.78^{v}	15.29^{e}	79.13^{k}	79.13^{j}	2.87^{l}	1.47^{o}	4.88^{g}	12.65^{j}
91	12C20677	14.34^{g}	1.20^{c}	18.04^{x}	76.63^{d}	76.63^{d}	3.00^{u}	1.50^{r}	6.13^{h}	1.15^{a}
172	12C21888	14.2^{f}	1.66^{r}	16.89^{q}	77.63^{f}	77.63^{f}	2.80^{i}	1.49^{q}	2.63^{d}	4.85^{d}
	Mean of selected hybrids	15.55^{o}	1.56^{n}	16.57^{n}	78.48^{i}	78.48^{i}	2.91^{m}	1.45^{m}	5.06^{g}	6.77^{f}
	Mean of population	9.82^{b}	1.47^{k}	16.382	80.17^{m}	80.17^{l}	2.83^{j}	1.40^{k}	5.21^{g}	5.98^{e}
	Check 1 (PAN3Q740 temperate)	9.28^{a}	1.04^{a}	14.63^{d}	77.85^{g}	77.85^{g}	2.77^{g}	0.89^{a}	2.50^{d}	2.00^{b}
	Check 2 (PAN67 tropical)	12.54^{c}	1.36^{h}	16.85^{q}	76.40^{c}	76.40^{c}	3.02^{w}	1.46^{n}	3.25^{e}	7.70^{g}
	Check 3 (SC633 tropical)	13.28^{e}	1.32^{f}	15.74^{i}	76.63^{d}	76.63^{d}	2.99^{t}	1.72^{v}	0.13^{a}	10.85^{i}
	Check 4 (PAN6Q445B temperate)	17.06^{v}	1.63^{q}	15.54^{f}	75.63^{a}	75.63^{a}	2.95^{q}	1.48^{p}	0.13^{a}	4.15^{c}
	Mean of checks	13.04^{d}	1.34^{g}	15.69^{h}	76.63^{d}	76.63^{d}	2.93^{o}	1.39^{j}	1.50^{c}	6.18^{ef}
	LSD(0.05)	0.12	0.01	0.05	0.11	0.17	0.01	0.01	0.43	0.62
	CV	17.38	9.2	4.43	1.92	2.96	5.2	10.53	124.52	151.67
	St dev	2.07	0.16	0.87	2.36	2.36	0.12	0.11	4.01	4.23
	St error	0.1	0.01	0.04	0.09	0.99	0.01	0.01	0.97	0.53
	Pr>F	**	**	**	***	***	***	NS	NS	*

AD-anthesis days; SD-silking days; PH-plant height (cm); EH-ear height (cm); SL-percentage stalk lodging; RL-percentage root lodging; EPP-number of ears per plant (ear prolificacy); MC-percentage moisture content at harvest; GYD-grain yield (t ha^{-1}); NS-not significant at $P = 0.05$; *,**,***significant at 0.05; 0.01; 0.001 level, respectively; temperate-temperate germplasm; tropical - tropical germplasm; Means with the same superscript letter in the same column are not significantly different at $P < 0.05$.

Table 8 Estimates of realized gain and predicted a gain of grain yield and its components of top-performing hybrids from Population B at 10% selection intensity across sites

Combined sites																
Realized genetic gain								Predicted genetic gain								
Traits	MS	MP	MBC	MCS	RG 1 (%)	RG 2 (%)	RG 3 (%)	δ^2_g	CGV (%)	h^2 (%)	CV	CGV/CV	St Dev	GG	GG (%)
AD	80.16	82.27	83.30	82.11	−2.57	−3.77	−2.38	3.71	2.40	43.56	2.45	0.01	1.09	0.84	1.04
SD	79.16	81.54	82.05	80.91	−2.92	−3.52	−2.16	2.25	1.90	36.33	2.44	0.01	1.09	0.70	0.88
PH	2.66	2.55	2.47	2.49	4.24	7.61	6.52	0.00	1.07	6.10	6.63	0.00	0.09	0.01	0.36
EH	1.26	1.25	1.23	1.22	1.08	3.04	3.33	0.00	5.45	42.21	9.64	0.01	0.09	0.07	5.30
SL	13.59	13.48	9.36	9.51	0.83	45.12	42.95	0.06	1.80	76.49	60.45	0.00	5.85	7.88	57.96
RL	2.52	2.31	0.31	0.43	9.25	706.59	484.62	1.79	53.13	55.23	83.83	0.01	1.96	1.91	75.59
EPP	1.27	1.25	1.61	1.30	1.43	−21.26	−2.34	4.53	167.57	30.40	18.79	0.09	0.12	0.06	5.06
MC	16.79	16.71	16.49	16.63	0.50	1.84	1.02	2.56	9.52	82.15	7.57	0.01	0.73	1.06	6.28
GY	6.14	4.89	6.99	6.34	25.43	−12.14	−3.20	0.11	5.46	75.88	26.88	0.00	0.53	0.71	11.53

MS-mean of a sampled population; MP-mean of the total Population; MBC-mean of the better check; MCS-mean of all checks; RG 1-percentage realized gain 1; RG 2-percentage realized gain 2; RG 3-percentage realized gain 3; δ^2_g–genetic variance; CGV-coefficient of genotypic variation; h^2 (%)–percentage heritability; CV-coefficient of variance; St dev-standard deviation; GG-genetic gain; GG (%)–percentage genetic gain; AD-anthesis days; SD-silking days; PH-plant height (cm); EH-ear height (cm); SL-percentage stalk lodging; RL-percentage root lodging; EPP-number of ears per plant (ear prolificacy); MC-percentage moisture content at harvest; GYD-grain yield (t ha^{-1}).

variation, while plant height and ear height had no genetic variation. The coefficient of genotypic variation was observed to be low for most of the economic traits, excluding root lodging and ear prolificacy, 53.13, and 167.57%, respectively (Table 8). Heritability estimates ranged from low (6.10) to high (82.15%) for plant height and grain moisture content at harvest. Root and stalk lodging were the only traits with a high coefficient of variation estimates, 83.83% and 60.45%, respectively. At individual sites, a similar trend was also observed (Table 8).

Mean performance of individual hybrids

Compared to Population A, only one experimental single-cross hybrid, 13XH349, had significantly superior grain yield potential performance (7.64 t/ha) performance relative to the best adapted commercial hybrid check (PAN6Q445B) in Population B across sites at ($P < 0.05$) (Table 10). Experimental single-cross hybrid 13XH349 also exhibited exceptional early physiological maturity through low grain moisture content at harvest (16.02%) and early anthesis and silking days 80.76 and 79.66, respectively, relative to best adapted commercial check PAN6Q445B that had 16.49% grain moisture content at harvest and flowering (anthesis and silking days) at 83.30 and 82.05 across sites, respectively. Standability data, plant and ear heights, stem and root lodging across sites (Table 10) highlighted exceptional performance from experimental single-cross hybrid 10HDTX11. The hybrid was not among the top-yielding hybrids, but it had plant height (2.41 m), ear height (1.07 m), stalk lodging (6.51%), and root lodging (0.15%) relative to the best commercial check hybrid (PAN6611) for standability; plant height (2.46 m), ear height (1.23 m), stalk lodging (9.36%) and root lodging (0.31%) at ($P < 0.05$).

Individual site data for grain yield and yield components (Table 11, 12 and 13) for Ukulinga Research Station, Cedera Research Station, and Potchefstroom Research Station, respectively, highlighted similar performance trends across site data. Grain yield potential performance data showed that at Ukulinga Research Station (Table 11), experimental single-cross hybrid 12C20258 displayed significantly higher grain yield potential performance (7.74 t/ha) relative to best commercial check hybrid

Table 9 Estimates of realized gain and predicted gain of grain yield and its components of top-performing hybrids from Population B at individual sites

Potchefstroom research station															
Realized genetic gain								Predicted genetic gain							
Traits	MS	MP	MBC	MCS	RG 1 (%)	RG 2 (%)	RG 3 (%)	δ^2_g	CGV (%)	h^2 (%)	CV	CGV/CV	St dev	GG	GG (%)
AD	84.63	86.87	91.06	88.00	−2.58	−7.07	−3.84	8.78	3.50	52.81	3.17	0.01	2.04	1.90	2.24
SD	82.91	85.97	88.00	86.38	−3.06	−5.79	−4.02	2.73	1.99	20.06	2.51	0.01	1.82	0.64	0.78
PH	2.32	2.17	1.98	2.11	0.15	17.56	10.13	0.02	5.90	80.99	5.52	0.01	0.09	0.13	5.53
EH	1.20	1.13	1.08	1.13	0.07	10.87	5.32	0.00	3.59	15.92	6.86	0.01	0.07	0.02	1.64
EPP	1.41	1.15	1.36	1.12	0.26	3.40	25.61	0.02	10.40	12.94	24.67	0.00	0.75	0.17	12.13
MC	19.01	20.96	19.11	19.32	−1.96	−0.56	−1.60	3.70	10.12	79.34	10.47	0.01	1.97	2.75	14.47
GY	2.75	1.44	2.56	2.25	1.31	7.33	22.39	0.75	31.53	100.00	34.08	0.01	0.44	0.77	28.15
Cedara research station															
AD	77.56	78.07	78.00	78.12	−0.65	−0.56	−0.72	0.10	0.41	8.62	1.16	0.00	0.59	0.09	0.12
SD	76.63	77.19	76.00	76.76	−0.73	0.82	−0.17	0.05	0.28	3.14	2.26	0.00	0.62	0.03	0.04
PH	2.25	2.26	4.52	2.75	−0.51	−50.12	−18.07	0.00	0.13	0.47	55.66	0.00	0.63	0.01	0.23
EH	1.23	1.25	1.24	1.22	−1.70	−1.13	0.49	0.00	2.27	4.76	6.19	0.00	0.09	0.01	0.61
SL	15.79	17.46	16.61	13.78	−9.56	−4.93	14.64	3.62	12.05	65.20	49.25	0.00	7.99	9.17	58.05
RL	3.01	0.71	0.16	0.16	325.76	1732.32	1732.32	0.26	16.95	2.79	150.54	0.00	0.86	0.04	1.40
EPP	1.20	1.28	1.05	1.57	−6.81	14.06	−23.74	0.24	40.74	100.00	12.05	0.03	0.16	0.28	22.98
MC	15.15	15.13	15.49	15.96	0.12	−2.24	−5.10	2.90	11.25	74.70	3.48	0.03	0.82	1.08	7.13
GY	11.65	7.83	12.93	11.32	48.82	−-9.88	2.89	5.82	20.71	100.00	13.85	0.02	1.05	1.85	15.86
Ukulinga research station															
AD	79.53	80.81	80.31	79.49	−1.58	−0.97	0.05	1.57	1.57	14.86	2.04	0.01	1.82	0.48	0.60
SD	78.94	80.59	80.25	78.83	−2.05	−1.64	0.13	3.83	2.48	42.02	2.51	0.01	1.88	1.39	1.76
PH	2.83	2.73	2.66	2.70	3.51	6.29	4.68	7.24	95.10	72.05	5.92	0.16	0.12	0.15	5.38
EH	1.28	1.26	1.24	1.19	1.59	3.28	7.49	1.03	79.17	37.34	8.66	0.09	0.10	0.07	5.13
SL	9.64	11.58	2.19	4.32	−16.79	340.54	122.92	1.58	13.04	34.29	67.65	0.00	6.55	3.95	41.02
RL	4.46	4.57	0.63	1.03	−2.45	613.13	332.20	0.59	17.24	21.70	58.48	0.00	3.51	1.34	30.08
EPP	1.28	1.15	1.64	1.23	11.09	−21.71	4.36	0.02	12.15	100.00	7.07	0.02	0.13	0.23	17.84
MC	14.12	14.11	14.16	13.77	0.09	−0.24	2.58	0.72	6.01	75.47	5.70	0.01	0.60	0.80	5.68
GYD	6.82	4.43	7.61	6.12	54.04	−10.31	11.49	5.07	32.98	100.00	16.47	0.02	0.78	1.37	20.12

MS-mean of a sampled population; MP-mean of the total population; MBC-mean of the better check; MC-mean of all checks; RG 1-percentage realized gain 1; RG 2-percentage realized gain 2; RG 3-percentage realized gain 3; δ^2_g-genetic variance; CGV-coefficient of genotypic variation; h^2 (%)-percentage heritability; CV-coefficient of variance; St dev-standard deviation; GG-genetic gain; GG (%)-percentage genetic gain; AD-anthesis days; SD-silking days; PH-plant height (cm); EH-ear height (cm); SL-percentage stalk lodging; RL-percentage root lodging; EPP-number of ears per plant (ear prolificacy); MC-percentage moisture content at harvest; GYD-grain yield (t ha^{-1})

PAN6Q4445B (7.61 t/ha) at $P < 0.05$. At Cedera Research Station (Table 12) six experimental single-cross hybrids 13XH349 (14.47 t/ha), 13XH495 (12.93 t/ha), 10HDT11 (12.56 t/ha), 12C22981 (12.01 t/ha), 13XH493 (11.79 t/ha), and 13XH641 (11.72 t/ha) had significantly higher grain yield potential performance relative to best commercial check hybrid PAN6Q4445B (11.65 t/ha). Similarly, at

Table 10 Summary of grain yield and its components of top-performing hybrids from Population B at 10% selection intensity across three sites

Entry	Name	GY	EPP	MC	AD	SD	PH	EH	SL	RL
112	13XH349	7.64^{j}	1.00^{b}	16.09^{g}	80.76^{h}	79.66^{g}	2.58^{a}	1.08^{a}	8.81^{h}	0.60^{e}
95	12C22776	6.96^{i}	1.36^{e}	16.02^{f}	80.76^{h}	79.66^{g}	2.74^{a}	1.54^{a}	25.75^{r}	10.22^{m}
123	13XH495	6.67^{h}	1.27^{d}	15.81^{e}	80.76^{h}	79.66^{g}	2.83^{a}	1.37^{a}	10.70^{k}	0.78^{g}
100	12C22981	6.38^{g}	1.23^{c}	15.42^{c}	75.28^{a}	77.80^{b}	2.50^{a}	1.29^{a}	39.10^{t}	0.06^{a}
103	13XH338	6.32^{g}	1.21^{c}	16.83^{k}	81.00^{ij}	80.24^{h}	2.61^{a}	1.27^{a}	3.42^{b}	0.65^{f}
128	13XH1060	6.26^{g}	1.47^{f}	18.01^{o}	80.00^{d}	79.07^{d}	2.72^{a}	1.51^{a}	13.78^{p}	7.43^{l}
152	10HDTX11	6.13^{f}	1.41^{e}	15.63^{d}	81.15^{j}	80.22^{h}	2.41^{a}	1.07^{a}	6.51^{f}	0.15^{b}
72	12C21724	5.93^{e}	1.56^{g}	18.46^{p}	80.98^{ij}	79.26^{e}	#	1.22^{a}	3.60^{c}	0.60^{e}
65	12C21445	5.92^{e}	1.33^{d}	20.42^{q}	80.01^{d}	80.11^{h}	2.72^{a}	0.99^{a}	6.00^{e}	5.60^{k}
110	13XH346	5.88**e**	1.15^{c}	14.64^{a}	80.33^{f}	79.52^{f}	2.65^{a}	1.51^{a}	24.63^{q}	0.15^{b}
121	13XH493	5.82^{d}	1.23^{c}	17.66^{m}	80.61^{g}	80.18^{h}	2.60^{a}	1.18^{a}	3.90^{d}	0.60^{e}
115	13XH353	5.72^{c}	1.30^{d}	15.34^{b}	78.85^{b}	77.69^{b}	2.73^{a}	1.35^{a}	33.66^{s}	0.60^{e}
76	12C21773	5.71^{c}	1.29^{d}	17.83^{n}	#	#	2.93^{a}	1.34^{a}	10.45^{j}	0.60^{e}
108	13XH344	5.64^{b}	1.32^{d}	17.02^{l}	79.39^{c}	78.13^{c}	2.74^{a}	1.14^{a}	12.83^{n}	11.10^{n}
145	13XH641	5.63^{b}	1.00^{b}	16.74^{j}	80.11^{de}	79.47^{f}	2.42^{a}	1.08^{a}	11.30^{l}	0.60^{e}
19	12C20266	5.63^{b}	1.17^{c}	16.79^{k}	82.42^{l}	76.72^{a}	2.68^{a}	1.24^{a}	2.99^{a}	0.60^{e}
	Mean of Population	4.89^{a}	1.25^{d}	16.71^{j}	82.27^{l}	81.54^{j}	2.55^{a}	1.25^{a}	13.48^{o}	2.31^{i}
	Mean of sampled Population	6.14^{f}	1.27^{d}	16.79^{k}	80.16^{e}	79.16^{de}	2.66^{a}	1.26^{a}	13.59^{o}	2.52^{j}
	Check 1 (PAN6611)	6.14^{f}	1.46^{f}	16.70^{j}	82.14^{k}	80.99^{i}	2.46^{a}	1.20^{a}	7.15^{g}	0.88^{h}
	Check 2 (PAN6Q445B)	6.99^{i}	1.61^{g}	16.49^{h}	83.30^{m}	82.05^{k}	2.47^{a}	1.23^{a}	9.36^{i}	0.31^{c}
	Check 3 (SC633)	5.89^{e}	0.83^{a}	16.69^{j}	80.89^{h}	79.68^{g}	2.55^{a}	1.24^{a}	12.00^{m}	0.10^{a}
	Mean of checks	6.34^{g}	1.30^{d}	16.63^{i}	82.11^{k}	80.91^{i}	2.49^{a}	1.22^{a}	9.51^{i}	0.43^{d}
	LSD (0.05)	0.02	0.02	0.07	0.18	0.15	1.42	0.96	0.15	0.07
	CV	26.88	18.79	7.57	2.45	2.44	6.63	9.64	60.45	83.83
	St dev	0.53	0.12	0.73	1.09	1.09	0.09	0.09	5.85	1.96
	St error	0.16	1.88	0.58	1.25	9.43	0.1	0.09	1.51	0.63
	Pr > F	**	**	***	***	***	***	*	***	***

AD-anthesis days; SD-silking days; PH-plant height (cm); EH-ear height (cm); SL-percentage stalk lodging; RL-percentage root lodging; EPP-number of ears per plant (ear prolificacy); MC-percentage moisture content at harvest; GYD-grain yield (t ha^{-1}); SE-standard error, NS-not significant at P = 0.05; *,**,***significant at 0.05; 0.01; 0.001 level, respectively. #-missing data; temperate-temperate germplasm; tropical-tropical germplasm; Means with the same superscript letter in the same column are not significantly different at P = 0.05.

Potchefstroom Research Station (Table 13), 75% of the selected experimental single-cross hybrids exhibited significant-high grain yield potential performance ranging from 11.72–14.47 t/ha relative to best commercial check hybrid PAN6Q4445B (11.72 t/ha) at $P < 0.05$.

Prolificacy data highlighted that at Ukulinga Research Station, experimental single-cross hybrid 11C2245 not only exhibited high grain yield potential performance but had ear prolificacy (1.81) that was better than the best commercial check hybrid PAN6Q445B (1.64) at $P < 0.05$. At Cedera Research Station, an experimental single-cross hybrid (13XH641) was the only hybrid that combined high grain yield potential performance (11.72 t/ha) and ear prolificacy (1.52) relative to the best commercial check hybrid (PAN6611). Similarly, at Potchefstroom Research Station, three experimental single-cross hybrids 12C22449, 12C21216, and 12C20565 combined high grain yield potential performance with high ear prolificacy 1.71, 1.49, and 1.92, respectively relative to best commercial check hybrid PAN6Q445B

Table 11 Summary of grain yield and its components of top-performing hybrid from Population B at 10% selection intensity at Ukulinga Research Station

Ukulinga research station										
Entry	Name	GYD	EPP	MC	AD	SD	PH	EH	SL	RL
18	12C20258	7.74^{p}	1.02^{d}	13.50^{f}	79.66^{g}	77.50^{d}	3.01^{a}	1.43^{a}	9.16^{i}	4.03^{e}
1	12C19358	7.42^{n}	1.30^{l}	11.30^{a}	78.66^{c}	76.50^{c}	2.95^{a}	1.07**a**	10.16^{k}	4.46^{f}
153	11C2245	7.41^{n}	1.81^{t}	13.95^{h}	80.66^{j}	79.50^{h}	2.86^{a}	1.35^{a}	18.16^{p}	10.03^{i}
112	13XH349	7.36^{m}	1.08^{f}	14.55^{j}	80.16^{h}	78.50^{f}	2.90^{a}	1.29^{a}	11.16^{l}	1.030^{b}
33	12C20582	7.28^{m}	1.40^{o}	15.20^{l}	81.66^{m}	83.00^{m}	2.58^{a}	1.32^{a}	4.16^{d}	20.03^{k}
16	12C19945	7.26^{l}	1.27^{j}	12.40^{d}	81.16^{l}	80.50^{j}	3.06^{a}	1.51^{a}	8.16^{h}	0.63^{a}
6	12C19529	7.22^{k}	1.00^{c}	13.80^{g}	81.66^{m}	84.00^{n}	2.79^{a}	1.21^{a}	4.16^{d}	4.97^{h}
110	13XH346	6.94^{j}	1.32^{m}	13.50^{f}	76.16^{a}	75.50^{b}	3.03^{a}	1.47^{a}	11.16^{l}	1.03^{b}
55	12C21014	6.48^{h}	1.30^{l}	13.00^{e}	80.66^{j}	81.00^{k}	2.36^{a}	1.16^{a}	4.16^{d}	1.44^{c}
106	13XH342	$6.4g^{h}$	1.44^{p}	14.85^{k}	83.66^{n}	81.50^{l}	2.94^{a}	1.24^{a}	15.16^{o}	1.97^{d}
53	12C20976	6.38^{gh}	0.98^{b}	15.40^{n}	76.16^{a}	75.00^{a}	2.59^{a}	1.13^{a}	9.16^{i}	1.03^{b}
13	12C19777	6.38^{g}	1.44^{p}	15.40^{n}	78.16^{b}	77.50^{d}	2.81^{a}	1.25^{a}	12.16^{n}	1.03^{b}
53	12C20976	6.37^{g}	1.57^{r}	15.50^{o}	76.16^{a}	75.00^{a}	2.79^{a}	1.27^{a}	22.16^{q}	1.97^{d}
108	13XH344	6.21^{f}	1.05^{e}	15.60^{p}	79.66^{g}	81.00^{k}	2.31^{a}	1.05^{a}	10.16^{k}	19.03^{k}
129	13XH619	6.19^{f}	1.21^{h}	12.70^{d}	78.16^{b}	77.50^{d}	3.49^{a}	1.67^{a}	3.84^{c}	1.03^{b}
151	11C1579	6.15^{e}	1.37^{n}	15.30^{m}	80.16^{h}	79.50^{h}	2.78^{a}	1.04^{a}	1.16^{a}	1.03^{b}
	Mean of population	4.43^{a}	1.15^{g}	14.11^{i}	80.81^{k}	80.60^{j}	2.73^{a}	1.26^{a}	11.58^{m}	1.03^{b}
	Mean of sampled hybrids	6.82_{i}	1.28^{k}	14.12^{i}	$79.53f^{g}$	78.90^{g}	2.83^{a}	1.28^{a}	9.64^{j}	4.57^{g}
	Check1 (PAN6611)	5.95^{c}	1.45^{q}	14.84^{k}	79.00^{d}	77.80^{e}	2.60^{a}	1.12^{a}	6.13^{g}	1.03^{b}
	Check2 (PAN6Q445B)	7.61^{o}	1.64^{s}	14.16^{i}	80.31^{i}	80.30^{i}	2.66^{a}	1.24^{a}	2.19^{b}	1.03^{b}
	Check3 (SC633)	4.81^{b}	0.60^{a}	12.3^{b}	79.16^{e}	78.50^{f}	2.84^{a}	1.22^{a}	4.66^{f}	1.03^{b}
	Mean of checks	6.12^{d}	1.23^{i}	13.77^{g}	79.49^{f}	78.80^{g}	2.7a	1.19^{a}	4.32^{e}	1.03^{b}
	St dev	0.78	0.13	0.6	1.82	1.88	0.12	0.1	6.55	3.51
	St error	0.15	0.01	0.06	0.13	0.16	1.27	0.86	0.55	0.18
	LSD (0.05)	0.03	0.01	0.07	0.15	0.18	1.42	0.96	0.15	0.07
	CV	16.47	7.07	5.7	2.04	2.51	5.92	8.66	67.65	58.48
	Pr > F	NS	NS	NS	**	*	NS	NS	**	***

AD-anthesis days; SD-silking days; PH-plant height (cm); EH-ear height (cm); SL-percentage stalk lodging; RL-percentage root lodging; EPP-number of ears per plant (ear prolificacy); MC-percentage moisture content at harvest; GYD-grain yield (t ha^{-1}); SE-standard error, NS-not significant at $P = 0.05$; *,**,***significant at 0.05; 0.01; 0.001 level, respectively. #-missing data; Means with the same superscript letter in the same column are not significantly different at $P = 0.05$.

(1.36) at $P < 0.05$. Early maturity traits that are shown by low grain moisture content at harvest and early flowering data indicated that at Ukulinga Research Station (Table 11), only one experimental single-cross hybrid (12C19358) demonstrated low (11.30%) grain moisture content at harvest and early flowering (anthesis days–78.66 and silking days–76.50) relative to best commercial check hybrid PAN6Q445B that had 14.16% grain moisture content at harvest and flowering (anthesis days–80.31 and silking days–80.30). Similarly, at Potchefstroom Research Station (Table 13), the top four experimental hybrids 13XH356, 12C22449, 12C22776, and 13XH350 had low grain moisture at harvest and early flowering (silking and anthesis days) relative to the best commercial check hybrid PAN6Q445B. However, at Cedera Research Station (Table 12), no experimental single-cross hybrid combined high grain yield potential and early maturity traits.

Table 12 Summary of grain yield and its components of top-performing hybrid from Population B at 10% selection intensity at Cedara Research Station

Cedera research station										
Entry	Name	GY	EPP	MC	AD	SD	PH	EH	SL	RL
112	13XH349	14.47^{p}	0.94^{b}	13.84^{c}	77.00^{b}	76.00^{a}	1.70^{b}	1.08^{c}	6.45^{c}	0.16^{b}
123	13XH495	12.93^{o}	1.05^{d}	15.49^{j}	78.00^{e}	76.00^{a}	4.52^{k}	1.24^{j}	16.61^{ij}	0.16^{b}
152	10HDTX11	12.56^{m}	1.35^{m}	14.54^{e}	78.00^{e}	76.00^{a}	1.70^{b}	1.29^{m}	39.78^{m}	0.16^{b}
100	12C22981	12.01^{l}	1.06^{e}	15.94^{l}	77.00^{b}	77.00^{c}	1.78^{c}	1.18^{f}	0.83^{a}	0.16^{b}
121	13XH493	11.79^{k}	1.13^{g}	14.64^{f}	76.00^{a}	76.00^{a}	1.64^{b}	1.08^{c}	6.45^{c}	0.16^{b}
145	13XH641	11.72^{k}	1.52^{p}	15.34^{i}	77.00^{b}	76.00^{a}	2.11^{e}	1.54^{q}	51.83^{n}	0.16^{b}
95	12C22776	11.57^{i}	1.13^{f}	19.24^{r}	77.00^{b}	76.00^{a}	2.08^{e}	1.42^{o}	6.45^{c}	0.16^{b}
71	12C21711	11.32^{h}	1.57^{q}	15.96^{l}	78.12^{f}	76.76^{b}	2.75^{g}	1.22^{h}	13.78^{f}	0.16^{b}
14	12C19794	10.79^{f}	1.84^{t}	16.21^{op}	77.79^{d}	76.73^{b}	1.88^{d}	1.23^{i}	16.54^{i}	0.10^{a}
38	12C20698	10.62^{d}	1.04^{c}	15.74^{k}	77.00^{b}	76.00^{a}	1.89^{d}	1.24^{j}	15.09^{gh}	0.16^{b}
19	12C20266	10.47^{b}	0.83^{a}	12.64^{a}	80.00^{i}	79.00^{f}	3.04^{h}	0.87^{a}	7.81^{d}	0.16^{b}
86	12C22336	10.31^{b}	1.22^{j}	14.84^{g}	78.00^{e}	77.00^{c}	1.88^{d}	1.51^{p}	26.94^{k}	6.83^{g}
106	13XH342	10.3^{b}	1.27^{k}	16.04^{m}	79.00^{h}	79.00^{f}	3.29^{j}	1.27^{l}	3.53^{b}	0.16^{b}
128	13XH1060	10.25^{b}	1.82^{r}	16.18^{no}	78.58^{g}	77.54^{e}	1.85^{d}	1.20^{g}	8.18^{d}	0.33^{c}
103	13XH338	10.23^{b}	1.83^{s}	17.34^{q}	78.00^{e}	77.00^{c}	0.89^{a}	1.22^{h}	14.34^{fg}	0.16^{b}
72	12C21724	7.83^{a}	1.28^{l}	15.13^{h}	78.07^{ef}	77.19^{d}	2.26^{f}	1.25^{k}	17.46^{j}	0.71^{d}
	Mean of population	12.61^{m}	1.45^{o}	16.14^{n}	78.00^{e}	77.00^{c}	3.24^{i}	1.07^{b}	15.30^{h}	0.71^{d}
	Mean of sampled hybrids	12.88^{n}	1.36^{n}	16.24^{p}	77.00^{b}	76.00^{a}	2.26^{f}	1.37^{n}	9.73^{e}	3.01^{e}
	Check1(PAN6611 temperate)	10.76^{e}	1.36^{n}	14.44^{d}	77.00^{b}	77.00^{c}	2.11^{e}	1.20^{g}	33.38^{l}	0.33^{c}
	Check2(PAN6Q445B temp)	10.51^{c}	1.21^{i}	14.44^{d}	77.00^{b}	76.00^{a}	1.92^{a}	1.17^{e}	6.45^{c}	0.00^{a}
	Check3(SC633 tropical)	10.9^{g}	1.20^{h}	12.74^{b}	78.00^{e}	76.00^{a}	1.91^{d}	1.09^{d}	6.06^{c}	0.16^{b}
	Mean of checks	11.65^{j}	1.20^{h}	15.15^{h}	77.56^{c}	76.63^{b}	2.25^{f}	1.23^{i}	15.79^{hi}	0.16^{b}
	St dev	1.05	0.16	0.82	0.59	0.62	0.63	0.09	7.99	0.86
	St error	0.13	0.02	0.48	0.23	0.16	0.56	6.19	0.59	1.51
	LSD (0.05)	0.10	0.01	0.05	0.08	0.15	0.07	0.01	0.88	0.08
	CV	13.85	12.05	3.48	1.16	2.26	55.66	6.19	49.25	150.54
	Pr > F	*	*	***	NS	NS	NS	*	*	***

AD-anthesis days; SD-silking days; PH-plant height (cm); EH-ear height (cm); SL-percentage stalk lodging; RL-percentage root lodging; EPP-number of ears per plant (ear prolificacy); MC-percentage moisture content at harvest; GYD-grain yield (t ha^{-1}); SE-standard error, NS-not significant at $P = 0.05$; *,**,***significant at 0.05; 0.01; 0.001 level, respectively; temperate-temperate germplasm; tropical-tropical germplasm; Means with the same superscript letter in the same column are not significantly different.

Plant standability traits depicted by data plant and ear heights and stem and root lodging at individual sites (Table 11, 12 and 13) illustrated that there were single-cross hybrids that combined high grain yield potential performance and good standability. At Ukulinga Research Station, experimental single-cross hybrid 12C20582 had shorter plant height (2.58 m) relative to the best commercial check hybrid PAN6Q445B (2.66 m). The rest of the top-yielding hybrids at Ukulinga Research Station had poor standability relative to the best commercial check hybrid PAN6Q445B. At Cedera Research Station, experimental single-cross hybrids (13XH349) combined significant ($P < 0.05$) high grain yield potential performance with excellent standability. This experimental single-cross hybrid had plant height (1.70 m), ear height (1.08 m), and stalk lodging (6.45%) relative to the best commercial check hybrid PAN6Q445B that had plant height (1.91 m), ear height (1.09 m), and stalk lodging (6.45%). Contrary to other individual sites, plant standability data, Potchefstroom Research Station had exceptional top-yielding hybrids with

Table 13 Summary of grain yield and its components of top-performing hybrids from Population B at 10% selection intensity at Potchefstroom Research Station

Potchefstroom research station								
Entry	Name	GY	EPP	MC	AD	SD	PH	EH
117	13XH356	3.31^{p}	1.46^{k}	17.47^{d}	78.00^{a}	76.38^{a}	2.38^{i}	1.05^{a}
89	12C22449	3.09^{o}	1.71^{o}	16.62^{c}	81.00^{c}	81.38^{f}	2.48^{k}	1.08^{b}
95	12C22776	3.08^{no}	1.36^{h}	17.54^{de}	86.00^{j}	85.88^{k}	2.28^{f}	1.08^{b}
113	13XH350	2.99^{m}	1.28^{g}	14.19^{a}	80.00^{b}	78.88^{b}	2.43^{j}	1.08^{b}
61	12C21216	2.80^{l}	1.49^{l}	21.07^{k}	88.00^{l}	86.88^{m}	2.28^{f}	1.13^{c}
29	12C20565	2.74^{jk}	1.92^{q}	21.25^{l}	83.00^{f}	83.38^{h}	2.43^{j}	1.13^{c}
11	12C19714	2.73^{jk}	1.15^{e}	15.43^{b}	88.50^{m}	87.38^{n}	2.43^{j}	1.13^{c}
51	12C20964	2.71^{ijk}	1.4^{ij}	19.87^{j}	84.00^{gh}	84.38^{i}	2.43^{j}	1.15^{d}
20	12C20306	2.7^{ij}	1.13^{de}	17.72^{e}	85.00^{i}	85.38^{j}	2.33^{h}	1.15^{d}
119	13XH358	2.68^{hi}	1.03^{b}	18.81^{f}	81.50^{d}	80.88^{e}	2.28^{f}	1.15^{d}
111	13XH348	2.65^{gh}	1.36^{h}	17.65^{de}	82.00^{e}	79.38^{c}	2.18^{e}	1.18^{e}
19	12C20266	2.63^{g}	1.02^{b}	22.45^{n}	96.50^{p}	80.88^{e}	2.38^{i}	1.18^{e}
50	12C20900	2.62^{g}	1.25f	21.6^{m}	84.50^{h}	82.88^{g}	2.18^{e}	1.20^{f}
76	12C21773	2.49^{e}	1.61^{n}	22.39^{n}	86.00^{j}	85.38^{j}	2.38^{i}	1.25^{h}
83	12C22166	2.41^{d}	1.55^{m}	18.89^{fg}	89.00^{n}	86.88^{m}	2.08^{b}	1.25^{h}
128	13XH1060	2.40^{d}	1.81^{p}	21.12^{kl}	81.00^{c}	80.38^{d}	2.28^{f}	1.25^{h}
	Mean of population	1.44^{a}	1.15^{e}	20.96^{k}	86.87k	85.97^{k}	2.17^{d}	1.33^{j}
	Mean of sampled hybrids	2.75^{k}	1.41^{j}	19.01^{gh}	84.63^{hi}	82.91^{g}	2.32^{g}	1.13^{c}
	Check 1 (PAN6611 temperate)	2.24^{c}	1.09^{c}	19.00^{g}	88.94^{n}	87.75^{o}	2.08^{b}	1.28^{i}
	Check 2 (PAN6Q445B temperate)	2.56^{f}	1.36^{h}	19.11^{h}	91.06^{o}	88.00^{p}	1.98^{a}	1.23^{g}
	Check 3 (SC633 tropical)	1.94^{b}	0.91^{a}	19.83^{j}	84.00^{gh}	83.38^{h}	2.28^{f}	1.33^{j}
	Mean of checks	2.25c	1.12^{d}	19.32^{i}	88.00^{l}	86.38^{l}	2.11^{c}	1.28i
	St dev	0.44	0.75	1.97	2.04	1.82	0.09	0.07
	St error	0.66	0.35	2.65	3.35	2.63	0.14	0.09
	LSD (0.05)	0.05	0.03	0.19	0.24	0.19	0.01	0.01
	CV	34.08	24.67	10.47	3.17	2.51	5.52	6.86
	Pr > F	*	*	*	*	**	ns	ns

AD-anthesis days; SD-silking days; PH-plant height (cm); EH-ear height (cm); SL-percentage stalk lodging; RL-percentage root lodging; EPP-number of ears per plant (ear prolificacy); MC-percentage moisture content at harvest; GYD-grain yield (t ha^{-1}); SE-standard error, NS-not significant at $P = 0.05$; *,**,***significant at 0.05; 0.01; 0.001 level, respectively; temperate - temperate germplasm; tropical - tropical germplasm; Means with the same superscript letter in the same column are not significantly different.

inferior standability data relative to best commercial check hybrid PAN6Q445B.

Discussion

Analysis of variance of the sites and maize hybrid varieties

Significant differences ($P < 0.01$) were observed for most of the traits for the experimental single-cross hybrids and commercial check hybrids evaluated in population A and B. The interaction between entries and the sites was also observed to be significant ($P < 0.05$) for most traits. This implies that the entries and genotype-by-site interaction made more significant contributions to these traits' expression than the site effect. The site effect only accounted for a small contribution to phenotypic variation. Increased influence of genotype-site interaction may suggest that the genotypes performed differently under diverse sites and that their performance was unpredictable across sites. Therefore there is a need to carry out multi-locational trials to identify hybrids that have yield stability across target sites and others that are more specifically adapted to particular locations.

Realized genetic gain

(Rutkoski 2019) realized genetic gain or expected genetic as a prediction of the phenotype's actual change that would occur due to the genetic changes brought about by a proposed selection or a proposed breeding strategy. Expected genetic gain can be estimated using parameters obtainable from breeding experiments and given various assumptions. While (Weng et al. 2008) define realized genetic gain as actually achievable gain in a breeding program; and state that it is crucial to establish the effectiveness of the breeding strategy, which is implemented to improve required traits. Realized genetic gain is the observed gain due to selection over cycles. In the current study, the Introgression of temperate germplasm into tropical elite maize inbred lines was generally effective in attaining realized genetic gains in both primary and secondary traits required in South African environments. Grain yield and ear prolificacy are the main primary traits in South African environments. The selected experimental single-cross hybrids had general superior performance relative to the population mean and significantly outperformed the best commercial check hybrid in each location. These generally positive genetic gains can be attributed to the moderate to high heritability values (Table 6.2 and Table 6.7), which ensured adequate breeding progress. Similar results for genetic gain attained in maize breeding programs have been reported for grain yield by (Darsana et al. 2004; Vashistha et al. 2013; Badu-Apraku et al. 2013; Mushayi et al. 2020). Darsana et al. (2004) reported a quadratic response for grain yield in South African environments. Abadassi and Herve (2000) reported the highest expected genetic improvement for grain yield from the introgression of temperate germplasm into an elite tropical maize population.

In comparison, Mushayi et al. (2020) reported improved yield stability from hybrids generated from crossing temperate and tropical inbred lines. Similarly, Masuka et al. (2017a, b) also reported genetic gain estimated at 0.85 to 2.2% yr $^{-1}$ under various conditions using CIMMYT Eastern and Southern Africa hybrid maize. Despite the commendable gains attained in the current study, there is still a need for further introgression of temperate germplasm to improve these primary traits of selected hybrids. The inferior performance was observed relative to the better check, the leading hybrid on the market, PAN6Q445B.

Secondary traits such as grain moisture content at harvest and flowering days generally exhibited moderate gains relative to the population mean and the mean of commercial check hybrids. Gains attained can be attributed to high values for the coefficient of genetic variance and heritability. This indicates that the traits can effectively be selected for during breeding, thus ensuring genetic gain. Breeding programs prefer high genetic gain that is associated with high heritability estimates to ensure sufficient progress. Similar results have been reported for secondary traits in maize by Darsana et al. (2004) on linear response to anthesis and silking days and grain moisture content for tropical germplasm introgressed with temperate germplasm in South Africa environments; Vashistha et al. (2013) on anthesis and silking interval, and plant and ear height; and Badu-Apraku et al. (2013) on anthesis and silking days, plant and ear height, ear prolificacy and stalk lodging. Despite the general gains reported in the current study, the selected hybrids' inferior performance relative to the better check and the Population mean was observed. This again calls for further introgression of temperate germplasm to attain the desired levels that can exceed the best commercial hybrid.

Plant aspects such as stalk and root lodging generally indicated the need for further introgression due to pronounced poor standing ability observed in the selected hybrids relative to commercial check hybrids. Poor standability observed in both populations can be credited to lower genetic variance for root and stalk strength. However, poor standability can also be attributed to frequent seasonal windstorms experienced in South African environments. Breeding progress can be achieved in a population that establishes and maintains enough genetic variation. Therefore, in future studies, there is a need to increase the genetic variation of introgressed inbred lines using additional donor inbred lines with excellent standing ability. The tropical recipient lines used during introgression came from an established breeding program; breeders tend to recycle germplasm during crop improvement, which results in narrow genetic diversity. Therefore, there is also a need to increase the genetic diversity of the tropical recipient lines through acquiring tropical germplasm from the Consultative Group on International Agricultural Research (CGIAR) institutes such as the International Maize and Wheat Improvement Centre (CIMMYT) and the International Institute of Tropical Agriculture (IITA). Many temperate inbred lines would then be used as temperate germplasm sources to introduce desired traits into tropical elite inbred lines.

Performance of individual hybrids

The general trend highlighted that the selected hybrids in both populations out yielded the tropical hybrids (SC633 and PAN67) and the temperate hybrids (PAN6611, PAN6Q445B, and PAN3Q740) in South African environments. This illustrates significant genetic gain in yield potential performance that can be credited to increased hybrids' adaptability. Most importantly, six selected experimental single-cross hybrids; 12C22785, 12C20628, 11C1774, 12C20264, 12C20595, 11C1645 and 13XH349 outperformed the best commercial check hybrid PAN6Q445B. This shows that temperate germplasm's introgression was effective for increasing the grain yield potential of tropical germplasm in South African environments. Kesornkeaw et al. (2009) report that there is low genetic diversity for ear prolificacy in tropical germplasm. However, genetic gain for ear prolificacy was observed in three selected experimental single-cross hybrids 12C20628, 11C1774, and 12C202595 that also exhibited high grain yield performance potential. The observed increase in-ear prolificacy of tropical germplasm demonstrates a positive gain in a primary trait important for South African environments.

Essential attributes for early physiological maturity, grain moisture content at harvest, and flowering days demonstrated that the introduction of temperate germplasm into tropical germplasm was generally ineffective in improving these attributes. Selected experimental single-cross hybrids had high grain moisture content at harvest and flowered late relative to commercial hybrid checks. An exception was noted for two experimental single-cross hybrids 12C20264 and 13XH349. The two experimental single-cross hybrids not only demonstrated early physiological maturity but had high grain yield performance potential across sites. According to Abadassi and Herve (2000), Musundire et al. (2019), and Mushayi et al. (2020), the lack of adaptability of tropical germplasm in South African environments is characterized by late flowering and high grain moisture content at harvest.

Contrary to this report, the two exceptional experimental single-cross hybrids (12C20264 and 13XH349) combined low grain moisture content, early flowering, and high yield potential in the South African environments. The desired combination of low grain moisture content and early flowering is an essential requirement in South African environments. It reduces costs related to artificial grain drying and losses due to delayed harvesting, particularly frost damage. Early harvesting also allows the farmer timely planting of winter crops. Therefore, introgressed inbred lines require further advances to improve these traits. The selected experimental single-cross hybrids illustrated that plant aspects such as plant and ear height, stalk and root lodging required further introgression to improve pronounced poor standability and increased rank growth relative to commercial hybrid checks. The selected hybrids lacked the desired traits that will ensure good standing ability in South African environments prone to seasonal windstorms. Nevertheless, there was an experimental single-cross hybrid (10HDTX11) that had exceptional standability.

Predicted genetic gains

The predicted genetic gain for grain yield and number of ears per plant indicated that higher gain was achieved in Population A relative to Population B. However, the general trend was that predicted genetic gains were higher than the actual (realized genetic gains). This means that the phenotypic selection method used was not effective in fully achieving potential breeding progress. Plant aspect, plant and ear heights, and root and stalk lodgings illustrate that predicted genetic gain was in the undesirable direction, an indication that attaining actual genetic gain of these requires a further adapted strategy. A similar trend was also observed for attributes of early physiological maturity, grain moisture content, and flowering days. This highlights that breeding tropical germplasm for adaptability in warm temperate environments still has opportunities for further gain.

Generally, negligible to low genetic variation and low coefficients of genotypic variation was observed for most traits of economic importance in maize hybrids. This means that there is likely to be low genetic gain during selection for these traits, resulting in slow breeding progress. Traits such as plant and ear height that did not show any genetic variation illustrated that phenotypic selection may not achieve the introgressed inbred lines' desired genetic gain. However, most of the economic traits showed heritability estimates that ranged from low to high, indicating that progress would be possible towards the desired phenotypes at least for some traits. However, Al-Tabbal and H. Al-Fraihat (2011) and Rutkoski (2019) reported that the coefficient of genotypic variation alone does not provide full insight into assessing heritable variation. Therefore, the coefficient of genotypic variation should be considered along with heritability estimates to provide reliable estimates of the amount of genetic gain to be expected through selection. High coefficients of variation for plant and ear height also indicate the need to improve the quality and precision of experiments through minimizing error during selection.

Conclusion

Generally, positive desired realized genetic gains were attained for grain yield (58%) and the number of ears per plant (26%) relative to the best commercial check hybrids. A (9%) genetic gain was noted relative to better commercial hybrid checks were observed. Secondary traits such as anthesis and silking days had desirable realized genetic gains ranging from 1 to 37% relative to the mean of the population. At the same time, stalk lodging made a 5% gain relative to commercial hybrid checks. The grain moisture content at harvest indicated that there was a negligible gain achieved relative to the population mean and the mean of commercial checks, as selected hybrids had higher grain moisture content at harvest. Stalk and root lodging did not attain the desired realized genetic gain, as the introgression hybrids' mean higher than the commercial hybrid checks. Despite the need for further improvement, some of the introgressed inbred lines performance *inter se*, that is, in hybrid combinations, indicated that significant improvements of grain yield potential and its components are possible following one breeding cycle. Most impressive was the exceptional performance of hybrids such as 12C22785, 12C20628, 11C1774, 12C20264, 12C20595, 11C1645 13XH349 that outperformed the best commercial check hybrid PAN6Q445B, a leading hybrid on the South African market for grain yield performance potential. These seven selected single-cross hybrids also combined high grain yield potential performance with good ear prolificacy, particularly experimental single-cross hybrids 12C20628, 11C1774, 12C202595. Two experimental single-cross hybrids 12C2064 and 13XH349, combined high grain yield performance potential with low grain moisture content at harvest and improved standing ability. This indicates that introgression of temperate germplasm into tropical maize elite inbred lines was useful for enhancing the adaptability of the tropical elite inbred lines in South African environments and their hybrid combinations. However, many of the selected experimental single-cross hybrids did perform poorly for standability data depicted by plant aspects such as plant and ear height, stalk, and root lodging. Therefore, there is a need to improve these plants further to enhance the adaptability of tropical germplasm in South African environments. Future breeding will emphasize these traits.

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Compliance with ethical standards

Conflict of interest The authors declare there to be no conflict of interest.

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