Performance of elite drought tolerant maize varieties

across eastern and southern Africa, season 2017-18

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Introduction

Maize (*Zea mays* L.) occupies more than 50% of total farmland devoted to crops in sub-Saharan Africa (SSA) (FAO, 2010). It is the main staple food crop in southern Africa, where it provides the highest caloric intake for most of the population (Smale, 1995; Smale et al., 2013). However, compared to maize yields in developed countries, maize yields in SSA remain suboptimally low at 1.5-2 t ha^{-1} (Vanlauwe et al., 2011). Maize is produced mostly under rainfed conditions in SSA, leading to substantial yield fluctuations from year to year due to frequent droughts and low N application (Cairns et al., 2013a; Shiferaw et al., 2011). Climate projections suggest that maize yields in SSA will decline by up to 10% by 2050 due to future climate scenarios (Tesfaye et al., 2015). Many of the current commercial varieties are susceptible to both heat and drought stress, making farmers vulnerable to food insecurity (Cairns et al., 2013a).

CIMMYT and its partners have been developing and deploying drought tolerant (DT) and heat tolerant maize varieties with high N use efficiency with the aim of reducing smallholder farmers' vulnerability to drought and poor soil conditions (Setimela et al., 2016). CIMMYT's strategy is to simultaneously select maize varieties under optimal (recommended agronomic management/high rainfall conditions), low N and random stress conditions (Bänziger et al., 2006). Conventionally, germplasm development activities are conducted under well managed conditions to ensure high heritabilities/repeatabilities while the few varieties that remain after the selection process are tested under smallholder farmers' conditions. The yields on-station are normally higher compared to yields in farmers' fields due to high variability in farmers. On-station yields range from 3-10 t ha^{-1} and on-farmers' fields yield range 1.0 to 2.9 t ha^{-1} respectively (Setimela et al., 2007).

Before new varieties are commercialized, it is important to evaluate them under smallholders' conditions, which are the target environments where they will be deployed. Evaluation under smallholder conditions helps breeders and agronomists measure the real genetic gains obtained through breeding (Masuka et al., 2017). To effectively deploy stress tolerant germplasm, breeders have to take into account smallholder farmers' maize growing conditions. The objective of this study was to compare the yield performance of the new DT hybrids against the best commercial varieties under farmer management conditions that will inform the uptake and release process of new varieties that are anticipated to improve farmers crop yield.

Materials and methods

Before the maize varieties were nominated for on-farm testing, they were first evaluated in four types of environments: (i) recommended agronomic management and high rainfall conditions (>750 mm per annum and a temperature range of 24-33 °C) (optimum); (ii) low N stress (about or less than 30 kg N ha^{-1}); (iii) managed drought; and (iv) random stress conditions on station (Magorokosho et al., 2015). For the on-station trials at each location, an alpha (0,1) lattice design with three replicates was used. Data were collected on grain yield (kg ha^{-1}), diseases and other important agronomic traits.

Varieties that performed well on-station were subsequently evaluated in on-farm trials for validation. Sixteen early to intermediate (<70 days to anthesis) and 16 intermediate to late (≥70 days to anthesis) varieties were evaluated in Malawi, Mozambique, Zambia and Zimbabwe under farmers' conditions in the 2017/2018 season (Table 1). The locations that were used cover different climatic conditions in terms of the amount and temporal distribution of rainfall, growing degree-day (GDD) accumulation, vapor pressure deficit (VPD) and solar radiation. They are spread over two main countries, Zimbabwe and Zambia and a few sites in Malawi.

Table 1. Characteristics of maize cultivars evaluated in on-farm trials in eastern and southern Africa.

Early maturing hybrids		Late maturing hybrids	
Genotype	**Status**	**Genotype**	**Status**
CZH142133	DTMA	CZH15024	DTMA
CZH142143	DTMA	CZH15065	DTMA
CZH142151	DTMA	CZH15075	DTMA
CZH15014	DTMA	CZH15070	DTMA
CZH15017	DTMA	CZH15149	DTMA
CZH15194	DTMA	CZH15044	DTMA
CZH142019	DTMA Repeat	CZH15064	DTMA
CZH132134	DTMA Repeat	CZH15026	DTMA
CZH132164	DTMA Repeat	CZH15092	DTMA
CZH15001	DTMA	CZH 15032	DTMA
CZH1257	Genetic Check	CZH1227	Genetic check
CZH1261	Genetic Check	CZH0837	Genetic check
SC513	Commercial Check	SC513	Commercial check
SC403	Commercial Check	PAN53	Commercial check
PAN413	Commercial Check	30G19	Commercial check
Farmers' Variety	Farmers' Variety	Farmers' Variety	Farmers' check

For each location, the weather data were retrieved from aWhere's Agriculture Intelligence API Platform (https://developer.awhere.com/api/about-our-data).

Daily GDD was calculated as:

GDD = ((Tmax+Tmin)/2) – Base temperature (8°C)

where Tmax = maximum temperature, and Tmin = minimum temperature

VPD (kPa) was calculated as:

*VPD = ((100 - RH)/100)*SVP*

where RH = relative humidity and SVP = saturated vapor pressure.

Commercial checks were selected from the most popular varieties in each country that are within the same maturity groups. The genetic gain checks were the best yielding hybrids from the CIMMYT drought tolerant breeding pipeline that have already been commercialized. Trials were conducted during the main maize growing season which normally runs from early November to late April.

A randomized complete block design was used for each trial. Each plot consisted of six rows that were five meters long with crop spacing determined by the farmers based on their standard practice. All trials were grown under rainfed conditions, with farmers using their own management system for fertilizer application, weeding, and pest and disease control. Data were collected from the four middle rows. Each farmer's plot was considered a replicate. Entries were randomized at each location, but plot numbers remained the same. For the analyses, sites were considered random factors, while varieties were considered fixed factors. The trials were subsequently divided into two categories based on yield levels: high-yielding trials (≥3 t ha^{-1}) and low-yielding trials (<3 t ha^{-1}). They were also subjected to analysis of variance across environments. Low-yielding trials were taken to be representative of smallholder farmers' conditions, where little or no nitrogen fertilizer is applied.

Results and discussion

Climatic characterization of the on-farm testing locations

The locations where these trials were conducted varied for key climatic parameters, i.e., rainfall, temperature and radiation. The location with the highest total rainfall (>700 mm) during the season was Mukushi in Zambia (Figure 1). In contrast, Gokwe in Zimbabwe received the least amount of rainfall, less than 300 mm in total (Figure 1). For the remaining locations cumulative rainfall ranged between 400 and 450 mm. In terms of rainfall distribution over the season, Mukushi presented a good rainfall pattern (Figure 2). The other locations had several windows with little or no rainfall, which may have negatively affected crop performance. Gokwe had good rainfall distribution but the amount of rainfall was quite small.

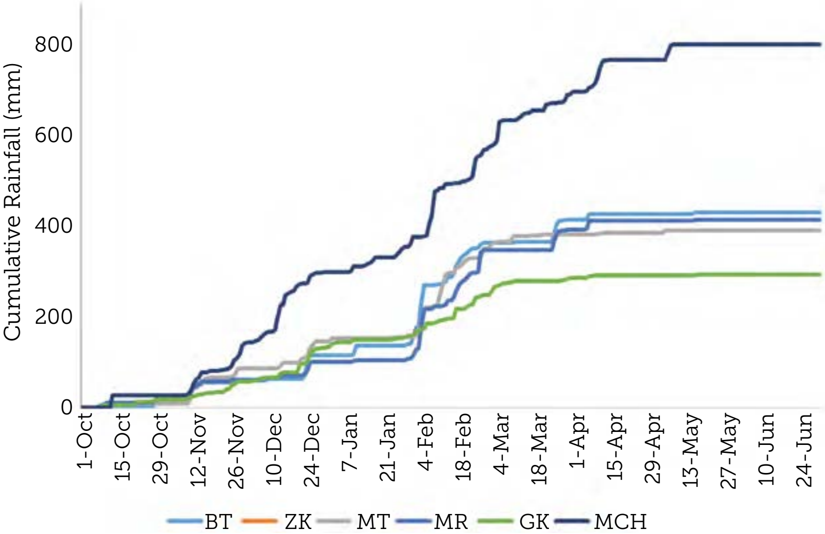

Figure 1. Cumulative rainfall variation between the main sites used for the on-farm trials. BT=Bitika, ZK=Zaka, MT=Mutoko, MR=Mrewa, GK=Gokwe, MCH=Mukushi.

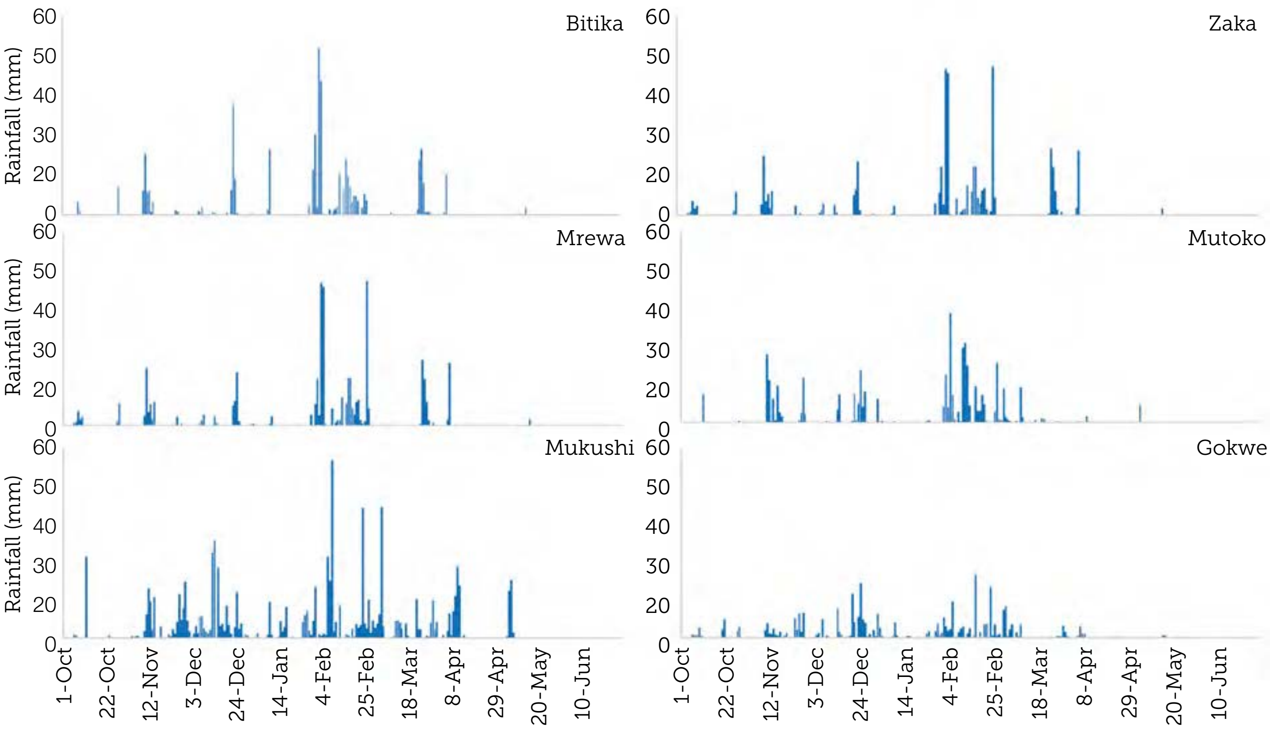

Figure 2. Seasonal rainfall distribution at the different locations where the on-farm trials were conducted.

In terms of GDD accumulation, Mutoko, Gokwe and Zaka showed faster accumulation as compared to the rest of the environments (Figure 3). Murewa had the slowest GDD accumulation. In addition to rainfall, VPD can be used to assess how stressful an environment is for a crop. The highest VPD values were recorded at the onset of the season with monthly average values above 3 kPa; Gokwe showed the highest values (around 3.5 kPa) (Figure 4). Average monthly VPD varied greatly during the vegetative and early flowering stages. During the flowering stage, Gokwe, Murewa and Bitika had higher VPD values than Mutoko and Mukushi.

Performance of early to intermediate maturing hybrids

Out of the 15 environments, nine were found to be high yielding (>3 t ha^{-1}) with the highest yielding variety producing an average of 4.55 t ha^{-1}, while the remaining six sites were classified as low yielding (<3 t ha^{-1}) with an average yield of 2.28 t ha^{-1} (Table 2). Broad-sense heritability was 62% for the high yielding environments and 42% for the low yielding environments. For the combined data across locations, heritability was 64%. Four hybrids (CZH142019, CZH142133, CZH15017 and CZH15001) outyielded the commercial checks, genetic checks and farmers' varieties under mild stress conditions. These high yielding varieties are new DT hybrids, an indication of the breeding progress that is being made. In the low yielding environments, three hybrids (CZH142151, CZH132134 and CZH142143) outyielded the commercial checks, farmers' varieties and genetic checks. Across both high and low yielding environments, CZH142019, CZH142143, CZH15007 and CZH15001 were the top yielders.

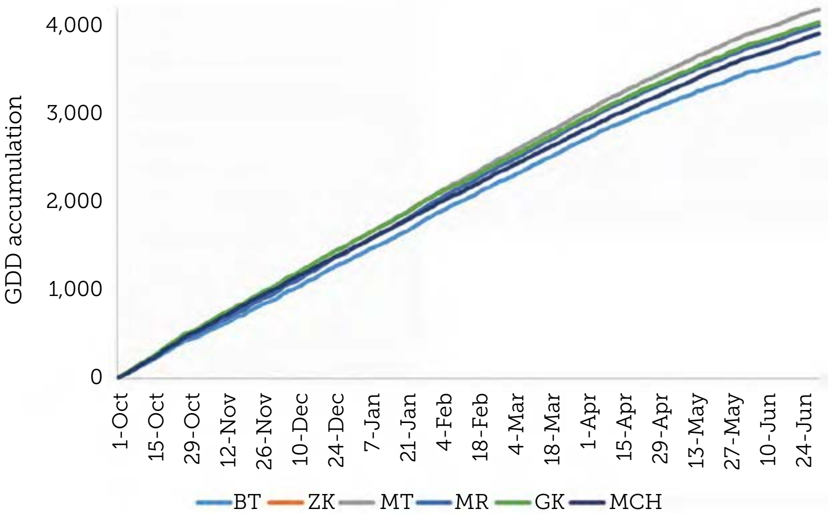

Figure 3. Variation of growing degree-days (GDD) accumulation at the different locations where the on-farm trials were conducted. BT=Bitika, ZK=Zaka, MT=Mutoko, MR=Mrewa, GK=Gokwe, MCH=Mukushi.

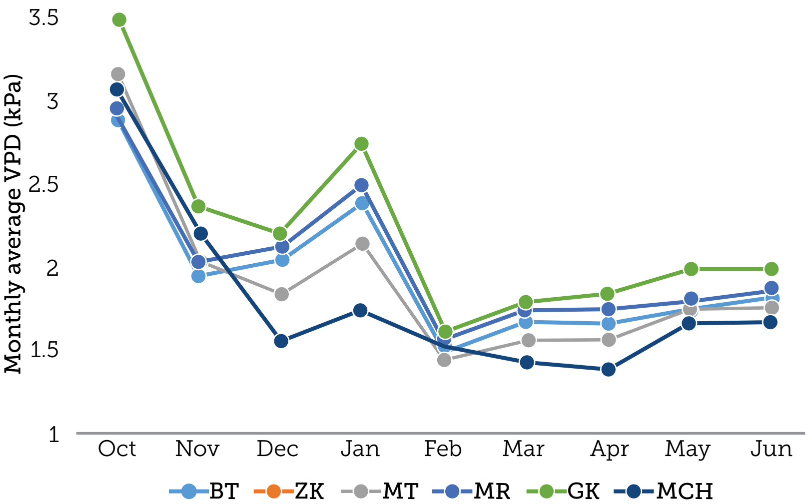

Figure 4. Variation of monthly average vapor pressure deficit (VPD; kPa) at the different locations where the on-farm trials were conducted. BT=Bitika, ZK=Zaka, MT=Mutoko, MR=Murewa, GK=Gokwe, MCH=Mukushi.

Table 2. Yield of early to intermediate maturing varieties grown in eastern and southern Africa in the 2017/2018 seasons.

Genotype	Status	Across Sites		Mild Stress		Random Stress	
		Grain Yield (tha^{-1})	Grain Yield Rank	Grain Yield (tha^{-1})	Grain Yield Rank	Grain Yield (tha^{-1})	Grain Yield Rank
CZH142133	DTMA	3.91	5	5.11	3	2.18	9
CZH142143	DTMA	4.21	2	4.91	4	3.10	3
CZH142151	DTMA	3.85	8	4.22	12	3.23	1
CZH15014	DTMA	3.77	9	4.68	7	2.38	6
CZH15017	DTMA	4.21	3	5.55	2	2.25	7
CZH15194	DTMA	3.89	6	4.65	8	2.72	4
CZH142019	DTMA Repeat	4.37	1	5.77	1	2.13	12
CZH132134	DTMA Repeat	3.88	7	4.35	11	3.13	2
CZH132164	DTMA Repeat	3.60	11	4.46	10	2.22	8
CZH15001	DTMA	3.95	4	4.89	5	2.52	5
CZH1257	Genetic Check	3.67	10	4.71	6	2.17	11
CZH1261	Genetic Check	2.77	16	3.58	16	1.58	15
SC513	Commercial Check	3.42	12	4.65	9	1.68	14
SC403	Commercial Check	2.96	14	4.04	13	1.41	16
PAN413	Commercial Check	2.84	15	3.59	15	1.68	13
Farmers' Variety	Farmers' Variety	3.06	13	3.64	14	2.18	10
Number of Locations		15		9		6	
Grand Mean		3.65		4.55		2.28	
Lsd (0.05%)		0.84		1.13		1.20	
Heritability		0.64		0.62		0.42	

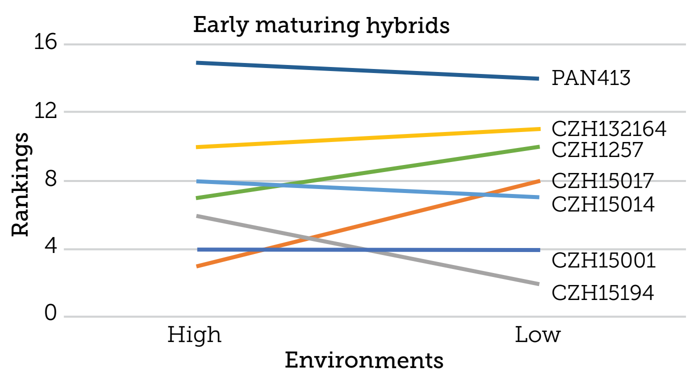

Figure 5. Ranking of early to intermediate maize varieties grown in eastern and southern Africa in the 2017/2018 season.

Crossover interaction

Hybrid CZH15001 maintained its superiority under high and low yielding conditions compared to the commercial and genetic checks. This hybrid was very stable by maintaining its rank in high and low yielding environments (Figure 5). Pan 413 had smaller changes in rank, indicating its stability but lower yielding potential compared to the new DT hybrids. Farmers prefer stable but high yielding varieties. The presence of crossover and non-crossover genotype×environment (GE) interaction among subsets of locations suggests that the target environments may be subdivided into mega-environments. A mega-environment is defined as a subset of locations that consistently share the best set of genotypes and where the growing regions are relatively homogeneous, with similar biotic and abiotic stresses and cropping system requirements (Yan and Hunt, 2001).

Mean versus stability GGE biplot

The mean versus stability view of genotypes (G) and genotype x environment (GE) interactions shows the relative mean performance and stability of hybrids (Figure 6). An ideal variety must have high mean yield and stability across environments (Yan and Hunt, 2001; Yan and Tinker, 2006). Three hybrids (CZH15001, CZH15194 and CZH15194) were high yielding and stable for grain yield across environments, whereas Pan 413, SC403 and CZH1261 were less stable and low yielding across environments (Figure 6). The genetic check CZH1257 was outperformed by the new DT hybrids in terms of yield and stability.

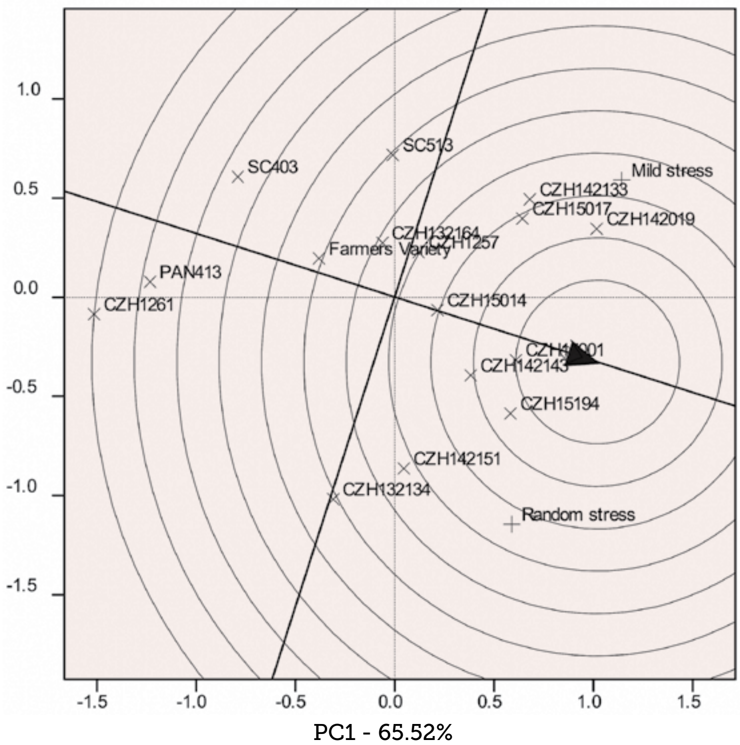

Figure 6. An average tester coordinate view showing the performance of twelve drought tolerant and four non-drought tolerant commercial varieties in the early to intermediate maturing group ranked based on mean performance and stability across mild stress and random stress environments. The biplot was produced based on genotype-focused singular value partitioning (SVP) and the data were environment centered.

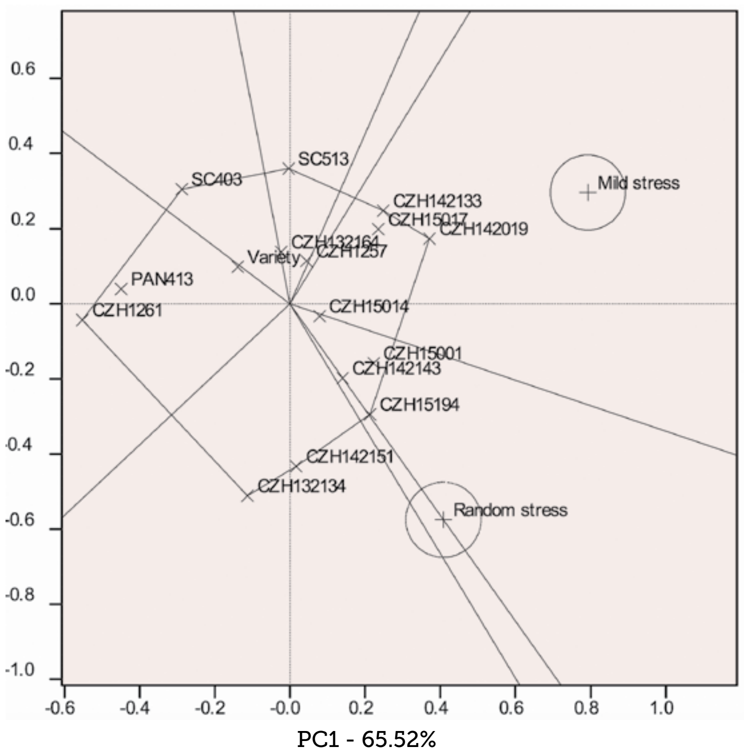

Figure 7. A which-won-where biplot of twelve drought tolerant and four non-drought tolerant commercial varieties in the early to intermediate maturing group. The biplot was produced based on symmetric focused singular value partitioning (SVP) and the data were environment centered.

Which wins where or which is best for what

The GGE biplot analysis was conducted to show which early to intermediate maize hybrids yielded the most in which environment (Figure 7). Four hybrids (CZH142133, CZH15017, CZH15064 and CZH15026) were associated with mild stress or high yielding environments, while four hybrids (CZH15001, CZH142143, CZH15194 and CZH014) were associated with random stress environments (Figure 3). In southern Africa, maize production and productivity is closely associated with rainfall and changes in temperature (Cairns et al., 2013b; Rembold et al., 2016). Therefore, to give farmers yield stability across seasons, it is important to identify varieties that are stable across environments.

Intermediate to late maturing hybrids

Out of the 12 locations under intermediate to late maturing hybrids, 10 locations were significant under mild stress, while two were significant under random stress. Grain yield for the intermediate to late maturing hybrids ranged from 4.4 t ha^{-1} to 6.5 t ha^{-1}, with a mean yield of 5.23 t ha^{-1} and Least significant difference (5%)of 1.12 t ha^{-1} under mild stress conditions (>3 t ha^{-1}). Under random stress conditions (<3 t ha^{-1}), the average grain yield was 1.9 t ha^{-1} with a maximum grain yield of 3.1 t ha^{-1} and a minimum grain yield of 1.0 t ha^{-1}. Hybrids CZH15065 and CZH15044 and local genetic check CZH1227 were the highest yielders under mild stress conditions, while hybrids CZH15024, CZH15044 and CZH15149 were the best under random stress conditions. CZH14044 performed well across both environments. Broad-sense heritability for grain yield was higher under mild stress conditions than under random stress (Table 3).

Table 3. Yield of intermediate to late maturing varieties grown in eastern and southern Africa in the 2017/2018 seasons.

Genotype	Status	Across Sites		Mild Stress		Random Stress	
		Grain Yield (tha^{-1})	Grain Yield Rank	Grain Yield (tha^{-1})	Grain Yield Rank	Grain Yield (tha^{-1})	Grain Yield Rank
CZH15024	DTMA	4.77	7	5.12	9	3.09	1
CZH15065	DTMA	5.63	1	6.38	1	1.88	9
CZH15075	DTMA	4.66	8	5.34	7	1.32	13
CZH15070	DTMA	4.54	10	5.20	8	1.20	15
CZH15149	DTMA	5.01	6	5.52	6	2.34	3
CZH15044	DTMA	5.22	4	5.63	5	3.07	2
CZH15064	DTMA	5.22	3	5.91	2	2.03	8
CZH15026	DTMA	5.24	2	5.86	4	2.27	5
CZH15092	DTMA	4.61	9	5.08	10	2.31	4
CZH 15032	DTMA	3.98	15	4.52	15	1.24	14
CZH1227	Local check	5.12	5	5.89	3	1.46	12
CZH0837	Local check	4.39	11	4.93	11	1.66	11
SC513	Commercial check	4.07	14	4.55	14	1.74	10
PAN53	Commercial check	3.84	16	4.38	16	1.01	16
30G19	Commercial check	4.25	12	4.69	12	2.04	7
Farmers" Variety	Farmer check	4.20	13	4.57	13	2.21	6
Number of Locations		12		10		2	
Grand Mean		4.67		5.22		1.93	
Least significance difference (5%)		0.97		1.12		1.85	
Heritability		0.58		0.57		0.21	

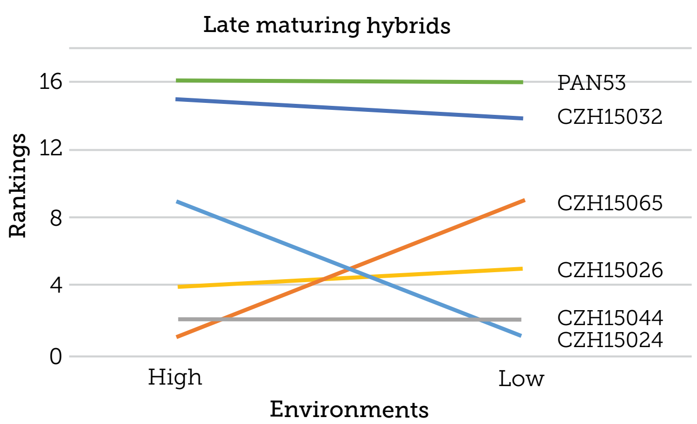

Figure 8. Ranking of intermediate to late maturing maize varieties grown in eastern and southern Africa in the 2017/2018 season.

Crossover interaction

Hybrids CZH15044, CZH026, and Pan 53 were the most stable hybrids under mild and random stress (Figure 8). Hybrid CZH044 was not only stable, but also high yielding across mild and random stress environments. Most of the hybrids had a large yield gap between high and low yielding environments.

Mean performance versus stability GGE biplot

The mean performance versus stability GGE biplot shows the hybrids' relative mean performance and stability. CZH15026 and CZH 15044 were the highest yielding and most stable hybrids across environments. Compared to the commercial and genetic checks, hybrids CZH15026 and CZH 15044 were less affected by the environment. Although stable, Pan 53, an earlier drought tolerant hybrid released in 2008, was low yielding (Figure 9).

A which-won-where view of the GGE biplot

A which-won-where view of the GGE biplot based on on-farm data revealed the existence of different groups of environments: mild stress, random stress and a combination of mild and low stress environments (Figure 10). The GGE biplot analysis was constructed to show which maize hybrids yielded the most at which environments. The line that starts from the biplot origin and perpendicular to the sides of the polygon divided the biplot into seven sectors. The which-won-where view of the GGE biplot shows that CZH15065 was associated with mild stress environments, whereas CZH15024 was associated with random stress environments. The best and worst yielding maize hybrids are shown in each environment, suggesting that they may be the best or worst yielders based on their distance from the biplot origin. This works well for making

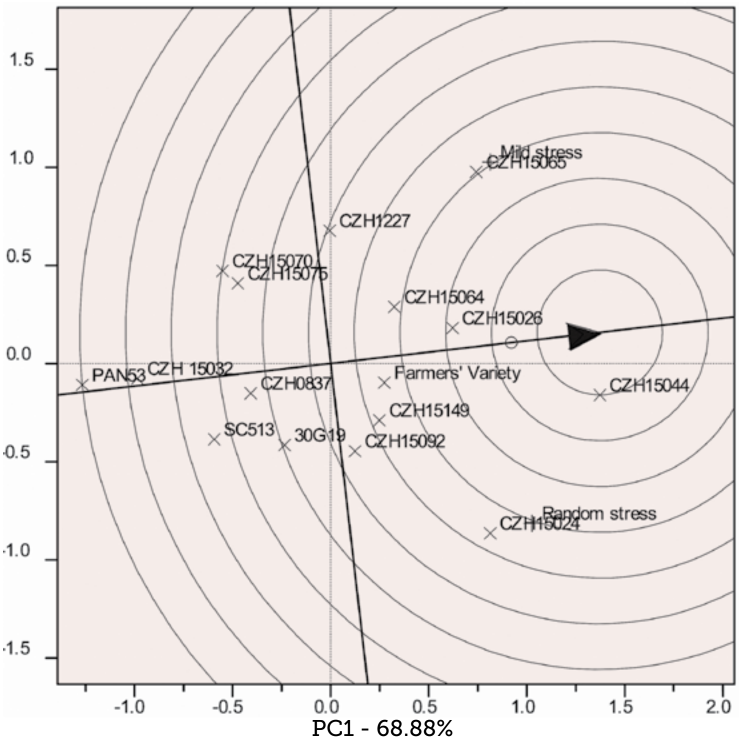

Figure 9. An average tester coordinate view showing the performance of twelve drought tolerant and four non-drought tolerant commercial varieties in the intermediate to late maturing group ranked based on mean performance and stability across mild stress and random stress environments. The biplot was produced based on genotype focused singular value partitioning (SVP) and the data were environment centered.

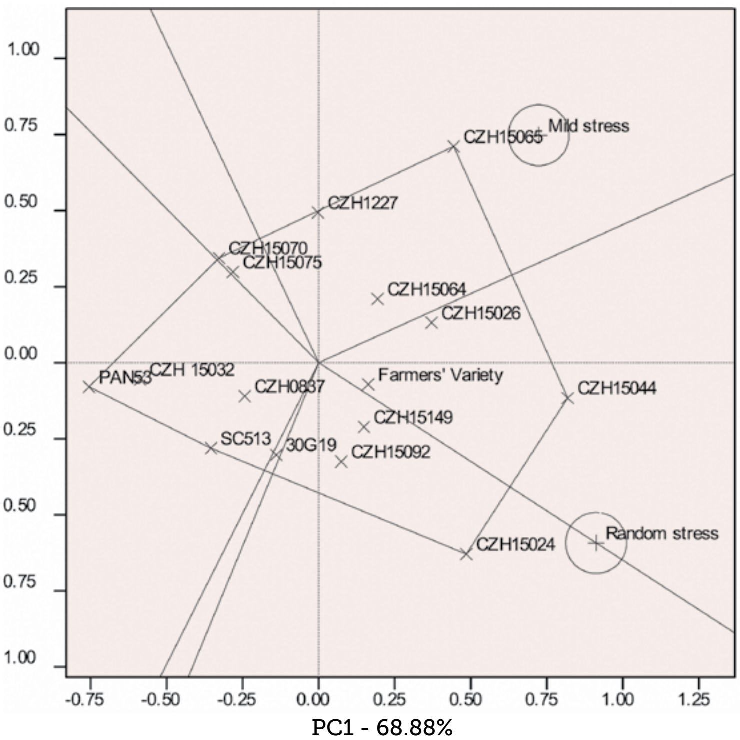

Figure 10. A which-won-where biplot of twelve drought tolerant and four non-drought tolerant commercial varieties in the intermediate to late maturing group. The biplot was produced based on symmetric focused singular value partitioning (SVP) and the data were environment centered.

variety recommendations, if major variables can be found that are responsible for hybrid performance in each environment.

Conclusion

The results of these on-farm trials show that progress continues to be made in breeding for drought tolerance in eastern and southern Africa. Several new DT hybrids yielded significantly more than commercial hybrids, with no significant yield penalty in optimal/high yield environments. Among the early maturing hybrids, CZH15001, CZH15194 and CZH15194 were high yielding and stable for grain yield, while among the intermediate to late maturing hybrids, CZH15026 and CZH 15044 were the highest yielding, most stable hybrids across the environments.. There were also new hybrids associated with certain environments, which means they can only be recommended for production in those environments.

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