On-Farm Yield Gains with Stress-Tolerant Maize in Eastern and Southern Africa

Peter S. Setimela,* Cosmos Magorokosho, Rodney Lunduka, Edmore Gasura, Dan Makumbi, Amsal Tarekegne, Jill E. Cairns, Thokozile Ndhlela, Olaf Erenstein, and Wilfred Mwangi

ABSTRACT
Maize (Zea mays L.) is the most important staple food in eastern and southern Africa (ESA) with human maize consumption averaging 91 kg capita⁻¹ yr⁻¹. Current maize yield averages 1.2 t ha⁻¹ and is barely sufficient for the region’s requirements due to drought and low N stresses. The objective of this study was to compare new drought tolerant (DT) maize hybrids and open pollinated varieties (OPVs) against the best commercial varieties in ESA under farmer management conditions and to validate on-station results. Maize varieties were simultaneously selected on-station in four types of environments across 44 locations in ESA during the 2008/2009 and 2009/2010 seasons. During the 2010/2011 and 2011/2012 seasons, 20 promising DT maize hybrids and OPVs were selected from the on-station based on their mean grain yield and stability. These selected varieties were compared with the best commercial check varieties on-farm across 80 locations in ESA in a randomized complete block design for two seasons. The genotype + genotype × environment comparison biplot showed variety CZH0616 together with other new DT hybrids to be stable and high yielding across 44 locations on-station in the ESA region compared to the commonly grown checks such as SC513. The new DT hybrids showed a yield advantage over the commercial check varieties both in the early and medium-late maturing categories by 4 to 19%, and the gains were bigger under stress conditions. Under farmers’ fields CZH0616, CZH0837, CZH0935, and CZH0928 were high yielding and stable across locations.

Core Ideas
• These selected varieties were compared with the best commercial check varieties on-farm across 94 locations in eastern and southern Africa in a randomized complete block design with three replications for two seasons.
• The new drought tolerant hybrids showed a yield advantage over the commercial check varieties both in the early and medium-late maturing categories by 4 to 19%.
• Among the CIMMYT hybrids, CZH0616 showed wide adaptation under stress and non-stress conditions, making it an ideal genotype for smallholders’ farmers.
• Under farmers’ fields CZH0616, CZH0837, CZH0935, and CZH0928 were high yielding and stable across locations in eight countries that represent major maize production environments in eastern and southern Africa.

Maize is a major food crop in sub-Saharan Africa (SSA) (FAOSTAT, 2015) where it is grown on over 25 m ha mostly by smallholder farmers producing about 38 t of grain (Smale et al., 2011). However, yields remain low ranging from 2 t ha⁻¹ to less than 1.5 t ha⁻¹ (Shiferaw et al., 2011) under smallholder farmer conditions compared to other regions (Ray et al., 2013). Drought and low N stresses are two of the major causes associated with low yields and high season-to-season yield variability (Shiferaw et al., 2014). In Angola and Zimbabwe more than 70% of maize is grown in areas with a 40 to 60% frequency of a failed season, while over one-third of maize in Kenya, Mozambique, and Tanzania is grown in areas with this frequency (Kostandini et al., 2013; Tesfaye et al., 2015). The annual yield loss in maize due to drought is estimated to be between 15 and 90% depending on the stage when drought occurs (Bünziger and Araus, 2007).

In SSA, particularly in southern Africa, season-to-season variability in maize yields is extremely high (Smale et al., 2011). In Lesotho and Zimbabwe the coefficient of variation in maize production over the last five seasons was more than 50% (FAOSTAT, 2015), while in Asia and the Americas coefficients of variation in production are in single digit (Smale et al., 2011). Drought stress and low N will remain major challenges in the region where most farmers have limited capacity to invest into the inputs (Cairns et al., 2013). At the Abuja Declaration on “Fertilizer for the African Green Revolution” P.S. Setimela, C. Magorokosho, R. Lunduka, A. Tarekegne, and J.E. Cairns, Global Maize Program, International Maize and Wheat Improvement Centre (CIMMYT), P.O. Box 163, Mt. Pleasant, Harare, Zimbabwe; D. Makumbi and W. Mwangi, Global Maize Program, CIMMYT, ICRAR House, United Nations Ave., P.O. Box 1041-00621, Nairobi, Kenya; T. Nhlela, Crop Breeding Institute, Dep. of Agricultural Research and Extension Services (AREX), P.O. Box CY550, Causeway, Harare, Zimbabwe; O. Erenstein, CIMMYT, Carretera México-Veracruz Km 45, El Batán, 56130 México. *Corresponding author (p.setimela@cgiar.org).

Acknowledgments: GRA, Alliance for a Green Revolution in Africa; CIMMYT, International Maize and Wheat Improvement Centre; DT, drought tolerant; DTMA, drought tolerant maize for Africa; E, environment; ESA, eastern and southern Africa; GCV, genotypic coefficient of variation; GE, genotype × environment interaction; GGE, genotype plus genotype × environment interaction; IITA, International Institute for Tropical Agriculture; MCMV, maize chlorotic mottle virus; MSV, maize streak virus; NARES, national agricultural research and extension systems; OPV, open pollinated maize variety; PC, principal component; PCV, phenotypic coefficient of variation; PI, preference index; SSA, sub-Saharan Africa.
in 2006, African Union Member States agreed to increase fertilizer use to 50 kg ha\(^{-1}\) by 2015. However, average fertilizer use remains between 5 and 10 kg ha\(^{-1}\) in most countries in SSA (FAOSTAT, 2015). The development and deployment of DT maize varieties with high N use efficiency is a relevant intervention to reduce vulnerability and food insecurity for smallholder farmers who depend on rainfall for crop productivity (Langyintuo et al., 2010; La Rovere et al., 2010). Kostandini et al. (2013) estimated that the adoption of DT maize could generate US$362 to US$90 million for consumers and producers, and reduce poverty by 5% within 13 countries in SSA.

From a maize breeding perspective, nutrient use efficiency and drought tolerance are complex polygenic traits (Ribaut et al., 2002) but can be selected for effectively using managed drought and low N environments (Edmeades et al., 2000; Bänziger and Cooper, 2001). To address the gap in maize genetic improvement for smallholder farmers in ESA the International Maize and Wheat Improvement Centre (CIMMYT) initiated a collaborative drought and low N maize breeding program in 1997 to increase yields in low input and/or drought prone environments (Bänziger et al., 2006). Using this simultaneous selection approach, Bänziger et al. (2006) developed hybrids that have shown a consistent yield advantage over private seed company hybrid checks for all testing environments. Masuka et al. (2017a, 2017b) evaluated genetic gains in the CIMMYT ESA maize hybrid and OPV breeding programs during the period 2000 to 2010. Hybrid gains in grain yield under optimal, managed drought, random drought, low N, and maize streak virus infested conditions were estimated at 1.4, 0.85, 0.85, 0.62, and 2.2% per season, respectively. In terms of realized gains, yields were estimated to have increased by 109.4, 32.5, 22.7, 20.9, and 141.3 kg ha\(^{-1}\) yr\(^{-1}\), respectively.

The relative yield gap between controlled conditions on experimental stations and farmers' fields is probably higher in SSA than anywhere else in the world. For example, yields in managed and random stress trials in experimental stations in Zimbabwe ranged from 1.0 to 2.9 t ha\(^{-1}\), while the national managed and random stress trials in experimental stations in SSA than anywhere else in the world. For example, yields in experimental stations and farmers' fields is probably higher in average yield in 2013 was 0.88 t ha\(^{-1}\) (FAOSTAT, 2015; fertilizer use remains between 50 kg ha\(^{-1}\) by 2015. However, average fertilizer use remains between 5 and 10 kg ha\(^{-1}\) in most countries in SSA (FAOSTAT, 2015). The development and deployment of DT maize varieties with high N use efficiency is a relevant intervention to reduce vulnerability and food insecurity for smallholder farmers who depend on rainfall for crop productivity (Langyintuo et al., 2010; La Rovere et al., 2010). Kostandini et al. (2013) estimated that the adoption of DT maize could generate US$362 to US$90 million for consumers and producers, and reduce poverty by 5% within 13 countries in SSA.

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**MATERIALS AND METHODS**

**On-Station Trials**

The on-station data were extracted from regional early to intermediate, and intermediate to late maturing maize variety trials evaluated across 80 locations for two seasons (2008/2009 and 2009/2010) in ESA. Out of the 80 locations, only 44 were used in the final analysis. Locations that had data for only one season were discarded from the final analysis. In southern Africa sowing and harvesting are done in November and April, respectively, while in eastern Africa sowing and harvesting are mainly done in April and August.

Before the maize entries were validated on-farm they were first selected simultaneously in four types of environments: (i) recommended agronomic management and high rainfall conditions (>7500 mm annum and a temperature range of 24–33°C) (optimum), (ii) low N stress about 30 kg N ha\(^{-1}\) (Badu-Apraku, 2007a, 2007b), (iii) managed drought, and (iv) random stress conditions. Detailed information on environments is described by (Bänziger et al., 2000, 2006) but briefly, low N stress experiments were conducted in sites that had been depleted of N for more than 5 yr to achieve about 30 kg N ha\(^{-1}\) and additional N of 50 kg ha is applied to avoid barrenness of cobs due to excessive N stress. For managed drought stress, trials were grown in the off season and the irrigation interval calculated based on the crop water balance (Bänziger et al., 2006) is doubled starting 2 wk before flowering. Under random stress, trials were grown during the main maize growing season experiencing random drought (approximately <600 mm rainfall yr\(^{-1}\)) and pests and diseases prone locations under rainfed conditions. The aims of the managed experiments under low N and drought stress were to had an average yield reduction of 25 to 40% (1.5–3.5 t ha\(^{-3}\)) compared to yield under optimal agronomic management conditions (6–9 t ha\(^{-1}\)). The objective of these trials was to simulate stresses that occurs in smallholder farmer’s fields where the grain yields are between 1 and 2 t ha\(^{-1}\) (Magorokosho et al., 2009, 2010, 2011). Thus, low N and managed drought trials were considered to represent the breeding target. In all trials, α-lattice design with three replications was used and plots consisted of three rows, 4 m long, with a plant density of 48 plants (9 m\(^{-2}\)) (equivalent to 53,333 plants ha\(^{-1}\)). A network of partners was established for testing entries in each country. The partners included national agricultural research systems and private seed companies that in turn contributed their best entries for testing within the network and also had access to CIMMYT germplasm to incorporate into their breeding programs as shown in Fig. 1.

**On-Farm Trials**

Selected genotypes from the on-farm trials were composed of commercial and DT hybrids, OPVs, and farmers’ variety choices were evaluated in farmers’ fields during the 2010/2011 and 2011/2012 seasons (Table 1) under farmer management practices. Poor performing materials were discarded and thus slightly different sets of 20 varieties were evaluated in these two seasons. Most of the on-farm trials were conducted in the mid-altitude and hot zones where most of the maize is grown in eastern and southern Africa (Setimela et al., 2012). These genotypes (Table 1) were selected from the regional on-station trials conducted in ESA (Magorokosho et al., 2009, 2010). The hybrids SC513 and Pan53 were used as checks. These varieties are medium maturing (Table 1), widely grown and have been marketed for many years but well adapted to mid-altitude conditions of ESA. A total of 80 trials were conducted in farmers’ fields in Ethiopia, Kenya, Malawi, Mozambique, Uganda, Tanzania, Zambia, and Zimbabwe over a two-season period. Trials were conducted during the main maize growing
reasons, November to April in southern Africa and April to August in eastern Africa. A randomized complete block design was used on each trial. Each plot consisted of six rows that were 8 m long with crop spacing decided by the farmers based on their normal practice. All trials were grown under rain-fed conditions, with farmers using their own management system for fertilizer application, weeding, and pest and disease control.

STATISTICAL ANALYSIS

On-Station

During data analysis of the on-station trials, the mean yield data was extracted from 44 locations in ESA across two seasons (2008/2009 and 2009/2010). The locations were nested in four different management systems that include optimum conditions, managed drought, Low N, and random stress. Forty entries that were consistent in the given locations and management systems across the two seasons were selected for analysis. Because some entries were dropped and the locations in different management systems were unbalanced, the data was analyzed using a randomized complete block design for the across management systems analysis of variance using the PROC MIXED model in SAS software (SAS, 2009). Thus, a variety × management system analysis of variance across the two seasons was done where the management system and variety were fixed factors while the seasons were random factors using the model:

\[ Y_{ijk} = v_i + m_j + vm_{ij} + s_k + e_{ijk} \]

where \( Y_{ijk} \) is the yield of the \( i \)th variety evaluated in the \( j \)th management system in the \( s \)th season, \( v_i \) is the fixed effect of the \( i \)th variety, \( m_j \) is the fixed effect of the \( j \)th management system, \( vm_{ij} \) is the interaction effect of the \( i \)th variety and the \( j \)th management system, \( s_k \) is the random effect of the \( k \)th season, and \( e_{ijk} \) is the random error term.

Table 1. Characteristics of varieties evaluated for grain yield on-farm in the 2010/2011 and 2011/2012 seasons in eastern and southern Africa (ESA).

<table>
<thead>
<tr>
<th>Variety</th>
<th>Origin</th>
<th>Variety type</th>
<th>Release period†</th>
<th>Variety</th>
<th>Origin</th>
<th>Variety type</th>
<th>Release period</th>
</tr>
</thead>
<tbody>
<tr>
<td>09SADVE-F2</td>
<td>CIMMYT</td>
<td>OPV†</td>
<td>New</td>
<td>09SADVE1-F2</td>
<td>CIMMYT</td>
<td>OPV</td>
<td>New</td>
</tr>
<tr>
<td>CKH08205</td>
<td>CIMMYT</td>
<td>Hybrid</td>
<td>New</td>
<td>CKH08205</td>
<td>CIMMYT</td>
<td>Hybrid</td>
<td>New</td>
</tr>
<tr>
<td>CKH08210</td>
<td>CIMMYT</td>
<td>Hybrid</td>
<td>New</td>
<td>CKH08210</td>
<td>CIMMYT</td>
<td>Hybrid</td>
<td>New</td>
</tr>
<tr>
<td>CZH0524</td>
<td>CIMMYT</td>
<td>Hybrid</td>
<td>New</td>
<td>CZH0524</td>
<td>CIMMYT</td>
<td>Hybrid</td>
<td>New</td>
</tr>
<tr>
<td>CZH0615</td>
<td>CIMMYT</td>
<td>Hybrid</td>
<td>New</td>
<td>CZH0615</td>
<td>CIMMYT</td>
<td>Hybrid</td>
<td>New</td>
</tr>
<tr>
<td>CZH0616</td>
<td>CIMMYT</td>
<td>Hybrid</td>
<td>New</td>
<td>CZH0616</td>
<td>CIMMYT</td>
<td>Hybrid</td>
<td>New</td>
</tr>
<tr>
<td>CZH0837</td>
<td>CIMMYT</td>
<td>Hybrid</td>
<td>New</td>
<td>CZH0837</td>
<td>CIMMYT</td>
<td>Hybrid</td>
<td>New</td>
</tr>
<tr>
<td>ZM627</td>
<td>CIMMYT</td>
<td>OPV</td>
<td>Old</td>
<td>ZM627</td>
<td>CIMMYT</td>
<td>OPV</td>
<td>Old</td>
</tr>
<tr>
<td>ZM527</td>
<td>CIMMYT</td>
<td>OPV</td>
<td>New</td>
<td>ZM527</td>
<td>CIMMYT</td>
<td>OPV</td>
<td>New</td>
</tr>
<tr>
<td>ZM309</td>
<td>CIMMYT</td>
<td>OPV</td>
<td>New</td>
<td>ZM309</td>
<td>CIMMYT</td>
<td>OPV</td>
<td>New</td>
</tr>
<tr>
<td>ZM521</td>
<td>CIMMYT</td>
<td>OPV</td>
<td>Old</td>
<td>ZM521</td>
<td>CIMMYT</td>
<td>OPV</td>
<td>Old</td>
</tr>
<tr>
<td>ZM523</td>
<td>CIMMYT</td>
<td>OPV</td>
<td>New</td>
<td>ZM523</td>
<td>CIMMYT</td>
<td>OPV</td>
<td>Old</td>
</tr>
<tr>
<td>Farmers</td>
<td>Seed companies</td>
<td>Various</td>
<td>Various</td>
<td>Farmers</td>
<td>Seed companies</td>
<td>Various</td>
<td>Various</td>
</tr>
</tbody>
</table>

† A variety that was released before 2008 is considered old.
‡ OPV, open pollinated maize variety.
random error. The appropriate $F$ test was done based on this model by dividing the mean squares for error into the mean squares for the seasons, varieties, management system, and the interaction of the varieties × management system (McIntosh, 1983). The variance components due to varieties ($\sigma^2_v$), variety × management system ($\sigma^2_{vm}$), and random error ($\sigma^2_{error}$) were estimated by solving the equations formed by equating the mean squares to their respective expected mean squares (Moore and Dixon, 2014). The broad sense coefficients of genetic determination (broad sense heritability based on fixed varieties) across management systems were estimated as $\frac{\sigma^2_v}{\sigma^2_v + \sigma^2_{vm} + \sigma^2_{error}}$, where $n_m = \text{number of management systems}$, $n_{ms} = \text{number of management systems} \times \text{number of seasons}$. The genotypic coefficient of variation (GCV) and phenotypic coefficient of variation (PCV) were calculated for grain yield, according to Singh and Chaudhary (2004), using the following equations:

$$\text{GCV} \% = \frac{\sigma^2_g}{\bar{y}} \times 100$$

and

$$\text{PCV} \% = \frac{\sigma^2_p}{\bar{y}} \times 100$$

where, $\sigma^2_g = \text{genotypic variance}$, $\sigma^2_p = \text{phenotypic variance}$, and $\bar{y} = \text{grand mean for grain yield}$.

The purpose of the on-station trials was to select varieties for advancement to the on-farm trials based on their preference by farmers (such as SC513) and based on the mean yield and stability across different management systems (for the new hybrids such as CZHF0616). Since the variety by management system was significant at 0.001 probability level, this allowed the genotype plus genotype × environment interaction (GGE) analysis to be done on the adjusted means from the across management systems × variety analysis of variance using GenStat version 17 software (GenStat, 2014) using the GGE biplot model was described by Yan et al. (2000), Yan and Hunt (2001) and Yan (2002). Based on this model the biplot is environment (management system) centered with genotype focused singular value partitioning using GenStat software version 17 (GenStat, 2014). Visualization of the mean yield and stability of genotypes using a genotype comparison biplot (Yan et al., 2000; Yan and Hunt, 2001; Yan, 2002) was used to visualize the mean yield and stability of genotypes using a genotype comparison biplot (Yan and Tinker, 2005, 2006). A line that passes through the biplot origin to the average environment was drawn followed by a perpendicular line that passes through the biplot origin.

The genotype means for each season were obtained and presented using bar graphs and the 5% least significant difference as the error bars. 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). Low-yielding trials were taken to be representative of smallholder farmers who apply little or no N fertilizer. The genotype means from each category were used to calculate the yield advantage of each genotype compared to the common best check, SC513. The yield advantage were calculated as the mean of a given genotype minus the mean of the check, SC513 and were expressed as a percentage. New varieties and check varieties were grouped based on maturity and yield level. The yield advantage per each yield level and maturity group were calculated as the mean of the group of new hybrids minus the mean of the checks in that maturity group and yield level, divided by the mean of the checks as expressed as a percentage.

**Farmers’ Maize Trait Preference Evaluation**

Pre and post-harvest surveys were undertaken in six districts in Zimbabwe, which included Murehwa, Mutoko, Gokwe, Bikita, Zaka, and Chiredzi. The surveys were conducted to...
identify and rank farmer preferred varieties. Extension agents conducted gender-disaggregated surveys with 10 female and 10 male plot managers at each location. To assist in the selection of the varieties that farmers liked or disliked, cards with smiling and frowning faces were acquired. Different colors were chosen for women and men, with the women’s cards being light blue and the men’s cards dark blue.

Researchers or the Agricultural Extension Officers explained the objective of the on-farm trial and the purpose of the variety/trait preference ranking to the group of farmers that were invited to the site. Farmers were allowed to view all the plots before making their choices. Then each farmer was allocated five “I like” cards and asked to drop the cards on the plots they liked most. These cards were collected, counted, and the number of cards by gender was recorded. A similar procedure was repeated for the “I don’t like” cards. From the farmers’ choices, the two most liked and the two most disliked varieties by gender were identified and the farmers were asked to give their reasons for liking or disliking those varieties.

Based on the voting for the varieties, a Preference Index (PI) was calculated using the formula:

\[
PI = \frac{\text{Number of positive votes} - \text{Number of negative votes}}{\text{Total number of positive and negative votes}}
\]

**RESULTS AND DISCUSSION**

**Variety Performance and Selection On-station**

Significant differences \((P < 0.001)\) were observed among varieties, management systems, and the interaction of the variety and management system (Table 2). The large variance component due to management systems (Table 2) suggest that most of the variability among genotypes is due to the effects of the environment. In most genotype × environment studies, the environment had bigger variance components compared to genotypes or the genotype × environment interaction components (Yan and Tinker, 2005). These results show that low N is a more severe abiotic stress, giving the lowest average grain yield compared to managed drought and random stress.

The trials had relatively high heritability (60%), high genetic coefficient of variation (GCV) that was slightly above half of the phenotypic coefficient of variation (PCV) (Table 2). The relatively high GCV and heritability values suggest enough genetic variability to allow selection under different management conditions. The hybrid CZH0616 was among the highest yielding hybrids under optimal trials and was the top yielder under all stress conditions that include random stress, managed drought and low N. When genotype × environment (management system) interaction was present and significant (Table 2), it reduced heritability and cause differential performance of varieties evaluated in different locations. In such situations, Yan and Tinker (2005, 2006) recommended selection of broadly adapted varieties based on the mean yield and stability. The comparison biplot (Fig. 2) managed to rank varieties according to their mean yield and stability. Varieties such as Pan53 and CZH0616 were found in the inner most part of the concentric rings and thus are high yielding and very stable. When 10% of the varieties including CZH0616 were selected from this trial, the response to selection was 135% (Table 2). This means that promising hybrids have been selected for advancement. The average grain yields across ESA from the on-station trials under the evaluated management practices are shown in Table 3. The highest mean yields (7.60 t ha\(^{-1}\)) were obtained under optimal trials followed by the random stress trials (3.47 t ha\(^{-1}\)) and managed drought (2.42 t ha\(^{-1}\)) while low N trials had the lowest grain yield of 1.75 t ha\(^{-1}\) (Table 3). Grain yield decreases as N decreases (Bänziger et al., 1997; Worku et al., 2007), thus selection for low N tolerance is more efficient in increasing yield under low N conditions. Similarly, selection for drought stress is more efficient under drought conditions (Bänziger et al., 2006; Windhausen et al., 2012).

![Fig. 2. Genotype comparison biplot for grain yield of 40 varieties evaluated for two seasons on-station in eastern and southern Africa (ESA). The data was environment centered with genotype focused singular value partitioning.](image)

**Table 2.** Mean square values and related genetic parameters for 40 varieties evaluated for grain yield in eastern and southern Africa (ESA) during the 2008/2009 and 2009/2010 seasons.

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>Mean square</th>
</tr>
</thead>
<tbody>
<tr>
<td>Season</td>
<td>1</td>
<td>146.044†</td>
</tr>
<tr>
<td>Variety</td>
<td>39</td>
<td>5.897†</td>
</tr>
<tr>
<td>Management system</td>
<td>3</td>
<td>1727.807†</td>
</tr>
<tr>
<td>Variety × Management systems</td>
<td>117</td>
<td>2.845†</td>
</tr>
<tr>
<td>Residual</td>
<td>719</td>
<td>1.656</td>
</tr>
<tr>
<td>δ Variety</td>
<td></td>
<td>0.530</td>
</tr>
<tr>
<td>δ Management systems</td>
<td></td>
<td>21.577</td>
</tr>
<tr>
<td>δ Variety × management system</td>
<td></td>
<td>0.595</td>
</tr>
<tr>
<td>δ error</td>
<td></td>
<td>1.656</td>
</tr>
<tr>
<td>Broad sense heritability, %</td>
<td></td>
<td>59.90</td>
</tr>
<tr>
<td>Grand mean for grain yield</td>
<td></td>
<td>5.003</td>
</tr>
<tr>
<td>Genetic coefficient of variation, %</td>
<td></td>
<td>14.553</td>
</tr>
<tr>
<td>Phenotypic coefficient of variation, %</td>
<td></td>
<td>25.722</td>
</tr>
<tr>
<td>Response to selection, %</td>
<td></td>
<td>135.553</td>
</tr>
</tbody>
</table>

† Significant at 0.1% probability level.
Table 3. Mean grain yield of selected hybrids grown in eastern and southern Africa (ESA) under optimal and different stress conditions on-station across the 2008/2009 and 2009/2010 seasons.

<table>
<thead>
<tr>
<th>Genotype</th>
<th>Drought</th>
<th>Low N</th>
<th>Random stress</th>
<th>Optimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>CZH0616</td>
<td>4.073</td>
<td>2.635</td>
<td>5.677</td>
<td>8.991</td>
</tr>
<tr>
<td>PAN53</td>
<td>3.7</td>
<td>2.745</td>
<td>5.577</td>
<td>9.163</td>
</tr>
<tr>
<td>07SADVE3</td>
<td>3.216</td>
<td>2.322</td>
<td>3.456</td>
<td>8.079</td>
</tr>
<tr>
<td>08SADVI</td>
<td>2.952</td>
<td>1.51</td>
<td>4.045</td>
<td>7.225</td>
</tr>
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<td>2.293</td>
<td>3.235</td>
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<td>2.247</td>
<td>2.939</td>
<td>7.345</td>
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<td>2.902</td>
<td>1.632</td>
<td>4.243</td>
<td>7.28</td>
</tr>
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<td>1.953</td>
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<td>3.11</td>
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<td>2.003</td>
<td>2.995</td>
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<td>08SADVL</td>
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<td>1.426</td>
<td>3.286</td>
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<td>1.619</td>
<td>4.262</td>
<td>7.074</td>
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<td>1.808</td>
<td>3.156</td>
<td>6.243</td>
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<td>ZM421</td>
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<td>1.842</td>
<td>3.037</td>
<td>6.43</td>
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<tr>
<td>VP077</td>
<td>2.524</td>
<td>1.936</td>
<td>3.256</td>
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<td>VP0717</td>
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</tr>
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<td>1.503</td>
<td>3.911</td>
<td>7.183</td>
</tr>
<tr>
<td>VP0720</td>
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<td>2.26</td>
<td>3.105</td>
<td>7.491</td>
</tr>
<tr>
<td>CZH0831</td>
<td>2.308</td>
<td>2.164</td>
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<td>8.605</td>
</tr>
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<td>CZH089</td>
<td>2.291</td>
<td>1.692</td>
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<td>6.773</td>
</tr>
<tr>
<td>CZH0735</td>
<td>2.101</td>
<td>1.598</td>
<td>3.391</td>
<td>7.425</td>
</tr>
<tr>
<td>SC533</td>
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<td>1.781</td>
<td>3.895</td>
<td>8.675</td>
</tr>
<tr>
<td>CZH087</td>
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<td>1.841</td>
<td>3.416</td>
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<td>CZH0839</td>
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<td>1.636</td>
<td>3.911</td>
<td>8.543</td>
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<td>1.532</td>
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<td>7.622</td>
</tr>
<tr>
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<td>0.477</td>
<td>2.577</td>
<td>9.405</td>
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<tr>
<td>CZH0829</td>
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<td>2.876</td>
<td>9.008</td>
</tr>
<tr>
<td>ZMS 652</td>
<td>1.649</td>
<td>0.805</td>
<td>1.778</td>
<td>8.76</td>
</tr>
<tr>
<td>CZH079</td>
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<td>1.229</td>
<td>2.678</td>
<td>8.621</td>
</tr>
<tr>
<td>SC513 hybrids</td>
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<td>1.816</td>
<td>3.118</td>
<td>7.37</td>
</tr>
<tr>
<td>CZH0713</td>
<td>1.45</td>
<td>0.987</td>
<td>2.76</td>
<td>8.771</td>
</tr>
<tr>
<td>ZMS 602</td>
<td>1.368</td>
<td>0.703</td>
<td>1.711</td>
<td>8.94</td>
</tr>
</tbody>
</table>

Grant mean per management system

| Relative yield advantage of CZH0116 over the population mean | 0.68 | 0.50 | 0.63 | 0.18 |
| Relative yield advantage of CZH0116 over the most farmer preferred check, SC513 | 1.68 | 0.45 | 0.82 | 0.22 |
| Yield reduction due to stressed environment | -0.68 | -0.77 | -0.54 | 0 |
In the on-station trials the average grain yield under drought stress was reduced by 68% (Table 3), which was close to the target reduction of 50% in agreement with Bänziger et al. (2000). Hybrids CZH0616 and PAN53 were among those that had a good average grain yield across the various management levels (Fig. 2 and 3) and better yield advantage of the famous check (SC513, Fig. 4), indicating their stability under diverse conditions. These results were in agreement with evaluations in multi-location trials under optimal, water stress (70% yield reduction) and low N environments (31% yield reduction), which showed consistent gains averaging 164 and 99 kg ha$^{-1}$ cycle under drought and optimal conditions (Bänziger et al., 1997; Edmeades et al., 1999).

### Performance of Drought Tolerant Maize in On-farm Trials

The significant differences among countries shows that environments in SSA countries are associated with similar predictable stress conditions that are however modified by some random factors in some seasons (Table 4). For example, most areas in SSA are prone to low N and drought but sometimes random stress may occur such as occurrence of pest, diseases, and dry spells of varied intensities. Significant differences ($P < 0.001$) were also observed on the farmers with countries. This is expected because different micro-environments are experienced at farm level due to

![Graphs showing performance of open pollinated (OPV) and hybrid maize varieties on-farm in 94 locations in eastern and southern Africa in (a) 2010/2011 and (b) 2011/2012.](image-url)
different management conditions practiced in addition to predictable and unpredictable physical factors. The significant differences ($P < 0.001$) among genotypes and the presence of genotype × environment interaction suggest that specific cultivars have to be selected. The genotype comparison biplots for the on-farm data for 2010/2011 and 2011/2012 seasons (Fig. 5 and 6) shows that the most stable and high yielding variety was CZH0616. Several other hybrids such CZH0837, CZH0935, and CZH0928 also performed much better in terms of mean grain yield and stability across locations in eight countries that represent major maize production environments in ESA. However, most commonly grown varieties such as SC513, ZM521, and SC403 had low yield and relatively poor stability compared to the newly developed hybrids under the DTMA project. Most of the time maize yields depend on the amount of rainfall in that particular season. These unpredictable stresses give rise to complex genotype × season interactions because stress tolerance varies among hybrids and throughout the season. The huge variability in the production environments in ESA is mainly contributed by the variations in soil N, rainfall patterns, and other random stress factors. In this situation development of stable and high yielding varieties such CZH0616 is highly recommended (Yan and Tinker, 2005, 2006).

**Fig. 4.** Yield benefit of drought tolerant maize varieties grown in eastern and southern Africa (ESA) against SC513 in 2010/2011 and 2011/2012

Yield Gains in Comparison to the Checks On-Station

Hybrid CZH0616, which is one of the new DT hybrids, out yielded SC513 by at least 20% under high and low yielding trials (Fig. 4). The yield gap was wider under low-yielding trials indicating the genetic progress made under drought conditions. Most of the seed companies select their hybrids only under optimum and random stress conditions as their
target environment and seed sales are mostly in non-stress environments. This explains why private seed company hybrids yield more under optimum conditions but perform poorly under drought and low N conditions. Bänziger et al. (2006) found similar results when a total of 42 hybrids from CIMMYT’s stress breeding program showed consistent advantage over private company hybrids. These results were consistent with Edmeades et al. (1999) who showed that hybrids developed under managed drought and low N conditions had the largest yield differentials between 2 to 5 t ha⁻¹ and the yield gap became less significant at higher yield levels over private seed company hybrids. To ensure adoption by farmers it is essential that new hybrids both perform well under the stressful conditions they are likely to experience within the target environment and contain farmer preferred traits (Mulatu and Zelleke, 2002; Tiwari et al., 2009).

Varieties from CIMMYT’s stress breeding program showed a yield advantage over commercial checks at all yield levels compared to commercial checks in the range of 4 to 19% (Table 5). For the early to intermediate maturing varieties the largest yield gap among individual means compared to commercial checks was in group of >4 t ha⁻¹. However for the intermediate to late maturing varieties the largest yield gap was in the group of between 1 and 2 t ha⁻¹ followed by yields in the group of between 3 and 4 t ha⁻¹. The yield gap was much narrower for the intermediate to late maturing varieties in the group yielding >4 t ha⁻¹. Most of the intermediate to late hybrids are targeted toward less stressful environments so as to utilize the full season and show their genetic potential thus the narrow yield gap is not of much concern. However, the early to intermediate hybrids are mostly targeted toward drought prone areas and thus a huge benefit will be derived from the new hybrids bred by CIMMYT. Private seed companies have been focusing breeding efforts on high rainfall/optimum conditions as most of the seed sales are in these environments, and neglecting the drought prone areas due to the small seed market. The release of high yielding, early and stress tolerant hybrids such as CZH0616 will attract the efforts of such companies in stress prone areas thus resulting not only in increased profits but also in the improvement of livelihoods of people dependent on maize (Kostandini et al., 2013).

### Table 4. Analysis of variance for grain yield of drought tolerant varieties grown in eastern and southern Africa (ESA) across the 2010/2011 and 2011/2012 seasons under farmers’ environments.

<table>
<thead>
<tr>
<th>Sources of variation</th>
<th>df</th>
<th>mean square</th>
<th>df</th>
<th>mean square</th>
</tr>
</thead>
<tbody>
<tr>
<td>Country</td>
<td>7</td>
<td>150</td>
<td>7</td>
<td>84*</td>
</tr>
<tr>
<td>Country/farmer’s field</td>
<td>41</td>
<td>58.98***</td>
<td>52</td>
<td>37.8483***</td>
</tr>
<tr>
<td>Genotypes</td>
<td>19</td>
<td>6.17***</td>
<td>19</td>
<td>5.7026***</td>
</tr>
<tr>
<td>Country × genotypes</td>
<td>133</td>
<td>2.80***</td>
<td>133</td>
<td>0.977***</td>
</tr>
<tr>
<td>Residual</td>
<td>778</td>
<td>0.97</td>
<td>976</td>
<td>0.68</td>
</tr>
<tr>
<td>Total</td>
<td>978</td>
<td>4.72</td>
<td>1187</td>
<td>2.91</td>
</tr>
</tbody>
</table>

* Significant at 5% probability level.
** Significant at 1% probability level.
*** Significant at 0.1% probability level.

Fig. 5. Genotype comparison biplot for 20 varieties evaluated across 94 on-farm locations in eight countries in eastern and southern Africa (ESA) in 2010/2011. The data was environment centered with genotype focused singular value partitioning.

Fig. 6. Genotype comparison biplot for 20 varieties evaluated across 94 on-farm locations in eight countries in eastern and southern Africa (ESA) in 2011/2012. The data was environment centered with genotype focused singular value partitioning.
Table 5. Summary results for the relative yield advantage of drought tolerant varieties on-farm against commercial checks in different trials during the 2010/11 and 2011/12 seasons.

<table>
<thead>
<tr>
<th>Maturity</th>
<th>Number of trials</th>
<th>CIMMYT varieties</th>
<th>Check varieties</th>
<th>Relative yield advantage</th>
<th>Statistical significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early to intermediate maturity</td>
<td>12</td>
<td>1.81</td>
<td>1.69</td>
<td>6.6</td>
<td>*</td>
</tr>
<tr>
<td>1–2</td>
<td>12</td>
<td>2.80</td>
<td>2.67</td>
<td>6.4</td>
<td>ns</td>
</tr>
<tr>
<td>2–3</td>
<td>16</td>
<td>3.31</td>
<td>2.94</td>
<td>11.2</td>
<td>***</td>
</tr>
<tr>
<td>&gt;4</td>
<td>16</td>
<td>5.60</td>
<td>4.55</td>
<td>18.8</td>
<td>***</td>
</tr>
<tr>
<td>Intermediate to late maturity</td>
<td>12</td>
<td>1.92</td>
<td>1.57</td>
<td>18.2</td>
<td>*</td>
</tr>
<tr>
<td>1–2</td>
<td>12</td>
<td>2.52</td>
<td>2.44</td>
<td>3.3</td>
<td>ns</td>
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<tr>
<td>2–3</td>
<td>16</td>
<td>3.89</td>
<td>3.27</td>
<td>15.9</td>
<td>***</td>
</tr>
<tr>
<td>&gt;4</td>
<td>16</td>
<td>5.68</td>
<td>5.27</td>
<td>7.2</td>
<td>***</td>
</tr>
</tbody>
</table>

* Significant at 5% probability level.
*** Significant at 0.1% probability level.

Farmers’ Preferences for Traits

Using the voting and calculated PI from the 29 trial sites in Zimbabwe, farmers preferred Pan53, CZH095, CZH0616, and CZH1021 (Fig. 7). This trend was similar for both men and women. The reasons for liking these varieties were given as big cob sizes, good vegetative standing, drought resistance, good tip cover, and good grain quality (Table 6). The PI shows that farmers disliked ZM309, SC403, and CZH0946. The reasons given were small cobs, poor vegetative standing, susceptibility to lodging, and inability to withstand drought (Table 6). It is interesting to note that the varieties preferred by the farmers were not necessarily high yielding, apart from CZH0616.

The decisions of farmers to like and adopt a particular maize variety are based on factors other than yield. In addition to biophysical, institutional and economic factors, Lunduka et al. (2012) found that farmers in Malawi considered a diversity of traits beyond grain yield when adopting new maize varieties, and similar findings were reported by Smale et al. (2001) from Mexico. Therefore, it is important that breeding programs consider traits other than high yield in their breeding programs (Setimela et al., 2012). Thus, it was fortunate that some hybrids like CZH0616 that are both high yielding and preferred by farmers have been identified.

It should be noted that there were some varieties that had other traits that were not appealing to the farmers but had been bred for adverse conditions and performed better than the more favored varieties under farmers’ conditions. For example, ZM521 and ZM309 performed poorly in the farmers voting because they were compared to superior varieties under good conditions. However, under severe drought conditions, these varieties tend to outperform the other hybrids. Therefore, there is a need to collect more biophysical data such as rainfall, soil fertility, and temperature to control for such conditions. Management of the trials under the farmers’ management practices is also critical and should also be controlled. Indeed, breeders may want to take into account some of the positive traits that farmers look for in the varieties and improve on the current disliked varieties.

Reaching Farmers with Drought Tolerant Maize

The DT maize product pipeline (Fig. 1) is closely linked with product delivery efforts. To realize the project’s vision there is a strong emphasis on seed production as well as promotion and delivery of adapted DT maize varieties to farmers. To achieve this, the project has been linked with other partners such as the Alliance for a Green Revolution in Africa (AGRA) through its arm called the Program on African Seed Systems (PASS) to coordinate seed company development activities with registration, production, and promotion of DT varieties. More than 180 DT maize varieties have been released from a strong, efficient DT product pipeline that involves the participation of a large number of public and private sector research and development partners across the project countries (Cairns et al., 2013). CIMMYT and IITA will ensure that sufficient quantities of breeder seed are produced to meet the needs of seed producers. Sustainability of seed production will also rely on the creation of effective demand...
for project products through the creation of awareness among national agricultural research and extension systems (NARES), non-governmental organizations, and seed suppliers. Private seed companies have been able to produce about 68,000 t of certified seed across the project countries. With climate change the demand of the DT varieties is expected to increase.

**CONCLUSIONS**

The results indicate that simultaneous selection under stress and non-stress conditions can result in significant increase in yield under farmers’ conditions. Variety performance in regional multi-location testing across a range of environments provided a good indicator that new DT varieties are likely to be successful and that increasing the precision of phenotyping is key in DT maize variety development. Precision and reducing genotype x trial interaction in managed drought trials played a key role. CIMMYT genotypes outperformed private seed company varieties under drought conditions but the yield gap was narrow under optimum conditions showing that the strategy of private seed companies was focused on breeding under non-stress conditions. On average the best CIMMYT genotypes out yielded private seed company genotypes by up to 19% under both stress and non-stress conditions indicating the extent of the contrast between CIMMYT elite germplasm and commercial checks that have been on the market for more than 20 seasons. Among the CIMMYT hybrids, CZH0616 showed wide adaptation under stress and non-stress conditions, making it an ideal genotype for smallholders’ farmers. Maize yields are currently very low in ESA and will decrease in most areas under climate change. These results confirm that extensive breeding efforts are conferring genetic improvement in farmers’ fields.

**ACKNOWLEDGMENTS**

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**REFERENCES**


