Expression of tolerance to drought and low nitrogen levels in maize inbred lines and hybrids in southern Africa

By

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Submitted in accordance with the academic requirements for the degree of

Philosophiae Doctor (PhD)

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August 2017

DECLARATION

I, Terence Tapera, declare that my thesis that I hereby submit for the Doctoral Degree in Plant Breeding at the University of the Free State, is my independent work, and that I have not previously submitted it for a qualification at another institution of higher education.

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SUMMARY

The increased incidence of drought and low fertility challenges in southern Africa emphasizes the continued need for innovations and technologies to improve the productivity of the maize-based production systems in the region. This region depends mainly on maize for food security, and thus breeding for drought and low N tolerance has been, and will continue to be a focal point and major objective in sub-Saharan Africa. The hybrids tested in this study were developed from CIMMYT maize inbred lines selected for drought and low N tolerance, for the tropical and sub-tropical regions. Trials were conducted in Zambia, Zimbabwe and South Africa under managed drought, low N stress and optimum conditions. This study was conducted to determine the combining ability of lines and testers and heritability of yield and agronomic characteristics of early and late maturity maize hybrids generated from a line x tester crossing design, to determine the testcross performance of the developed hybrids and to determine yield stability of early and late maturity hybrids using AMMI and GGE models.

Yield reduction due to stress conditions of 28.6-79.0% was observed for hybrids grown under low N and drought conditions. Late maturity maize hybrids face a larger risk of exposure to drought conditions that eventually reduces yield drastically. The reduced yields under random drought and low N stress observed in this study indicated the potential threats to maize-based production systems in the southern African region.

Combining ability studies indicated the importance of both additive and non-additive effects across the stress environments. GCA of lines and testers and SCA effects for hybrids were significant across all locations, which indicates the importance of both additive and non-additive gene action in the genotypes evaluated. Lines which showed positive GCA effects for grain yield across all the environments can be successfully utilized as potential sources for hybrid breeding programmes across areas where drought and low N stresses are a challenge.

Testcross performance results indicated that several hybrids (both early and late maturity) performed better than the local commercial checks evaluated and warrants further evaluation for stability and consistency, and can be recommended for use as hybrids across varied environments in southern Africa.

AMMI and GGE models were efficient in differentiating the performance of maize hybrids across the test environments. Several hybrids performed better than the local commercial checks, indicating their suitability as potential cultivars under stress and non-stress environments.

Entries 46, 82, 32, 15, 100, 6, 21 and 83 (early maturity hybrids) and entries 109, 115, 22, 63, 1, 24, 21, 20, 2, 19, 5, 6, 10, 14, 25, 9, 108 and 114 (late maturity hybrids) performed better than all commercial check hybrids and were consistently identified by the AMMI and GGE biplots as performing above average in terms of yield and stability, and warrants recommendation as hybrids under both stress and non-stress environments in southern Africa. The results indicated the success story of the developed drought and low N stress hybrid breeding programme in reducing the effects of these stresses, which will help to sustain and improve the efficiency of the maize-based production systems in southern Africa, and other regions of sub-Saharan Africa where these stresses are intense.

Key words: GCA, SCA, broad and narrow sense heritability; testcross performance, BLUPs, AMMI, GGE biplots, stability, G x E interactions, random drought stress, low N stress, maize productivity, southern Africa

DEDICATION

This work is dedicated to my late father and mother Silvester and Priscilla Tapera, and my late brothers Tinos, and Ruramai, and my late sister Majestic, who did not wait to see this achievement.

"That some achieve great success, is proof to all
that others can achieve it as well."
-Abraham Lincoln

ACKNOWLEDGEMENTS

HaKadosh Baruch Hu, the Most High God; *Ribboni kol Ha Olamim*; Master of the Universe, *Aleichem Shalom*, Grantor of Peace, in whose mercy and peace, I stand; this wasn't going to be possible without your utmost guidance, and provisions, and everything else I needed. It's so true, when you become the shepherd, we will never lack (Psalms 23). Your love, peace, emotional and spiritual guidance, His Holiness, Dr. Nehemiah Mutendi has made who I am today, I thank you.

I would like to extend my gratitude to my major promoter, Prof. Maryke Labuschagne for the guidance, constructive criticism and her dedication, and mentorship throughout my studies. She always gave me hope to press on. Dr. Lebaka, my co-promoter, your guidance throughout the research period and write-up is also highly appreciated. I would also like to express my warmest gratitudes to my other co-promoters, Dr. Amsal Tarekegne (CIMMYT-Zimbabwe) and Dr. Kingstone Mashingaidze (ARC-South Africa) for their guidance, motivation, encouragement, all rounded support and valuable comments throughout the research period. I appreciate your efforts, and I will always be thankful for the assistance you gave me. It was really an interesting experience working with you.

I am indebted to CIMMYT and the National Research Fund (NRF) for funding my studies, through Dr. Jill Cairns (CIMMYT) and Prof. Maryke Labuschagne (University of the Free State) for the facilitation of the funding of my studies.

I would like to express my gratitude to the following individuals and organizations who contributed immensely in terms of resources and knowledge;

- CIMMYT-Zimbabwe through Dr. Amsal Tarekegne for the maize genotypes (released and non-released inbred lines) used in this study, and the management and coordination of trials in and out of Zimbabwe.
- ARC – Grain Crops Institute through Dr. Kingstone Mashingaidze for your involvement and seeing some sense in what I was planning. You saw something sensible, and decided to help me.
- ARC – Grain Crops Institute through Lebogang Madubanya, "Shamwari yangu", for SNP molecular genotyping. It was so tiresome, yet you helped me through.
- ARC – Biotechnology Platform through Prof. Jasper Rees and his entire team for sequencing my materials and the warm hospitality during this period.

I would also like to convey my appreciation to my friends and colleagues who always gave me encouragement during this period. My friends and mentors from CIMMYT-Zimbabwe include Dr. Thokozile Ndhlela; Dr. Jill Cairns; Dr. Cosmos Magorokosho; Dr. Mainassara; Alice Tariro Moyo; Amini Mataka; Alex Chikoshana; Patience Ndaruza; Mr. Tawanda Mushandu; Rumbidzai Mutasa-Matemba; Esnath Hamadziripi; Mr. Mafio; Mr. Freddy; Melody Mutengezanwa; Netsai Mhlanga (Cambridge University); Christine Diepenbrock (Cornell University) and everyone else at CIMMYT-Zimbabwe. You gave me a good time during the entire tenure at CIMMYT. It was like home with you.

The University of the Free State lecturers and mentors; Dr. Adré Minnaar-Ontong; Dr. van de Merwe; Dr. Joyce Moloi; Dr. Chrisna Steyn, and Prof. Liezel Herselman. My PhD fellows at the University for Free State, Dr. Pepukai Manjeru; Oswell Ndoro; Martin Chemonges; Julius Siwale; Sajjad Akhtar; Stefan Pelser; Mavis Mbiriri; fellow classmates, Harlod Katondo; Hilda Shawa and Rafael Banda, I thank you for your cooperation and assistance, academically and socially.

If my life was a movie, Professor Sivave Mashingaidze should have been the main actor. Thank you for your guidance, encouragements when things were getting tough in life.

I would like to thank my beloved brothers Dr. Admark Moyo; Peter; Pedzisai; Douglas; Darlington; and sisters, Medwin; Mavis; Molly, Naume and Merit; Ellen; Tsitsi Tapera for their patience and comfort throughout this period. I would like to acknowledge my friends, who stood by me during this period, including David Zezai; Edwin Mugwira; Tsitsi Murenje; Edmore Chiurayise; Adv. Kumbirai Toma; Dr. Alexander Maune; Tafuma Fundira; Chishamiso Debra Fundira; Coordinator Winston Matunya; Adv. Dominico Chidakuza; Adv. Tinashe Mavhaire; Edmore and Rumbidzai Muzirwa; Piniel Mushayanyama; Jasper Mangwana; Macdonald Kunze; Euvona Gamuchirai Marume; Nyasha Marufu; Simbarashe Mugwira; Tauya Zimano; Kenneth Mugwira; Sanctions Mutendi; Hubert Mutendi; Happymore Tawanda Mutendi; Memory Dhaudha and Tinashe Magara among my many friends.

My gratitude also goes to Sadie Geldenhuys our Divisional Plant Breeding Secretary for the administration she did throughout my study tenure at the University of the Free State. It was awesome working with you.

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ABBREVIATIONS AND SYMBOLS

%	Percent
∑	Summation
AD	Days to 50% anthesis
AEA	Average environmental axis
AEC	Average environment coordination
AMMI	Additive main effects and multiplicative interaction
ANOVA	Analysis of variance
ARC	Agricultural Research Council
ASI	Anthesis silking interval
CIMMYT	The International Centre for Maize and Wheat Improvement
cm	Centimetre
CML	CIMMYT maize line
CSA	Central Statistical Agency, Ethiopia
CV	Coefficient of variation
CZL	CIMMYT Zimbabwe line
df	Degrees of freedom
DH	Doubled haploid
DNA	Deoxyribonucleic acid
E	Environment
ED	Ear diameter
EH	Ear height
EL	Ear length
ENSO	*El Niño* southern oscillation
EPO	Ear position
EPP	Number of ears per plant
ER	Ear rot
ESA	Eastern and southern Africa
ET	*Exserohilum turcicum*
FAO	Food and Agriculture Organization
FAOSTAT	FAO statistical Database
FAS USDA	United States Department of Agriculture Foreign Agricultural Service
FEWSNET	Famine early warning system network
G x E	Genotype x Environment
G	Genotype
GCA	General combining ability
GCV	Genotypic coefficient of variation
GD	Genetic distance
GEI	Genotype x environment interaction
GGE	Genotype and genotype x environment interaction
GLS	Grey leaf spot
GS	Genomic selection
GY	Grain yield

H^2	Heritability in the broad sense
h^2	Heritability in the narrow sense
ha	Hectare
HC	Husk cover
HI	Harvest index
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
ICARDA	International Center for Agricultural Research in the Dry Areas
IFPRI	International Food Policy Research Institute
IITA	International Institute of Tropical Agriculture
IMF	International Monetary Fund
IPCA	Interactive principal component analysis
ITCZ	Inter-tropical convergence zone
K	Potassium
kg ha^{-1}	Kilogram per hectare
kg	Kilogram
LSD	Least significant difference
M	Metre (s)
MABC	Marker-assisted backcross
MARS	Marker-assisted recurrent selection
MAS	Marker-assisted selection
Masl	Metres above sea level
Max	Maximum
Min	Minimum
MLN	Maize lethal necrosis
MSE	Mean square error
MSV	Maize streak virus disease
MT	Metric tonnes
N	Nitrogen
NARS	National Agricultural Research Stations
NE	Number of ears
NUE	Nitrogen use efficiency
^{o}C	Degrees Celsius
Opt	Optimum
OPV	Open pollinated varieties
P	Phosphorus
PC	Principal component
PCA	Principal component analysis
PCV	Phenotypic coefficient of variation
PH	Plant height
PS	*Puccinia sorghi*
pH	Soil acidity or alkalinity
ppm	Parts per million
QPM	Quality protein maize
QTL	Quantitative trait loci

REML	Restricted Maximum Likelihood
RL	Root lodging
RNA	Ribonucleic acid
SCA	Specific combining ability
SE	Standard error
SEN	Senescence
SL	Stem lodging
SSA	Sub-Saharan Africa
SVD	Singular value decomposition
t ha^{-1}	Ton per hectare
TEX	Grain texture
UPGMA	Unweighted pair group method with arithmetic mean
USA	United States of America

CHAPTER 1

General introduction

1. Background of the study

Maize (*Zea mays* L.) feeds more than 1.2 billion people in sub-Saharan Africa (SSA) and Latin America. It is a key crop in Asia, and is Africa's most important staple crop – feeding more than 300 million of the continent's most vulnerable people (Prasanna, 2015), making it one of the most important food crops on global level. These people depend on maize both directly, as a source of calories in diets (some as a staple food) and as a source of income or fuels (Shiferaw et al., 2011). It is a principal crop in Africa, accounting for an average of 32% of consumed calories in eastern and southern Africa, rising to 51% in some countries. Maize is planted on 33 million of the 194 million hectare agricultural land area in SSA every year (CIMMYT, 2015). Since its introduction in Africa five centuries ago, it has been grown under sub-optimal conditions, and with the diversity available, a potential 200 million hectares can be successfully utilized for maize production (Deininger and Byerlee, 2011).

Sub-Saharan Africa countries suffer tropical and sub-tropical region-specific constraints. These constraints range from drought and heat stress, low nutrient recapitalization, soil acidity and alkalinity, loss of soil biodiversity, low levels of soil organic matter, increased incidences of pests and diseases, among others (Cardoso and Kuyper, 2006). Most of these challenges are climate-related, and with the regional population estimated to reach 1.3 billion by 2050 (Drummond et al., 2014), food production, especially maize, must be doubled. According to Shiferaw et al. (2011) there is increasing need for the world to double productivity in maize-based farming systems by improving the resilience and sustainability of these systems to counter the increasing demand, poverty and malnutrition, climate changes and the general natural resource depletion. Van Ittersum et al. (2016) reported the existence of a yield gap between the actual farm yields and the yield potential of the currently grown cultivars, which causes the SSA region to not be self-sufficient, thereby relying on imports to meet its cereal demand. The yield gap is widening due to the effects of climate change, increased population, and change of diets. For Africa to meet its cereal demand and to initiate a possible Green Revolution, robust approaches need to be put in place, such as prioritizing breeding for resilience to major yield reducing factors.

Globally, maize production has been lower than demand, and input (fertilisers, pesticides and other related production costs) prices are generally high and unaffordable to millions of resource-poor smallholder farmers. Unless vigorous measures are taken to accelerate the increase of yield, the outcome will be less food for millions of poor maize consumers.

Drought and low nitrogen (low N) has been implicated as prime yield reducers in southern Africa (Heisey and Edmeades, 1999). Additional constraints causing significant yield and economic losses annually include waterlogging and pests and diseases. These stresses are going to become more important with the increase of cultivation on marginal and less fertile soils (FAO, 2010). There is need to improve maize tolerance to the combined effects of drought and low N, which have been reported to jointly cause up to 80% yield losses (Bänziger et al., 2006). The International Centre for Maize and Wheat Improvement (CIMMYT) has been developing several inbred lines, among them early and late maturing white maize lines, for drought and low N stress tolerance under optimal and sub-optimal conditions. These inbred lines are test-crossed with specific testers developed by CIMMYT to determine their general (GCA) and specific combining ability (SCA) across optimal and sub-optimal test environments. Apart from filling the knowledge gap existing on the performance of these selected genotypes, this research also aimed to boost maize yield productivity and minimise yield losses due to drought and low N fertility in SSA.

Despite the efforts made by plant breeders, physiologists and other stakeholders, maize yields remain low and highly variable between years across SSA at an average of 1.6 t ha^{1}, only just enough to reach self-sufficiency in many areas (Bänziger and Diallo, 2001). Much has been achieved in terms of meeting the world food demands due to continued efforts from breeding and good agronomic practices. Major breakthroughs were made during the Green Revolution (which involved the development and use of high-yielding cereal grains and the use of modern equipment (irrigation), synthetic fertilisers, improved uses of pesticides and other modernised farming techniques), a project pioneered by dr. Norman Borlaug and his team in the 1960s, which paid dividends to the Asian countries, meeting their food demands, and even creating surplus for export. Moreover, many characteristics linked to yield have been researched by scientists from CIMMYT and national research centres on the globe, with good gains in yield. Maize yields, specifically in SSA have, however, remained low, despite major breakthroughs in other regions. These achievements in maize have not been achieved in Africa yet, and this is highly linked to the challenges due to climate, declining soil fertility, limited use of inputs, lack of tolerant varieties, poor dissemination and poor adoption of knowledge and poor agronomic practices (Jones and Thornton, 2003; Fischer et al., 2005; Karanja et al., 2011; Vanlauwe et al., 2015).

Soils in most of SSA have inherently low fertility, especially low N, and nutrient replenishment every year is not adequate. This is caused by the deterioration of soil properties (physical, chemical or biological), decline in organic matter and soil biological inactivity, loss of soil structure, and the reduction of both macro and micronutrients, without adequate replenishment. Tarekegne and Das (2015) cited drought and low N fertility, together with heat, as the major stresses in SSA that reduce maize yields. The consumption and use of mineral fertiliser (N:P:K) has been recorded to be the lowest at about 11.2 kg ha^{-1} yr^{-1} (in low income countries) and 17.5 kg ha^{-1} yr^{-1} (SSA) in comparison with the 90 kg ha^{-1} yr^{-1} world average; 88.6 kg ha^{-1} yr^{-1} (Middle East and North Africa); 128.2 kg ha^{-1} yr^{-1} (North America); 151.5 kg ha^{-1} yr^{-1} in South Asia and 336.5 kg ha^{-1} yr^{-1} in East Asia and Pacific (World Bank, 2016). Low fertiliser use has been linked to poor funding opportunities in the SSA region, and unaffordable costs. The development of low fertility stress tolerant cultivars, affordable to resource poor communities, will greatly improve agricultural productivity in this region.

Droughts have also played a significant role in reducing yields in SSA where the maize production systems are largely rain-fed, with yield being highly prone and sensitive to climate variability. According to Fisher et al. (2015), over 40% of Africa’s maize growing regions face drought stress, which frequently cause between 10-25% yield losses and around 25% of the maize grown suffers frequent droughts, with 50% yield losses incurred. Drought can cause yield losses up to 100%. The major challenges facing farmers are inadequate funding for irrigation facilities and unprecedented and frequent droughts during critical stages of maize growth. Millions of farms in southern Africa recently have been hit by El Niño, causing problems on sustaining the population across the region. Global losses due to El Niño alone during the 2015/2016 cropping season has been estimated to reach $ US 8 billion with SSA contributing much to the losses (Andersen, 2015). In most parts of the SSA region, the changes in the occurrence of both drought and low fertility are likely to outstrip efforts to manage the changes. Plant breeding and physiology will be required to manage the changes by the utilization of genetic tolerance as a sustainable way to counter these challenges.

The development of improved germplasm by CIMMYT, the National Agricultural Research Stations (NARS) and private organizations to meet the needs of future generations has been a major undertaking in the light of climate change and population growth and is of the utmost importance (Easterling et al., 2007). A possible Green Revolution in SSA will need increased uses of organic fertilisers, better soil and water management, and the use of better N and water use efficient cultivars (World Bank, 2012). According to Smale and Jayne (2003), improved maize varieties have consistently been shown to be superior to local varieties at different fertiliser applications, and various soil fertility and rainfall conditions. Farmers who cannot afford high priced fertilisers, pesticides and irrigation equipment for their fields now depend on these crops with higher levels of stress tolerance in order to maintain high yields, and limit crop yield losses.

Because of its wide adaptability, maize has emerged as one of the most important crops in the world. Through its ancestry, maize has survived through the harshest environments, which made its adaptation wide enough for cultivation and resistance or tolerance genes are available in the maize genome to counter these challenges. According to Meng and Ekboir (2001), the demand for maize in developing countries will exceed that of wheat and rice by the year 2020, with an estimated consumption projected to be between 50% and 93% in SSA, justifying the need and importance of the crop in Africa, and globally. It will act as a check to the increased importance of greenhouse gases and temperatures, low rainfall incidences which further threatens the already compromised maize production. This justifies the urgency for a scientific intervention in the sub-tropical regions, to ensure food security.

1.1 Research questions

The specific questions that were addressed in this study included:

- How effective are the newly developed inbred lines and testers of CIMMYT in terms of low N and drought stress tolerance?
- What are the GCA and SCA and heritability for yield and yield related characteristics of the maize lines against the given testers (early maturing and late maturing hybrids)?
- How do the testcrosses (early maturing hybrids and late maturing hybrids) perform with respect to yield and other agronomic characteristics under stress and optimal conditions?
- What are the relationships between yield and other agronomic characteristics under drought, low N and optimal conditions?

- How stable are the testcrosses under optimal, drought and low N conditions?

1.2 Objectives and hypotheses

The major aim of this study was to determine the breeding value and testcross performance of inbred lines developed under sub-optimal and optimal conditions in SSA, specifically for low N and drought tolerance.

The specific objectives of the study were:

1. To determine the combining ability and heritability of early and late maturing maize hybrids under random drought, low N stress and optimal environments.
2. To determine the testcross performance of hybrids developed from early and late maturing inbred lines under stress and optimal conditions.
3. To determine yield stability of selected early maturity maize hybrids across optimal and stress environments using AMMI and GGE models.

High heritability among newly developed CIMMYT lines is pivotal to the selection of good parents to initiate crosses for pedigree, backcross and potential marker assisted recurrent selection (MARS) populations for future advanced line extractions. The resulting new lines will then be used in developing new improved drought tolerant and low N tolerant hybrids and open pollinated varieties (OPVs) for release or advancement to regional multi-environment trials. In addition, classification of inbred lines into heterotic groups will facilitate exploitation of heterosis which can contribute to hybrid performance.

Hypothesis

The hypothesis is that there exists enough genetic variability among CIMMYT-developed maize inbred lines and hybrids for both low N and drought stress tolerance which can be efficiently utilized as sources of drought and low N genes for stress tolerance breeding in southern Africa.

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CHAPTER 2

Maize improvement for drought and low N tolerance in southern Africa

Abstract

Drought and low N fertility poses huge challenges to maize based cropping systems in eastern and southern Africa. Total crop losses have been recorded, as these stresses decimate maize, which feeds over 1 billion people, and will be a principal crop for meeting the global food demand in the near future. Maize uses range from food, livestock feed, and industrial applications, the importance of maize is continuing to grow. Maize is a unique crop, as it is adapted to so many environments, making it suitable for extensive production. Due to high climate variability, the dream of a maize-based Green Revolution is still elusive. There are currently changes in precipitation, and precipitation patterns, increased temperatures and carbon dioxide, and an increase in greenhouse gases, causing global warming. Heat stress is also projected to increase in future, and disease and pests challenges will also surge due to the ongoing climate changes. With a high productivity per unit area as compared to other major cereals like wheat and rice, maize is a strategic crop to meet global food demands to feed 9.7 billion by 2050 and 11.2 billion people by 2100. The objective of this chapter was to review the progress in terms of breeding for drought and low nitrogen (N) stresses in eastern and southern Africa. It also highlights the use of both conventional and marker-assisted selection as potential ways of arresting crop losses. Vigorous research efforts have to be made in order to curb food shortages in the region. The region has the potential to feed itself, and export, rather than the current annual imports. There are large areas of land which can be made productive. Germplasm with tolerance has been developed, and ways to accelerate breeding processes have been invented. Scientists have to collaborate with the private and public sectors to challenge food deficiencies in the region, which depends much on maize as a staple food.

2.1 Introduction

2.1.1 Maize, its global value and economic importance

Maize is a strategic crop for meeting the global food demands of billions of people. In SSA, maize production is dominated by smallholder farmers and covers an extensive 25 million ha, all of which is highly prone to drought, as it is grown under rain-fed conditions, which is very unpredictable and unreliable in the region. SSA houses a potential 88 million ha of land (Jayne et al., 2010) which can be utilized for maize production. It is among the three major cereals that form staple diets in many countries, providing more than 30% calories of over 61% of the global population in 94 countries. It forms major staple diets for more than 1.2 billion people living below US $2/day in Africa, Latin America and Asia (IITA, 2009). It is also consumed indirectly in the form of poultry, eggs, beef and pork, cheese products, corn syrup and milk. In SSA, maize accounts for 40% of the total cereal production, and 85% of the maize produced in eastern and southern Africa (ESA) is used as food. It occupies a strategic position in ESA with respect to its nutritional components (Araus et al., 2002); and economic features (agronomic management and storage) which makes it a competitive product among the cereals. According to James (2001), the global cereal demand shift will favour maize, due to urbanization, which is highest in developing countries, with the growth in meat consumption driving demand for maize feed for poultry and swine. In SSA, Central America and South Asia, the increasing population growth and on-going poverty continues to drive a high demand for maize as a food source. Globally, maize is the most important feed crop, including developing countries. It also has other uses such as biofuel, and with the increasing population, the demand for fuels will also increase, putting more challenges on maize production, which is already constrained by climate changes and low yield per unit area per year. Since 1980, cereal production has been vulnerable due to climate trends and variability with significant decrease in both maize and wheat productivity. According to FAS-USA (2017), yield production levels are decreasing with 1.8% globally, while substantial decreases were noted in South Africa (55%); Ethiopia (22%) and Zimbabwe (7.5%). Only Zambia, among the recorded countries in ESA, recorded 5.9% increases between the 2013/2014 and 2015/2016 agricultural seasons. Among the three fundamental crops to food security; wheat, rice and maize; maize will be more preferred in future due to its productivity per unit area, and as such, the major focus for boosting its productivity is vital to food security and meeting food demands.

2.1.2 Economic importance of maize in eastern and southern Africa

Maize alone in SSA contributes over 90% to the people’s diets. Maize is a native crop from Mexico and only arrived in Africa 5 centuries ago, and has since rapidly increased its dominance, especially white maize (Pingali, 2001), as a major food crop due to its huge phenotypic plasticity across diverse environments (McCann, 2001). It is the staple food for 24 million households in ESA. Out of 194 million cultivated area in SSA, maize covers almost 17% of the total area (approximately 33 million ha) (CIMMYT, 2015). It was forecasted that by the year 2020, 52 million ton will be required up from 21.3 million ton in 1990 (Rosegrant et al., 1995). More than 200 million people in SSA are exposed to poverty, malnutrition and food insecurity, most of which are smallholder farmers who cannot meet their daily food needs. The role of maize as a staple crop is shown by its wide production dominance in the SSA region (Diallo et al., 2004). Consumption levels in southern Africa per capita per year varies from 138 kg (Swaziland), 149 kg (Lesotho), 153 kg (Zimbabwe), 168 kg (Zambia), 181 kg (Malawi, and 195 kg (South Africa). In eastern Africa, consumption levels are lowest in Burundi (40 kg) and highest in Kenya (105 kg) (Hassan et al., 2001). Sub-Sharan Africa is characterised by severe outbreaks of droughts, unfavourable soils, poor access to fertilisers and major diseases and pests that further reduces yields, despite the on-going low yields per ha obtained by these farmers. Maize occupies 75% or more of cereal area. Despite this, the region cannot meet demand (Pingali and Pandey, 2000; FAOSTAT, 2008; Rajendran et al., 2017); and imports maize in order to meet consumption demands. Most countries in the region are yet to legalize the use of biotechnology (genetically modified crops) as a way of improving yields and studies has shown that it is a viable way of sustaining the African maize market and reducing food insecurity in the region. The use of improved and sustained cultivars will greatly impact on meeting food demand in the region (Pingali and Pandey, 2000).

2.1.3 Adaptation of maize in eastern and southern Africa

Maize is cultivated across diverse ecological regions from temperate climates, across both tropical and subtropical (humid and drier) regions (Dowswell et al., 1996). Its suitability of production across these wider and varied climates chiefly led to its success. CIMMYT identified eight mega-environments (Setimela et al., 2005); and assigns and develops germplasm specific to each particular environment, with the major climates sub-grouped into smaller constituent zones. This has contributed toward improvements in the development of well-adapted cultivars specific to particular mega-environments.

2.1.4 Maize production in eastern and southern Africa

The ESA region, though much in need of maize to feed its population, makes the lowest contribution to the global total maize production. Maize yields in the region are very low; 0.48 t ha^{-1} in countries like Zimbabwe to the highest South African mean of 3.42 t ha^{-1} (Fig. 2.1) according to the FAS-USA (2017) report. SSA accounts for over seven times lower yields than in industrialised countries (M'mboyi et al., 2010), and the 5.2 t ha^{-1} global average (Fischer et al., 2014). In temperate climates, yields have been as high as 15 t ha^{-1}, while in subtropical regions the averages are below 2 t ha^{-1}.

Table 2.1 Maize production in selected countries, including eastern and southern African countries

Country/ Region	**Area (Million hectares)**			**Yield (metric ton ha^{-1})**			**Production (million metric ton)**			**% change 2014-2016**
	2013/4	2014/5	2015/6	2013/4	2014/5	2015/16	2013/14	2014/15	2015/16	
World	180.28	179.76	177.50	5.49	5.63	5.48	990.47	1 012.84	972.13	-1.85
USA	35.39	33.64	32.68	9.93	10.73	10.57	351.27	361.09	345.49	-1.65
China	36.32	37.12	38.12	6.02	5.81	5.89	218.49	215.65	224.58	2.79*
South Africa	3.08	3.05	1.90	4.85	3.49	3.42	14.93	10.63	6.50	-56.46
Ethiopia	2.00	2.23	2.15	3.25	2.95	2.35	6.49	6.58	5.05	-22.19
Zambia	1.00	1.21	0.96	2.54	2.78	2.78	2.53	3.35	2.68	5.93*
Kenya	1.80	1.65	1.70	1.56	1.61	1.65	2.80	2.65	2.80	0.00
Zimbabwe	0.90	1.50	1.53	0.89	0.97	0.48	0.80	1.46	0.74	-7.50

(FAS-USA, 2017)

According to Amoako (2003), SSA region contributes the lowest global shares in terms of both area covered and production, and is one of the global regions where food insecurity, poverty and malnutrition continues to increase.

South Africa is the continental giant (Baloyi, 2011) producing more than 10 million metric ton of maize per year (FAOSTAT, 2014), and has the largest area covered with maize, amount produced and highest yields. In the 2013/2014 season, 3.08 million hectares were planted with estimated averages of 4.84 t ha^{-1}. Production went down to 1.9 million ton during the 2015/2016 season with an estimated yield of 3.42 t ha^{-1}. With the recent production trends, SA will be forced to import over 5 million metric ton to meet demand of maize in the country. The discrepancies have arisen due to the current drought and heat stress in maize production areas. All of the ESA region will this year be forced to import maize to meet both food and feed demands. The poor smallholder farmers are the most affected when drought occurs, because they directly depend on the crop for their survival.

2.1.5 Major stresses affecting the maize crop in eastern and southern Africa

The effects of climate changes and variability, especially drought and extreme heat stresses has increased recently, affecting maize production in the US and the world (Moore and Lobell, 2015; Ray et al., 2015; Zipper et al., 2016). Crop losses to stresses are a world phenomenon, with the United States losing $US4.1 billion since 2001 and US$17.3 billion in 2012 due to stresses (NRDC, 2013). Soltani et al. (2016) estimated maize about 50% yield losses to weeds in USA and Canada, which amounts to 148 million tonnes (US$26.7 billion) annually for seven years. Drought, heat, poor soil fertility, especially N and P, and waterlogging are major yield reducing factors in maize production in the region. The dominant biotic constraints to maize production in SSA include maize diseases; maize streak virus (MSV), maize lethal necrosis (MLN, highly prevalent in eastern Africa), grey leaf spot (GLS) caused by *Cercospora zeae maydis*, head smuts caused by *Sporisorium reilianum* (Kuhl); leaf blight caused by *Exserohilum turcicum* (ET); ear rots caused by *Fusarium* species; common rusts caused by *Puccinia sorghi* and leaf spot caused by *Phaeosphaeria maydis*. Pests are also a common challenge during crop maturity in the fields (20-40% losses) and during storage (30-90%), causing significant yield losses. These include maize stalk borer (*Busseola fusca*); African armyworm (*Spodoptera exempta*); African bollworm (*Helicoverpa armigera*); maize weevils (*Sitophillus zeamais*); large grain borer (*Prostephanus truncatus* Horn); and weeds (65-92%) causing yield loses (IITA, 2015) with parasitic weeds like *Striga* species being the greatest common challenges across the SSA region. The occurrence of these stresses has caused between mild to total yield losses when severity is high and when environment is favourable. Yield losses can be offset by proper agronomic management, supplemental irrigation, good fertilization and the use of improved cultivars (Gibbon et al., 2007).

2.1.6 Maize improvement and adoption in sub-Saharan Africa

From the time five centuries ago when maize was introduced to Africa, the crop was grown under sub-optimal conditions which induced differential stress levels in the crop. Despite being low yielding in some regions, maize gave “life” to millions of people living in the region. The introduction of maize in these sub-optimal regions induced some level of selection on the hybrids, as susceptible varieties were eliminated. Breeding was initiated in the 1920s, with the success of the first globally cultivated single cross hybrid, SR52 that was developed in Southern Rhodesia, now, Zimbabwe. This hybrid, together with SR11, and Hickory King, an OPV from the United States were grown almost exclusively in SSA. The success story of this commercial hybrid led to 46% yield increases in Zimbabwe (Mashingaidze, 1994), with the southern parts of Africa and other eastern countries like Ethiopia also benefitting from new varieties. Adoption of new varieties in Zimbabwe has been more than 96% since 1990 (López-Pereira and Morris, 1994), while in Kenya, over 75% improved varieties are used. Better hybrids, apart from out-yielding the unimproved cultivars, have better resistance to major pests and diseases, better tolerate drought and low N fertility regimes, and have good water and nutrient use efficiency, that makes them better options for meeting the delayed African Revolution. However, current adoption rate data per country in SSA is still not available (Smale et al., 2011).

The successes of maize in the region has been possible because of the heavy presence of international research centres like CIMMYT; IITA (International Institute of Tropical Agriculture); ICRISAT (International Crops Research Institute for Semi-Arid Tropics) among others, and the growth of both the private and NARS have all contributed significantly to the development of the ESA seed sector and agricultural productivity in SSA. These institutions, like CIMMYT, were successful in implementing improved technologies and provision of improved cultivars, with better tolerance to major stresses, better water and N use efficiency, and well adapted to different cultivation ecologies. The research was highly targeted, with high level constraints on the agenda, like breeding for drought and low N fertility, MSV and other highly prevalent constraints. Though these procedures were successful in reducing the effects of stresses, climate changes bring more challenges into the maize production systems. Some diseases and pests which were tertiary and secondary as crop yield reducers are becoming more important and primary. The incidence of MLN in Kenya in 2011 is an example of a disease which graduated into a prime yield limiting stress in eastern Africa. The multi-stress environments of ESA will need a multi-dimension breeding strategy, together with good agronomic practices, adequate funding policy environments from the governments and non-governmental institutions, in order to realise the yet to come African Green Revolution.

2.2 Drought

Passioura (1996; 2007) has implicated drought as the most challenging yield-reducer of maize in the tropics. There has been an increasing trend of global maize production areas exposed to drought, with statistics indicating a doubled effect between 1970 and 2000 (Isendahl and Schmidt, 2006). Research has indicated that maize suffers significantly globally due to drought effects, which is one of the most economically important abiotic stresses in SSA, with Diallo et al (2004) observing 17% losses, which were an equivalent of US$280 million during only a one year period. Drought has been associated with reduced crop establishment or total crop failure, leading to various amounts of yield losses depending on the stage of crop development, intensity and duration of drought periods. The severity of losses is also dependent on the crop's developmental stage, with highest losses occurring during seedling, flowering and the grain filling stages. Droughts occurring during the vegetative stage will greatly reduce the leaf size, and photosynthetic efficiency is greatly reduced (Nilson and Orcutt, 1996) and can cause between 10-50% yield losses (Heiniger, 2001).

Drought is a region wide phenomenon in ESA. Usually drought and heat stress occur together, leading to total crop losses. The incidence of El Niño southern oscillations (ENSO) causes severe challenges to maize production across the eastern and the southern region of Africa. The unpredictable rainfall patterns are also a growing concern for farmers, breeders and governments. This has caused far less maize production than the projected levels for 2016. The Bureau for Food and Agricultural Policy reported that low production areas were again hit by serious drought and heat in 2016, causing crop failure across South Africa, Zambia, Zimbabwe, Kenya and Ethiopia. Farmers could not afford to irrigate their crops because dams and rivers were all dry. In South Africa, the largest producer of maize, land planted to maize was 39% less for white maize in 2016 (approximately 4.7 million ton) compared to 2015 (BFAP-Baseline, 2016). The FAO-GIEWS (2016) also highlighted the sharp decrease in the projected output for 2016, estimated at 7.7 million ton (commercial and non-commercial) translating to a 28% decrease compared to the 2015 harvest. They highlighted the record high temperatures and overall severely suppressed seasonal rainfall between October 2015 and February 2016 to the prevailing and weakening ENSO episodes as a cause of the trend.

There are several forms of the drought phenomenon, including meteorological (no rainfall during the normal periods); agricultural (insufficient moisture for good crop establishment and crop water requirements); hydrological (water levels in the surfaces or sub-surfaces is depleted) and socio-economic (when the demand for economic goods exceeds supply due to the unavailability of precipitation). These are usually region specific, since regions have different environmental variabilities contributing to precipitation deficiencies (Eslamian and Eslamian, 2017).

The extent of drought causing yield losses also depends on time of planting and the choice of a variety within a particular drought-prone environment. Some varieties are short season, and are suitable for regions experiencing late season droughts. Breeding for phenotypic plasticity will improve gains from selection, as better cultivars suited for a particular environment can be selected (Turner, 2002).

Scientists have developed stress conditions for specific stress objectives, with managed drought stress trials conducted in winter regions receiving no rainfall, and for low N stresses, using soils that were N-depleted for several years. N-depletion is done by removing stover after every harvest, and by planting non leguminous crops (wheat) during the winter period, that is also removed before it reaches physiological maturity. Scientists have also developed secondary characteristics selection strategies, like selection for anthesis-silking interval (ASI), stay-green and the number of ears per plant, as a way of indirectly improving yield of genotypes under stress conditions (Bänziger and Lafitte, 1997; Diallo et al., 2004; Mhike et al., 2012). Drought stress during the vegetative stage will affect leaf development, assimilation and translocation of assimilates from the sink (leaves) to the source (grain). When leaf development is impaired, photosynthesis is reduced, kernel abortion occurs, and yield is highly reduced. In essence, the reduction of leaf area reduces primary productivity of maize under drought stress.

In order for breeders to win against drought, which is a complex stress, they have to utilize diversity, especially the maize genotypes which have been grown in sub-tropical regions for a long period. Maize is a stress-sensitive crop, responding differentially to environmental heterogeneity, which makes it prone to genotype x environment (G x E) interactions (Smale et al., 2011). Drought in particular, has been a major cause of G x E interactions, affecting genotypes with differential magnitudes based on the environment and seasons (Bruce et al., 2002; Löffler et al., 2005; Setimela et al., 2005). In order to stabilise maize yields across seasons and localities, scientists have to overcome drought effects, using cultivars that are highly water-use efficient, that have prolonged resilience to stresses and have significantly higher yields (both under stress and optimal conditions) as a viable option against drought incidence (Edmeades et al*.*, 1997; Campos et al*.*, 2004).

2.2.1 The anthesis silking interval and drought stress

Anthesis silking interval (ASI) is a very important trait when assessing hybrids or inbred lines for drought stress. Cattivelli et al*.* (2008) indicated that ASI and grain yield are highly correlated. The physical separation of the male and female organs causes significant challenges in maize improvenemt. When water is limiting; silking is delayed, while anthesis is speeded up (causing a high ASI), causing asynchrony and poor seed set and/or no kernel set. This will affect the 'nicking' (overlap between silking and anthesis) of the time when pollen is available and the silk is receptive. Breeders are interested in genotypes which show a lower ASI, especially during the stress period. Asynchrony (absence of nicking) during this phase has been a cause of crop failure under drought stress (Byrne et al*.*, 1995). Anthesis silking interval is highly correlated with kernel set, and if this interval is extended, there is poor synchrony between anthesis and silking, causing poor kernel set and crop failure under drought stress. Insufficient pollen supply causes a decrease in the number of grains per ear (or plant) especially when pollen production is reduced by 80% and when ASI exceeds eight days (Bassetti and Westgate, 1994). Anthesis silking interval has been indicated as a trait of considerable usefulness when ascertaining the water potential status of a plant and the grain number and even the growth rate of the female spikelet (Edmeades et al*.*, 2000). Genotypes which have good tolerance to drought stress always show a lower ASI. So ASI has been indicated as a good measure for tolerance and susceptibility of a genotype to drought stress conditions. Plant breeders are now utilizing ASI as a useful secondary selection trait for measuring the tolerance levels of maize genotypes to drought stress.

2.2.2 Drought during the vegetative and grain filling stage

Drought paralyzes the plant's ability to absorb water and nutrients, thus hindering all the plant's developmental processes (Erdem et al., 2001). As a universal solvent, it transports all the required metabolites for biochemical and physiological processes. And with increased intensity and duration in susceptible cultivars, it will lead to complete crop loss. The incidence of drought stress during germination affects the number of plants germinating and poor establishment of crop stands (Harris et al., 2002). Plants exposed to drought conditions have a reduced plant height, failure to produce ears (barrenness) or uneven kernel set, and leaf senescence from the bottom of the plant (Yadav et al., 2004). Yield losses during drought stress occurs as a result of incomplete or no kernel set during the grain filling stages, reduced kernel weight, loss in crop stand, and premature death. Kiniry and Ritchie (1985) and Fischer and Palmer (1984) also reported a decrease in the number of kernels per plant under stress conditions.

During both the vegetative and grain filling stages, water stress causes leaf senescence. The grain filling process in maize involves four key enzymes (Taiz and Zeiger, 2006); including starch branching enzyme; starch synthatase; adenosine diphosphate-glucose-pyrophosphorylase and sucrose synthatase; by which, during drought stress are either inactivated or switched off, causing cessation of growth. Yield reduction of 79-81% was observed under water stress by Monneveux et al. (2005) during grain filling. Atteya (2003) observed between 25-60% during vegetative, and 32-92% yield losses during the reproductive stages; Chapman and Edmeades (1999) observed yield losses of between 70-74% during the reproductive stage; and Kamara et al. (2003) between 63-87%. The biggest losses in grain yield were observed during the flowering stages of plant development. Genotypes that can withstand stress, and reduce yield losses during the reproductive phase are desired by plant breeders and are usually selected for. Grain losses during the grain filling stages can be attributed to stand loss, failure of fertilization, abortion of fertilized ovules, decreased kernel weight and premature death (Nielsen, 2013).

During the grain-filling period, photosynthesis is reduced, and stem reserves are mobilized as they become the main sources of carbohydrate for the grain filling process (Blum, 1996). Any drought stress occurring during this period will affect the relative sizes of the sink (grain endosperm), in terms of its size and its quality. The size of the grain will affect the amount of starch, proteins, vitamin A and other micro nutrients, thereby lowering the grain endosperm quality. Premature hanging of the cobs has also been noted under drought stress (www.pannar.com/assets/documents/know_the_maize_plant.pdf).

The sink-source relationship has a large influence on the grain weight. The leaves (source) determine photosynthesis and carbohydrate assimilated. Leaf area can play a pivotal role in the photosynthetic efficiency of the plant during stress periods (Blum, 1996; 1997). When water is limiting, the number of leaves for active photosynthesis is reduced due to senescence, and once the photosynthetic machinery has been reduced, the carbohydrates formed and assimilated are affected negatively. There is dry matter remobilization from the leaves (starting with the lower leaves which are closer to the roots) to the roots, thereby affecting the root-shoot ratio. The occurrence of severe drought incidence will trigger root growth (by producing enzymes promoting root growth) and dry matter accumulation towards the roots, and away from the leaves and the grains (Sharp et al., 2004; Ober and Sharp, 2007; Ribaut et al., 2009; Trachsel et al., 2010).

2.2.3 Mechanisms of drought tolerance

Plants have several ways to respond to water stress. The main ways are drought avoidance (tilting and leaf rolling to avoid water loss by transpiration); drought escape (early maturity before moisture stress occurrences); drought tolerance (plant's ability to withstand stress by triggering biochemical and physiological processes) and drought recovery (Turner et al., 2001; Yue et al., 2006; Luo, 2010; Lawlor, 2013). When plants are exposed to drought stress, they stop all growth, and reduce photosynthesis. Wilting occurs as a result of resource mobilization from the leaves (especially bottom ones) to the roots, leading to a higher root-shoot ratio, and the osmotic adjustment of roots and shoots (Mitra, 2001; Mundree et al., 2002; Bennett, 2003; Amede et al., 2004; Nakashima and Yamaguchi-Shinozaki, 2013). These processes will affect plant height, usually resulting in short plants, early maturation, and a greatly reduced number of leaves per plant. Plants that are highly tolerant to drought will have good ASI, are taller (plant height), have more grains per cob, a higher number of ears per plant, mature earlier to escape drought, have a higher root density and depth, and high water use efficiency (Arve et al., 2011; Anjum et al., 2011; Ciarmiello et al., 2011). The same authors also noted that other drought tolerance mechanisms involve activating the antioxidant defense systems, photochromic hormones like abscisic acid and reducing the chlorophyll content, thus limiting photosynthesis and water losses.

2.2.4 Strategies to manage drought

Drought can be mitigated by the economical use of agronomics to minimize water loss, and maintain an environment sustaining growth of crops in the event of low soil moisture levels. Supplementary irrigation is the most effective way of mitigating yield losses to drought. Drought is a cause of lack of water (moisture availability to plants), and any addition of supplemental irrigation will reduce the effects of drought. Supplemental irrigation is expensive and when targeting the smallholder farmers who dominate maize production in ESA, this is not viable. Apart from supplementing water through irrigation, the use of good soil management techniques like minimum tillage, mulching and integrated water management systems that involve soil and water conservation, are some other ways to minimize yield losses due to drought. This can also include effective control of weeds and addition of organic matter, which can help minimize water loss from the ground and minimize yield losses due to drought.

During the 2015/2016 cropping season, there was not enough water in dams to supplement water to crops. Commercial farmers have large fields which require a good deal of water to manage drought. The use of improved hybrid cultivars with high levels of tolerance to drought is the best mitigatory measure against yield losses to drought. According to Mhike (2013), improved drought tolerant varieties, with good water use efficiency, and other drought tolerance attributes like longer roots, reduced leaf senescence, stay green, canopy temperature depression, and a lower ASI can help reduce the impact of drought on maize yields. Hence, the use of improved cultivars with good drought tolerance with high water use and nutrient use efficient under drought will be the most viable, and economical way of reducing yield losses to droughts. This option is highly favourable to smallholder farmers in the ESA who cannot afford the high costs of irrigation.

2.3 Low soil fertility

Increasingly declining soil fertility is a major setback for agricultural productivity in ESA. According to Sanchez (1997), 75% of the soils in the region are intrinsically poor in fertility. Nutrient replenishment through biomass transfer, use of manure or by the use of chemical fertilisers, is still insignificant (Sanchez, 2002). Basically crops that are on the market are highly responsive to nutrition, and most of them are heavy users of nutrients. Nutrient mining every season (the ratio of 60%:40% of P used in grain and stover respectively, while 30-50% of N is used for grain) and poor agronomic systems contribute much to the declining soil fertility in ESA. Africa depends on crops that need high levels of nutrients and the rate of growth of any crop will be directly linked to nutrition, if all other factors are optimal. Soils in ESA are intrinsically low in fertility for macro (N, P and K) and micronutrients that support effective plant growth. This is further exacerbated by low use of mineral fertilisers. Africa uses less than 10 kg ha^{-1} year^{-1} fertiliser on average (Crawford et al., 2006), as compared to other regions with more than 130 kg ha^{-1} year^{-1}. Causes of poor soil fertility in this region are poor soil management and the fragile nature of the tropical soils accounting for heavy losses of nutrients through erosion, and nutrient leaching (Hossner and Juo, 1999). Deforestation, overgrazing, the continued use of marginal lands and nutrient mining every season without replacing them, has contributed much to the current soil infertility levels in the region. Poor cultivation practices caused decreased soil fertility and reduced the soil organic matter content of the soil and the increased acidification of soils (Aihou et al., 1998). Smaling and Janssen (1993) noted that nutrient depletion rates per hectare exceed 30 kg N and 20 kg K in several SSA countries. Soil nutrient depletion has been estimated by Sanchez et al. (1997) to be over 700 kg N, 100 kg P and 450 kg K per hectare for the past 30 years on over 100 million ha cultivated land in the SSA region, making it one of the largest bio-physical constraint in maize production systems.

Poor agricultural policies of several governments also led to the current soil infertility levels. Lack of government subsidies for mineral fertilisers also hinders maize production. Zambia is emerging as a major exporter of maize due to revised agricultural policies, which is seeing its rise in both production, and adoption of improved varieties. Zambia increased its mineral fertiliser use from 11 kg ha^{-1} in 2006 to more than 50 kg ha^{-1} in 2015, thereby meeting the Abuja Declaration on Fertiliser for the African Green Revolution (Abuja Fertiliser Summit, 2006). This indicated the potential use of policies in changing food security in Zambia, which can also be used by other member states to improve food security and smallholder farmers' livelihoods. According to Smale and Jayne (2010), Zambia represents a major scientific and policy achievement in African agriculture, as the government of Zambia successfully developed and disseminated improved maize, and heavily subsidised inputs, which was later dismantled under pressure from by the International Monetary Fund (IMF), the World Bank and the donors. But this has led to the success of the Zambian maize Green Revolution, even now. South Africa, Nigeria, Kenya and Ethiopia are the major users of mineral fertilisers in the SSA region, but recently, the use of fertilisers has been declining, with climatic challenges being cited as the reason. The use of mineral fertilisers will boost maize production, especially when combined with good agricultural practices, use of improved varieties, with good tolerance to major stresses like drought, low N fertility, MSV and MLN diseases, among others. Nutrient use efficient cultivars, and low fertility tolerant improved cultivars will reduce the need for these mineral fertilisers. The use of all available technologies will have better results than using single improved technologies (Zhang et al., 2011, 2017).

2.3.1 Nitrogen and its economic value

Nitrogen plays a crucial role in the growth and development of all organisms. It is a major constituent of nucleic acids (DNA and RNA), together with chlorophyll and proteins. Several plant processes, including metabolic reactions in plants, has N as one of their constituents (Marschner, 1995; Bungard et al., 1997). N is only available to plants in the form of nitrates (NO_3^-) or ammonium (NH_4^+) and a very little as organic urea. As N movement in the soil depends on water, the movement is highly impaired under drought conditions, hence drought and low N stress are highly associated (Derera, 2005). All plants, except legumes which fix N_2

from the atmosphere, usually depend on N in nitrate or ammonium forms, and responds positively to mineral N applications. Low and declining soil fertility is the biggest production constraint across the four CIMMYT mega-environments. Apart from drought, low fertility is also among the greatest challenges for maize-based cropping systems in the region. Statistics indicate that the SSA region utilizes very low levels of N, at an average of 11 kg ha^{-1} yr^{-1} (Sommer et al., 2013), despite the 90 to 120 kg ha^{-1} yr^{-1} recommended rates. Fertiliser costs are the main reasons why fertiliser use in the region is low (Heisy and Mwangi, 1996). There was a slight increase in fertiliser use in SSA, from 6-7 kg ha^{-1} yr^{-1} (2008) to 11 kg ha^{-1} yr^{-1} in 2014, and 12 kg ha^{-1} yr^{-1} in 2015, that is far lower than the Abuja target of 50 kg ha^{-1} by 2015 (Wanzala, 2011). According to Logrono and Lothrop (1997), an estimated yield loss of 10-50% per year occurs in SSA due to low fertility. To correct this, the region has to rely heavily on low N tolerant varieties as the most viable and economical way to reduce crop losses to low N stress. Funding policies are the major bottleneck to fertiliser use and fertility improvement in SSA.

2.3.2 Low nitrogen stress in maize

Maize responds positively to any additions of N fertilisers (Lafitte, 2000), and any N stress will reduce yield levels. Low N stress during the early and vegetative stages of plant development causes premature leaf yellowing of leaves (deficiency of N symptoms). It causes retarded growth, reduced plant size and reduced photosynthesis, which will lead to reduced biomass production and eventually low grain weight, and reduced grain kernel numbers (Muchow and Davis, 1988; Vance, 2001). The effect of stress as a result of low soil N leads to decreased yields due to reduced photosynthesis. Photosynthesis is reduced chiefly because of the reduction of leaf area development during stress, accelerated leaf senescence, and the reduction of photosynthesis itself. Leaves form the basic units for photosynthesis and their reduced growth, and limitations by senescence will affect biomass production by photosynthesis. Leaf senescence proceeds from the bottom of the plant, as N is relocated from older leaves to younger leaves and grain (Bänziger et al., 2000). Severe low N stress will cause higher ASI, causing poor fertilization which causes both ear and kernel abortion, accelerates leaf senescence, and reduces photosynthetic capacity, thus lowering biomass productivity. If N stress occurs during the grain-filling stage, accelerated leaf senescence occurs, subsequently reducing the plant size and kernel weight. Bänziger et al. (2000) indicated that low N stress before flowering has more severe yield consequences than after anthesis.

2.3.3 Managed low nitrogen stress

Breeding for low N is a complex process due to low heritability, and difficulties in identifying variation between low N tolerant genotypes. CIMMYT adopted managed low N stress breeding as a way of accessing potential genes for low N tolerance in maize. Some levels of N must be in the soil in order for significant yields to be obtained. The primary goal of managed low N stress is to have yields 25-35% lower than the potential yield under optimum conditions. If an ideal genotype yields 7 t ha^{-1} under full fertilization, under low N, that genotype must yield 1.5 - 2.5 t ha^{-1} less (Bänziger et al., 1997). Under managed low N conditions, the soil is considered low N when it has 7 ppm N (Ndhlela, 2012). Research on low N tolerance at CIMMYT utilizes previously N-depleted plots. The level of depletion varies with the plot with some plots having been depleted for one year, two years, up to seven years. Depletion is achieved by growing maize during the summer season, and irrigated wheat during the winter season, continuously. Maize and wheat stover is taken out of the field, to ensure that there is no carry over mineralization of N back into the soil. At 7 ppm N (translating to 54 kg ha^{-1}) in the upper 30-60 cm soil depth, the soil still has the capacity to supply N to plants, and is considered managed low N. Plant breeders, especially at CIMMYT, prefer using a continuously depleted N block (plot) over several seasons to manage low N stress from season to season. N stress can be increased by continuously using the same low N block or plot, choosing a sandy soil texture field (where other factors are not limiting); growing non-leguminous crops during the off-season; reducing the time when land is fallow and removing or burning stover after every harvest. The higher the biomass produced, the higher the N depleted. When N stress is too high (yields falling below 20% of the yields under well fertilized soils), additions of N fertilisers (20 kg N ha^{-1}) is recommended. All other nutrients are maintained constantly in these fields.

2.3.4 Occurrence of drought and low nitrogen fertility

The occurrence of drought (together with heat) has been linked to crop failure in SSA. The persistence, intensity and unpredictability of these factors, inclusive of low N fertility, has affected income, increased the risks of poverty, increased the vulnerability to malnutrition-related diseases and caused acute food shortages to millions of people dependent on maize as a food source (Vermeulen et al., 2012). Maize production systems in ESA are largely rain-fed, and their successes are highly sensitive to climate variability. The majority of maize production in SSA is within drought prone areas (Kostandini et al., 2013). According to Fisher et al. (2015), over 40% of Africa’s maize growing regions faces drought stress, which frequently cause between 10-25% yield losses; and around 25% of the maize grown suffers frequent droughts, with 50% yield losses incurred. In Zimbabwe three-quarters of maize is grown within regions with more than 20% frequency of total crop failure, while in Kenya half of maize is grown in regions of more than 20% frequency of total crop failure. Kenya experienced chronic droughts in 1974, 1982, 1992-1993, , and 1999-2001 that affected millions of people (OCHA, 2001). More than 90% of South Africa is either arid or semi-arid, with the potential of total crop losses to drought (Vogel, 1994; Rouault and Richard, 2003). Zambia has frequently occurring droughts, once every three years, with variable maize losses across the region, with some approaching total crop failure. In Ethiopia, agricultural land is 70% dry land, with 45% arable. Fifty percent of the arable land is exposed to drought (Nedessa and Wickrema, 2010), with an estimated crop failure of over 90%. Droughts are now a common feature in SSA, with the current drought caused by the ongoing ENSO effect recorded the worst on record (Fewsnet, 2016). The ENSO effect, apart from droughts, and changes in climate variability, also caused significantly higher temperatures (heat stress) which further decimated the maize crop in Southern Africa. The effects are likely to continue, thereby reducing the maize-based maize productivity levels in the region.

2.4 Interactions between drought and low nitrogen fertility stress

Drought stress during plant development will reduce the rate of absorption of nutrients (Sanaullah et al., 2012) by reducing nutrient supply through mineralization as well as the movement of nutrients in the soil (Lambers et al., 2008). Enhanced mineralization occurs when rewetting occurs, following a drought stress period (Austin et al., 2004) due to the nutrient release from dead microbial biomass that has accumulated during the period of stress (Borken and Matzner, 2009). The absorption, utilization and mobilization of these nutrients are very critical for plant growth and development. Under drought stress conditions, the nutrient use efficiency of a plant is highly reduced. Although nutrient use efficiency, including nutrient uptake, transport, assimilation and remobilization are dependent on the genetic and environmental effects, the influence of limited water conditions greatly reduce these processes (Xu et al., 2012). The imbalance between water supply and nutrients, especially N, reduces nutrient use efficiency. Sufficient N supply has been observed to positively affect N use efficiency (Costa et al., 1997).

2.5 Genetic gains under drought and low nitrogen fertility

Genetic gain studies are useful to predict the success of selection for important characteristics (Castleberry et al., 1984; Duvick, 2005; Campos et al., 2006; Wang et al., 2011). Genetic gains milestones have been reported in many countries and regions, with substantial contributions to yield, with the list including the USA (Duvick et al., 2004); Argentina (Eyherabide and Damilano, 2001); Canada (Tollenaar, 1989) and China (Ma et al., 2015). Genetic gain studies in SSA are difficult, since the material used and the management levels differ, and numerous cultivars have been released. Badu-Apraku et al. (2014) reported genetic gains from 2.28 to 2.61 t ha^{-1} under low N and from 3.2 to 3.65 t ha^{-1} under high N, giving the same relative gain of 30 kg ha^{-1} for the three season period of research under both management levels.

According to Duvick (2005), there has been substantial genetic gains through breeding, but any significant increases above that will only be incurred through the use of improved agronomic practices, pest and disease control and fertiliser use. Breeding for drought tolerance was initiated by CIMMYT using a lowland tropical maize populations, *Tuxpeño Sequía*; *La Posta Sequía* and Pool 26 *Sequía* as sources of drought tolerance (Bolaños and Edmeades, 1993; Edmeades et al., 1999) and yield gains of 108 kg ha^{-1} yr^{-1} under drought were reported. Initial improvement for low N tolerance was also conducted by CIMMYT on Across 8328 (based on its superiority under low and high N conditions), a yellow-grained, late-maturing genotype that was adapted to the lowland tropical regions. Initial selection gains in Across 8328 according to Edmeades et al. (1994) were 84 and 120 kg ha^{-1} under low N and high N respectively. Several lines were selected from Across 8328 BN C5 based on higher frequency of low N tolerant top crosses.

Bello et al. (2014) evaluated six hybrids from 1980, through 1990 to 2000 for genetic gains under different N levels, reporting 0.67 to 4.89 t ha^{-1} gains in grain yield. Genetic gains in yield per se were 42% between 1980 and 2000; and 36% between 1990 and 2000 under optimal fertilization. This means the responsiveness of modern cultivars was higher than that of the hybrids used in the 1980s and 1990s. Kim (1997) estimated a yield advantage of between 20-40% in high yielding environments, especially for research stations with grain yield of over 14.7 t ha^{-1}. Adebo and Olaoye (2010) and Kamara et al. (2004) observed a 24% yield increase between the 1970s and 1990s and 0.41% per year between 1970 and 1999 for hybrid cultivars.

2.6 Genetic gains in maize using marker-assisted selection

Improvements made in drought tolerance were largely by conventional plant breeding. The challenge of conventional breeding was the time taken to develop a required inbred line or hybrid. The invention of molecular markers has enhanced plant science and increased food security across all food crops. The use of marker-assisted selection (MAS), marker-assisted backcrossing (MABC); marker assisted recurrent selection (MARS) and genomic selection (GS) can be used for robust development and deployment of improved germplasm. In the last decades, the use of molecular markers added much to the development of plant science. Markers that were associated with quantitative trait loci (QTL), for example for drought and grain yield, were observed using different molecular markers. MABC involves the transfer of one or a few genes or major effect QTLs that are fine mapped and then validated across genetic backgrounds. Veldboom and Lee (1996), Ribaut et al. (1997), Semagn et al. (2013) and Almeida et al. (2013) used a resistant donor parent and a drought susceptible recurrent parent to map QTLs linked to yield components and flowering. Tuberosa et al. (2007) and Araus et al. (2008) reported gains in yield and ASI, though the identified QTLs didn't have large individual effects, limiting their application in crop improvement for drought tolerance. Semagn et al. (2013) worked on improving drought tolerance using MABC, conducting meta-QTL analysis across 18 bi-parental populations of tropical origin, reducing grain and ASI QTLs from 183-68. The results indicated low effect QTLs, which also limited their application for maize improvement under drought stress conditions. The use of MARS has been helpful as it allows the use of large medium-high QTLs that can provide for easy manipulation for crop improvement (Bernardo, 2008; Xu et al., 2012).

Though conventional breeding was successful in causing genetic gains under drought stress (100 kg ha^{-1} yr^{-1}) for both temperate and tropical crops (Löffler et al., 2005; Bänziger et al., 2006), MAS has also greatly improved these genetic gains under stress environments. The use of MAS for improving genetic gains in maize has yielded substantial results. Beyene et al. (2015) worked on eight bi-parental populations under drought stress environments and observed that GS recorded higher mean grain yields than the best checks. Beyene et al. (2016) conducted a MARS trial using 10 bi-parental populations of tropical origin, for drought tolerance in maize. The overall gains for grain yield were 105 kg ha^{-1} yr^{-1} and 51 kg ha^{-1} yr^{-1} for optimum and drought stress conditions, respectively. GS (Meuwissen et al., 2001; Lorenz, 2013), has also been successfully utilized to predict the genetic value of parents for selection based on whole genomic data. The results observed by Beyene et al. (2015, 2016) using MARS, indicated a slight advantage of GS as MAS tool for drought stress in maize improvement. Tarekegne and Das (2015) and CIMMYT (2014) project genetic gains from MAS in the IMAS programme (Improved Maize for Acid Soils) to range between 16-32% for fertiliser use rate of between 30-59 and 0-29 kg ha^{-1} yr^{-1} respectively, with the use of transgenics causing even higher gains of 40% and 20% on the same respective fertiliser use rates.

Semagn et al. (2015) estimated genetic gains in selected cultivars using MAS, comparing them with pedigree selection. Overall gains in grain yield using MAS were 37.8 kg ha^{-1} yr^{-1}, which was seven-fold the 5.4 kg ha^{-1} yr^{-1} using pedigree selection. Masuka et al. (2017) also identified more genetic gains (3-7 times more) under managed drought and under well-watered conditions in SSA using MAS as compared to conventional methods. The use of gene pyramiding, by molecular techniques, forming recombinant inbred lines, can be one of the greatest improvements in crop breeding and genetics to improve food security. The hybrids will be carrying a wide range of tolerance attributes, which makes them better across multi-stress environments, like in ESA.

2.7 Inbred line and hybrid development in maize

Maize is a cross pollinating crop, which requires crossing with distant relatives to obtain hybrid vigour. The use of the doubled haploid (DH) technique has also accelerated the development of hybrids, from the conventional eight years, which is usually needed for a line to reach near homozygosity, to the two years or less needed using the DH technique. It allows rapid development of lines that are highly homozygous and represents a population because of the initial recombination occurring before the DH technique is performed (Forster and Thomas, 2005). Most characteristics that are of importance agronomically are quantitatively inherited, and thus prone to G x E interactions, which limit their usefulness, hence the DH technique eliminates that and improves the reliability and efficiency of field based selections (Bonnet et al., 2005). The DH technique involves the use of haploid cells (pollen) from each parent, which is doubled to form viable, pure breeding genotypes. The presence of a required gene is identified by a molecular marker and pollen from that specific plant will be used to develop inbred lines homozygous to the condition, thereby speeding up the breeding process. In general, DH technology increases the speed and efficiency of inbred line development, while making phenotyping and genotyping more predictive (Curran, 2008; Geiger and Gordillo, 2009; Chang and Coe, 2009). It also allows for the per se selection and integration of desirable agronomic characteristics, and offers the best platform for MAS while reducing developmental costs (Geiger and Gordillo, 2009). The genetic gains per cycle will be increased and ensure that products reach farmers in an affordable time unit.

For hybrid development, inbred lines are selected based on their intrinsic tolerance levels, and their breeding value. Usually several inbred lines are produced for a specific objective. Before these lines are recommended for hybrid development, they are screened under the stress they were developed for and crossed to a common known tester which has a good combining ability, and a wider genetic base; thus GCA and SCA of each line is estimated. Parental (inbred lines) which are good combiners, i.e. they produce relatively high yields with the testers, are selected for and advanced trials across locations are done.

Breeders utilize the concept of combining ability, which provides relevant information about the performance of a given parent as a way to boost maize productivity. Maize parents are selected based on their breeding value, which is the ability to transmit favourable genes to their progeny. It involves crossing selected parents with other lines, allowing favourable characteristics to be transmitted to their progeny (Crossa et al., 2010). It is estimated in terms of GCA (breeding value) and SCA, the additional genetic value due to the interactions of the parents. They were first reported by Sprague and Tatum (1942) in maize breeding programmes. The most commonly used designs to estimate GCA and SCA are the diallel, line x tester and the North Carolina mating designs. GCA effects (average performance of a parent in hybrid combinations) are due to additive gene action while SCA (parental combinations performing better or worse than the parental average), are due to dominance and epistatic interaction effects (Sprague and Tatum, 1942; Crossa et al., 2010; 2012). Bello and Olaoye (2009) reported that additive gene action (GCA) was the main effect determining yield and agronomic characteristics in maize. Devi and Singh (2011) indicated that non-additive gene action was more responsible for grain yield as higher SCA values were observed at the expense of GCA effects. These results indicate that both additive and non-additive gene effects are equally important in determining the yield in maize. Marilia et al. (2001) and Shukla and Pandey (2008) reported the usefulness of both GCA and SCA effects in selection of suitable parents with favourable alleles for use in hybrid programmes. For successful breeding programmes, the knowledge of gene action controlling both primary characteristics like yield, and secondary characteristics, is very important. Betrán et al. (2003) indicated the predominance of additive gene action under drought stress environments, while non-additive gene action was highly dominant under low N environments. The GCA and SCA effects also helps in the study of heterotic behaviour and relationships (gene frequency between crossed lines) between and among inbred lines, which is so important in the development of a successful maize hybrid programme (Falconer, 1981).

2.8 Testcrossing

Several inbred lines are developed with different breeding objectives. Before these inbred lines are commercially available for hybrid seed production, they are tested for their combining ability with specific testers, which can be inbred lines or single crosses. Tester options range from broad genetic base populations to elite inbred lines and most breeding programmes will have their own criteria for tester selection, based on their specific needs and goals. Testers can be single crosses (Horner et al., 1976) or inbred lines (Russell and Eberhart, 1975). However, any tester selected must meet certain requirements to be considered effective. An effective tester correctly ranks inbred lines for performance in hybrid combination, and it should maximise the variance between testcross progeny to allow for efficient discrimination of new inbred lines (Rawlings and Thompson, 1962). Allison and Curnow (1966) stated that the use of any tester followed by selection will lead to an increase in mean yield but they will do so at different rates, depending on gene action of the trait and allele frequencies in the tester.

Early generation testing has proved to be beneficial in plant breeding as it ensures efficient evaluation and production of desired inbred lines in maize. Initial testcrosses are designed to identify genotypes with good GCA and wide adaptation. For estimating the GCA of a new inbred line, Matzinger (1953) found that testers with increasing levels of genetic heterogeneity performed better. As the heterogeneity of a tester increases, the component of variance due to line x tester interaction decreases. Thus in theory, an F1 tester provides a more accurate ranking of new lines for GCA than an inbred line tester. However, he also found that using inbred line testers produced larger testcross variances, indicating they provide a more efficient discrimination between lines. Zambezi et al. (1986) found that using unrelated inbred lines as testers in maize produced rankings for GCA that were very similar to the rankings provided by using the population from which the inbred testers were derived as the tester. This provides evidence that unrelated inbred line testers and population testers are similar in their ability to correctly rank lines.

Hallauer and Lopez-Perez (1979) compared the testcross variances produced by several different types of maize testers to identify those providing the largest variances. For related testers, the variance produced by inbred line testers was highly dependent on the performance of the tester for the trait being measured. As the performance of the inbred line testers improved, the testcross variances they produced diminished. However, when an unrelated elite inbred line tester was used, large variances were produced in early generation testing. While an unrelated elite tester will be fixed for many favourable alleles, the allele frequencies are sufficiently different to allow more of the genetic effect of new lines to be observed, thereby increasing the testcross variance.

2.9 Line x tester design

Kempthorne (1957) developed the line x tester breeding method as a way to estimate combining ability of inbred lines and their hybrids. Together with the diallel analysis, the line x tester method offers reliable information regarding the breeding value of parents, which will be used to develop hybrids and hybrid combinations (Ahuja and Dhayal, 2007). The uses of these techniques are almost worldwide especially in quantitative genetic studies (Sharma et al., 2004). The line x tester method is a modified top cross method, where a broad based genotype is used as a tester to test for both GCA and SCA (Singh and Chaudhary, 2004). Though useful in cross pollinated crops, the line x tester method has also been useful for self-pollinated crops to select favourable parents and crosses, and to determine their GCA and SCA (Ceyhan et al., 2008). The design is analogous to the North Carolina design II (NCII); both are factorial experiments that measure the variance of male and female main effects and the male x female interactions (Kempthorne, 1957). Testers, both inbred lines (Russell and Eberhart, 1975) and single crosses (Horner et al., 1976) have been successfully utilized to study combining ability effcts in maize (Menz et al., 1999), and has facilitated breeding programmes, as useful sources of required germplasm are identified at earlier stages (Ali et al., 2011), thus reducing the cost of working with undesirable lines.

2.10 Genotype x environment interaction and stability

2.10.1 G x E interaction

G x E interaction causes genotypes to perform differently across environments (the ranking of genotypes change in different environments) (Bull et al., 1992). Plant breeders utilise this concept to identify stable cultivars. This can be broad adaptation (genotypes perform well across environments) and specific adaptation (genotypes perform well in specific environments). Stability analysis has greatly facilitated characterisation of the three sources of variation in trials; genotypes; environments and their interactions (Ahmad et al., 1996). Plant breeders identify and select individuals with the highest yield across diverse environments (Becker and Léon, 1988; Ceccarelli, 1989), while also checking adaptability (Ramagosa and Fox, 1993; Basford and Cooper, 1998). G x E interactions are most common for characteristics that are inherited quantitatively.

2.10.2 Statistical analysis for G x E interaction – the analysis of variance

For multi-environment trials, variance components for genotypes (G) over seasons (Y) and locations (L) are estimated, together with the G x E interaction, that is further partitioned into G x

L; G x Y and G x L x Y. The effect of L and Y and replication are also estimated. The variance components are useful in plant breeding programmes to estimate heritability and to predict gains from selection for the characteristics under investigation (Crossa, 1990). Several stability measures have been used, including Wricke's ecovalence (Wricke, 1962); Eberhart and Russell's linear regression method (1966); Shukla's procedure (Shukla, 1972) and cultivar performance (Lin and Binns, 1988). Though these stability analysis procedures are still useful, the use of additive main effects and multiplicative (AMMI) and genotype, and genotype by environment interaction (GGE) models are more common.

2.10.3 The Additive Main Effects and Multiplicative Interaction

The AMMI biplot method was developed by Gauch (1988), as a graphical representation that displays main effect means of the abscissa and scores for IPCA1 values as ordinate of both genotype entries and environments at the same time. AMMI analysis is a useful method to characterise genotypes across diverse environments (Gauch and Zobel, 1988; Crossa, 1990). It is a fixed linear model that uses singular value decomposition of the residuals of a specific linear model to decompose the G x E interaction effects into a sum of multiplicative terms (Rodrigues et al., 2016). The method utilizes both the classical analysis of variance (ANOVA) and the principal component analysis (PCA) (Gauch and Zobel, 1988). Its utility is based on the ability to analyze G x E interactions by reducing the background noise. The AMMI graphically identifies both the main effects and the G x E interaction effects (Kang, 1996). Zobel et al. (1988) and Crossa et al. (1991) indicated that the position of environments and/or genotypes further or closer to the origin measures their interaction levels, with those closer to zero having small interaction effects while those further away are highly interactive.

2.10.4 GGE biplot analysis

Among the very useful statistical methods for measuring stability is the GGE biplot analysis, an important multivariate tool that graphically displays results and therefore facilitates easy understanding and presentation. A biplot is a scatter plot of values that uses points and vectors to represent a particular structure. The use of biplots was originally proposed by Gabriel (1971) as a graphical tool to present results from PCA. The PCA is a mathematical process that decomposes a covariance matrix into eigenvalues and column eigenvectors. These biplots have been successfully utilized to study relative differences between genotypes, environments and their interactions.

GGE biplots are very useful due to their ability to graphically display results that are easy to interpret even in the presence of complex G x E interactions in multi-environments. The GGE biplot uses the first two principal axes (PC1 and PC2) to analyse the interrelationships among rows (entries) and columns (testers), which can be, amongst others, environments or characteristics, based on environment-centered PCA. Though the total variation of a phenotype/trait could be partitioned into the genotype (G), environment (E), and the G x E interaction factors, the GGE biplot models consider only G and G x E interactions as relevant to cultivar evaluation (Gauch and Zobel, 1996), removing the environment effect. This is so because the concept of crop performance and stability are centered on G and G x E interaction effects only, irrespective of how large the E effect is.

The GGE biplot uses genotype, environment, symmetric and equal-space scaling (singular value partitioning) methods. A scaling method describes the type of standardization used for the mean values before the analysis is carried out (Yan, 2002). In genotype-focused scaling, the mean scores for the genotypes are in principal coordinates, while the environment scores are standardised (DeLacy et al., 1996). In environment-focused scaling, the mean scores for the environments are in principal coordinates while the genotypic scores are standardised. The first is the polygon view which reveals the winning entry (vertex genotype) in different testers (which may be environments, characteristics or strains). The second view is the average tester coordination (also known as 'mean-versus-stability') view, which ranks entries according to their performance and stability (consistency) across testers. Entries are ranked based on their mean performance along the average-tester axis (ATC abscissa), which has an arrow pointing to a higher value all testers. The vector view of the GGE biplot (the third view) indicates the discriminating ability (the ability of a tester to differentiate among entries being tested), and is displayed by the length of the vector, which approximates the standard deviation of the tester and representativeness (the ability of the tester to represent other testers of its group) of the tester (Yan and Tinker, 2005).

The GGE biplot has gained wide application in many major areas of agronomy, plant breeding and genetic analysis such as genotype selection, G x E interaction analysis, test location evaluation, identification of mega-environments, and the identification of suitable inbred lines better suited for hybrid development programs, and the evaluation of potential cultivars for release for commercial production.

The GGE biplot was originally designed to analyse complex G x E interactions. It complements the results of the ANOVA in that, after the ANOVA had shown significant mean squares for G x E interactions, GGE biplot graphically analyses the nature of the interactions. The investigation into G X E interactions become more interesting with the introduction of the concept of crossover interaction and the GGE biplot has increasingly been used in G x E interactions data analysis in agriculture (Yan et al., 2000; Crossa et al., 2002; Badu-Apraku et al., 2010). For this type of analysis, Gauch (1992) reported that the GGE biplot is superior to other multivariate statistical tools, especially the AMMI in that the GGE biplot has many visual interpretations and it particularly allows visualization of crossover G x E interactions . The polygon view (which-won-where) of the GGE biplot displays graphically the interactions among and between genotypes and environments, and showing which genotypes performs better in a particular environment. The GGE biplot vector vies will analyze the interrelationships between two or more environments in relation to the average (target) environment. This will help to identify mega-environments, evaluate the discriminating ability and representativeness of the environment with a view to identifying redundant locations that can be culled without sacrificing important information about the genotypes. According to Yan et al. (2000), the average tester coordination ('mean-vs-stability') view of the biplot displays the performance as well as the stability of the genotypes across the test locations. The GGE biplot has been useful also in assessment of repeatability of test environments using model 2 of the GGE biplot (Scale = 2). As a multivariate tool for trait analysis, the genotype-by-trait analysis component of GGE biplot integrates some features of AMMI, joint regression, and genetic correlation in its analysis of data, which makes it superior to other multivariate methods.

The phenotypic expression of a plant trait is a product of the genotypic constitution as it is modulated by environmental factors prevalent during the growing season. Breeders are more interested in estimating genetic parameters because they increase the efficiency of prediction of gains from selection to improve crop cultivars. GGE biplots have been extensively applied in the analysis of combining ability and identification of heterotic patterns using diallel data, and which can also be utilized under the line x tester design. The biplot can also be used to estimate the combining ability of inbred parents and classify them into distinct heterotic groups. The GCA of the inbred parents and SCA of the F1 hybrids are visually displayed by the projections of the entries and testers. The identification of the best testers and classification into heterotic groups obtainable from GGE biplot analysis of diallel data give it an added advantage over the conventional Griffing methods (Griffing, 1956). The major drawbacks of GGE biplots occurs when the environments (especially stress environments) and the trait genetics under investigation are complex, that often leads to smaller proportions of PC 1 and PC2 being accounted for (Badu-Apraku et al., 2011) especially when the inbred lines were specifically developed for a different stress.

2.11 Conclusions

Maize is a principal crop in SSA due to its value mostly as a food crop. Droughts, heat and low fertility challenges, especially low N has limited the potential of maize-based cropping systems, leading to food insecurity in the region. The use of tolerant hybrids to offset yield losses to these challenges is a viable way of improving food productivity in the region. Literature has provided evidence of the utility of different plant breeding applications on solving both drought and low N stress challenges using the available diverse resources from the maize gene banks. Breeding for enhanced tolerance can be beneficial to the smallholder farmers who cannot afford the high input costs of irrigation equipment (to supplement when there are droughts), fertiliser and chemical, and labour costs.

2.12 References

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CHAPTER 3

Combining ability and heritability estimates in early maturity maize inbred lines and their hybrids under optimal, random drought and low N stress conditions in southern Africa

Abstract

Drought and low N are the major stresses affecting smallholder communities in southern Africa. Drought and low N tolerant hybrids can off-set yield loss from these stresses and will be useful to farmers. Detailed knowledge on combining ability of inbred lines and heritability of major characteristics is important for breeding programmes in stress-prone environments. The aim of this study was to identify the combining ability and heritability estimates in early maturing genotypes across the selected test environments. A total of 120 hybrids were generated using a line by tester mating design, comprising 10 lines and 12 testers. The trials were evaluated in an alpha lattice design, with two replications across 12 stress and non-stress test environments in Zambia, Zimbabwe and South Africa during the 2014/15 crop season. The yield losses of 29-52% confirmed the serious consequences that drought and low N stresses have on maize yields. High narrow and broad sense heritability estimates for grain yield and agronomic characteristics observed under stress environments indicated that genetic gains under these test environments could be improved. GCA of lines and testers and SCA effects for hybrids were significant ($P < 0.05$) across all locations, which indicates the importance of both additive and non-additive gene action in the genotypes evaluated. Lines 1, 3, 4, 6, 10 and 11 had significant positive GCA, indicating their potential as good combiners for grain yield. Lines 3, 4, 5, 6 and 7 contributed to earliness. Lines 1, 5, 6, 7, 8 and 9 were good combiners, as they contributed to better anthesis-silking synchronization. The results, which indicated the usefulness and efficiency of the tested germplasm against drought and low N stress constraints, from this material can be utilised for the benefit of smallholder famers in the stress-prone environments of southern Africa.

3.1 Introduction

Maize occupies a prime share in terms of total production per unit area, and as an integral part of the human diet in southern Africa. The occurrence of drought and declining soil fertility have been implicated as the greatest yield-limiting factors in maize, which is a food security crop in this region. Maize is sensitive to drought and low soil fertility stress, especially low N. The dominance and preference of maize in Africa has been a result of its suitability of production in diverse environments, and probably its diversity. The crop can be grown in the temperate, as well as tropical and sub-tropical regions, thus it has been adopted as a staple in many communities. In the tropics, especially in SSA, however, most maize is grown under stressed environments (Bänziger et al., 1997; Diallo et al., 2004). Drought and low soil fertility, among other stresses, can reduce yields by 80-100% when the stresses are severe at certain crop developmental stages (Betrán et al., 1997; Bänziger et al., 1997; 2006; Weber et al., 2012). Yields can be greatly improved by the adequate supply of fertilisers and supplementary irrigation where rainfall is limiting. However, these agricultural needs are far beyond the reach of millions of smallholder farmers who depend on maize as their staple diet in major maize production regions. This emphasizes the need of efficient breeding strategies to meet the challenges of stress-prone environments. Plant breeders have developed ways to improve maize yields in the presence of these challenges, mainly through the use of stress tolerant genotypes. The objectives of all plant breeding programmes are to improve yield, mostly by the use of secondary characteristics that are highly heritable. Heritability determines genetic advance and response to selection under stress environments, emphasizing the need of secondary characteristics for developing stress tolerant varieties, especially under drought or low N stress (Bolaños and Edmeades, 1996; Bänziger and Lafitte, 1997; Bänziger et al., 2000; Mhike et al., 2012).

World food security is dependent on continuous crop improvement with increased tolerance to abiotic stresses, especially drought and salinity (Denby and Gehring, 2005). Research has indicated that the genetic and phenotypic response of genotypes under different environments is largely due to the occurrence of G x E interactions. Breeders prefer stable genotypes which interact less with the environments. Yield stability can be increased by improving tolerance levels for the important stresses with the use of genetics. Improved genetics for tolerance to several abiotic and biotic stresses can be packaged in a seed, which is one of the best options to improve plant productivity (Bänziger et al., 2000).

Availability of rich genetic diversity for drought tolerance in maize enables plant breeders to develop drought tolerant maize inbred lines. Knowledge on the diversity patterns of genetic resources is very important in maize breeding. It helps to maintain diversity among breeding lines and to maximise heterosis in hybrid combinations (Warburton et al., 2002). Screening of parents before their use in breeding programmes, and combining ability analysis based on progeny test data are useful methods for evaluating parents and their progeny for a wide range of quantitative characters. Early generation testing is a pivotal method for plant breeders to discard undesirable material and generate desirable inbred lines for the production of hybrids (Ali et al., 2011). Due to early testing, the best performing inbred lines are identified at early stages, and the resulting progeny can be used for further improvement of different characteristics.

Exploitation of hybrid vigour and selection of parents based on combining ability has been used as an important breeding approach in crop improvement. Breeder’s objectives are to select hybrids on the basis of expected levels of heterosis as well as SCA. Heterosis and good combining ability are prerequisites for developing a good hybrid maize variety. Combining ability is an important analysis tool for the selection of desirable parents and for the generation of information regarding the nature of, and magnitude of gene effects controlling quantitative characteristics (Basbag et al., 2007).

Heritability is a quantitative measure which provides information about the correspondence between genotypic and phenotypic variance. According to Dabholkar (1999), it is used to describe the ratio, expressed as a percentage of variance due to hereditary differences (σ^2g) to the total phenotypic variance (σ^2p). This ratio, which is now known as broad sense heritability, is useful if the interest is in relative importance of genotype and environment in the determination of phenotypic values. A major restriction is that it fails to indicate the progress which might be made through selection within a particular population. To counter this, narrow sense heritability was proposed, which is the ratio of the additive genetic variance (σ^2a) to the phenotypic variance (σ^2p) (Dabholkar, 1999). Narrow sense heritability measures the extent of correspondence between breeding values and phenotypic values. The objective of this study was to identify lines with good GCA and SCA attributes across stress and optimum environments using the line x tester method and to estimate heritability of yield and yield components under these conditions.

3.2 Materials and methods

3.2.1 Plant materials

One hundred and twenty three-way hybrids generated from a 12 x 10 line x tester design, together with six local commercial checks were used for this study (Table 3.1). The inbred lines used in this study have been selected for several pedigree generations for their tolerance to both drought and low N stress. The testcross hybrids were tested, together with local commercial checks, in 12 environments. The genotypes which had adequate seed were included for analysis and they amounted to 109 testcross hybrids. Trials were done for only one season, as this project was done at and with CIMMYT, and they do not repeat trials for a second season. Due to the high number of trials in the season used, this was seen as sufficient to make good conclusions from.

Table 3.1 Early maturity maize inbred lines and testers used for crosses, with the local checks

Line/Tester code	Pedigree	Description
1	CML444/CML546	Tester
2	CML543/CKDHL0089	Tester
3	CML543/VL05420	Tester
4	CML536/CML312	Tester
5	CKDHL0228/CZL99017	Tester
6	CML312/CML444	Tester
7	00SADVEB-#-74-1-1-1-1-1-B/CML546	Tester
8	CKL05001/CZL99017	Tester
9	CML444/CML442	Tester
10	VL05420/CML395	Tester
1	CZL0814	Line
2	00SADVEA-#-28-1-2-1-1-1-2-3-B-B-B-B	Line
3	VL05420	Line
4	00SADVEB-#-17-2-1-1-1-B-B-B-B	Line
5	(CML539*/OFP9)-2-3-5-2-1-B	Line
6	(CML539*/OFP9)-4-1-2-1-1-B	Line
7	(CML539*/OFP27)-2-1-2-1-1-B	Line
8	(CML539*/OFP14)-2-1-1-2-2-B	Line
9	(CML539*/OFP14)-2-2-1-1-1-B	Line
10	(CML537*/OFP106)-5-1-3-1-1-B	Line
11	(CML537*/OFP106)-5-2-5-2-1-B	Line
12	(CML537*/OFP106)-7-3-3-1-1-B	Line
	SC403	Local commercial check
	SC513	Local commercial check
	SC627	Local commercial check
	PAN53	Local commercial check
	PAN 4M-21	Local commercial check
	P2859W	Local commercial check

3.2.2 Testing environments

Twelve test environments, including four low N sites (Gwebi, CIMMYT Harare A and B in Zimbabwe, and Potchefstroom in South Africa); seven optimum sites (Gwebi, ART and Ivordale in Zimbabwe; Mpongwe and Lusaka in Zambia and Cedara 1 and 2 in South Africa) and random drought stress at Potchefstroom, South Africa, were used (Table 3.2). The testing environments represented the major climatic and soil characteristics of southern Africa based on descriptions by Bänziger et al. (2000). Genotypes were screened under random drought, low N stress and optimal conditions (managed by irrigation, especially during the rain free periods), according to Vasal et al. (1997) and Chapman and Edmeades (1999). Droughts occur frequently and randomly in southern Africa throughout the growing season, though mid-season droughts occur more. All random drought stress test environments received >200mm of rainfall and thus drought was moderate (Chapman and Barreto, 1996; Bänziger et al., 2000). Research on the advanced germplasm suited for the tropical and sub-tropical environments is aimed at selection and production of genotypes performing well under both stress and non-stress conditions (Edmeades and Bänziger, 1997; Vasal et al., 1997).

Table 3.2 Test environments used in the study

				Coordinates		Altitude
Country	Location	Management	Location code	South	East	masl
Zimbabwe	Gwebi	Low N	1	17o40'60''	30º52'	1438
Zimbabwe	Harare A	Low N	2	17o46'	31o02'	1406
Zimbabwe	Harare B	Low N	3	17o46'	31o02'	1407
South Africa	Potchefstroom	Low N	4	26o42'17''	31o02'46''	1400
Zimbabwe	Gwebi	Optimum	5	17o40'60''	30o52'	1438
Zimbabwe	Art Farm	Optimum	6	17o26'	31o3'48.4''	1480
Zimbabwe	Ivordale	Optimum	7	17o40'60''	31o25'	1273
Zambia	Mpongwe	Optimum	8	13o33'	32o31'	1035
Zambia	Lusaka	Optimum	9	15o19'60''	28o0'	1153
South Africa	Cedara1	Optimum	10	29o32'15''	30o16'09''	1037
South Africa	Cedara2	Optimum	11	29o32'15''	30o16'09''	1037
South Africa	Potchefstroom	Random drought	12	26o42'17''	31o02'46''	1400

Masl metres above sea level

3.2.3 Experimental design and trial management

The experiments were arranged in an alpha-lattice design (Patterson and Williams, 1976) with two replications. The evaluation of the maize genotypes' responsiveness to drought and low N stress, including random stress and optimal conditions were performed and similarity in response to the two stress conditions determined. The low N sites had been depleted of N through growing summer maize and irrigated winter wheat continuously for six years. According to the soil analysis, the soil had the capacity to supply some N, since it contained both 7 ppm in the top 30 cm of the soil and soil depth 30-60 cm. In terms of kg ha^{-1} this translates to 54 kg ha^{-1}. The 7 ppm was therefore considered as low N. Optimum trials were supplied with the recommended fertilisers and irrigated when needed. Random drought experiments were not irrigated at all. Each plot comprised of two row plots of 4 m, 0.75 m between rows, and 0.25 m within the row, at a planting density of 53 333 plants per hectare. Basal fertilisers were applied at planting in the form of compound (NPK) 2:3:4 at 250 kg ha^{-1} of N; 83 kg ha^{-1} of P and 111 kg ha^{-1} of K. Two hundred kilograms of N (top dressing fertilization) was applied at four weeks after emergence. The herbicides, gramoxone, dual, basagran and 2,4-D were applied to control weeds. Later, weeds were controlled using hand weeding to keep the fields relatively weed-free throughout the season. Carbaryl was applied in maize leaf whorls for stalk borer control. Karate, an insecticide, was applied to control cutworms at planting and seedling emergence.

3.2.4 Data collection

Data collected on plot basis were recorded for 24 agro-morphological characteristics described by IBPGR-CIMMYT (1991). Agronomic data included days to 50% anthesis, recorded as the time taken for 50% of the plants in a plot to shed pollen (Tollenaar et al., 2004; Lee et al., 2005). Days to 50% silking was recorded as the time taken for silk emergence of 50% of the plants in a plot (Tollenaar et al., 2004). ASI was calculated as the difference between days to 50% silking and days to 50% anthesis. Two weeks after pollen shed, plant height and ear height were measured as the distance from ground level to the first tassel branch or to the node bearing the main ear, respectively (Guzman and Lamkey, 2000). Harvested plants and ears were counted at harvest in all plots at all sites. Number of ears per plant was obtained by dividing the number of ears per gross plot by the total number of plants harvested per gross plot. An ear was counted if it had at least one fully developed grain. The moisture content of grain from each plot was measured using the Seedburo GMA 128 (Seedburo, Equipment Co., Chicago, USA). Grain weight from all the ears of each experimental unit was measured and used to calculate grain yield (expressed in ton ha^{-1} and adjusted to 12.5% moisture content). Husk cover was measured as the percentage of plants with ears that were not completely covered by the husks; ear rot was measured as the percentage of ears that were rotten; GLS was measured as the score for the severity of GLS symptoms rated on a scale from 1 (clean, no infection) to 5 (severely diseased); *P. sorghi (PS)* scores for the severity of common rust symptoms rated on a scale from 1 (clean, no infection) to 5 (severely diseased). *Exserohilum turcicum* was measured as the score for the severity of northern leaf blight symptoms rated on a scale from 1 (clean, no infection) to 5 (severely diseased). Ear aspect (EA), ear position (EPO), leaf senescence (SEN), root lodging (RL) and stem lodging (SL) were also measured (IBPGR-CIMMYT, 1991).

3.2.5 Statistical analysis

Before data was subjected to ANOVA, ASI was normalized using $\ln\sqrt{(ASI+10)}$, as suggested by Bolaños and Edmeades (1996). ANOVA for grain yield and agronomic characteristics for each environment and combined ANOVA were computed in Fieldbook using the restricted maximum likelihood (REML) method in the mixed model and using the built-in R-analysis in Fieldbook (Lugo-Espinosa et al., 2013). Genetic analysis was done using the Analysis of Genetic Designs with R for Windows (AGD-R) software (Rodríguez et al., 2015). The data was also analyzed using a mixed model for computing the least square means for each genotype at individual environments and across environments using Multi Environment Trial Analysis with R for Windows (META-R, Alvarado et al., 2015). Genetic and phenotypic correlations were also estimated using META-R. The Fisher's LSD was used to compare the mean grain yield and agronomic characteristics of the genotypes. Variance components and their standard errors for random effects were calculated using the REML model. The REML is used mostly to cope with unbalanced experimental designs, and has been utilized to eliminate bias in the estimation of variance components that arises when fixed effects are subject to error. The estimators maximise only the portion of the likelihood that does not depend on fixed effects. Genotypes were considered fixed effects whilst replications and incomplete blocks were considered random effects. The SAS programme for the line x tester analysis was used to compute the GCA and SCA effects following the procedure of Singh and Chaudhary (1977). The following line x tester model was used:

$Y_{ijk} = \mu + g_i + g_j + s_{ij} + r_k + e_{ijk}$

Where: Y_{ijk} = mean value of a character measured on cross i x j in k^{th} replication; μ = population mean effect; g_i = GCA effect of ith parent; g_j = GCA effect of the parent j; s_{ij} = SCA effect of cross i x j; r_k = replication effect; e_{ijk} = environmental effect peculiar to $(ijk)^{th}$ individual

Broad sense heritability (H^2) was calculated as the ratio of genotypic variance to phenotypic variance. Narrow sense heritability (h^2) of all the characteristics was calculated using the narrow sense formula according to Hallauer and Miranda (1988) and is given by the model; $h^2 = 2\sigma^2GCA/(2\sigma^2GCA + \sigma^2SCA + \sigma^2_e)$

Where: h^2 = narrow sense heritability
σ^2GCA= mean squares of general combining ability
σ^2SCA = mean squares of specific combining ability

The significance of SCA and GCA sources of variation was computed using the lattice effective error variance in single environments, and the corresponding interaction of GCA or SCA with environments in multi-environment analyses. The significance of SCA x environment and GCA x environment interactions was determined using the pooled lattice effective error. SCA and GCA variance components were determined assuming a fixed model for the line x tester analysis. The relative importance of additive and non-additive effects was estimated as the ratio between the variances of GCA and SCA. For combined environments, the estimates are similar, but have G x E components in the denominator. Means and magnitudes of genetic variances estimated in stressed environments were compared with those from non-stressed environments. Genotypic coefficient of variation (GCV) and phenotypic coefficient of variation (PCV) expressed as a percentage, were calculated as follows; GCV (%) was given as the square root of genotypic variance, divided by the grand mean multiplied by 100%; PCV (%) was calculated as the square root of phenotypic variance, divided by the grand mean multiplied by 100%.

3.3. Results

3.3.1 Analysis of variance

There were highly significant variations for GCA of lines ($P < 0.001$) and testers ($P < 0.01$) observed for grain yield under random drought stress (Table 3.3). Both line and tester GCA effects for grain yield were highly significant ($P < 0.001$) across low N and optimum environments and across all test environments. There were highly significant differences ($P < 0.001$) among the hybrids evaluated across low N, optimum and across all test environments. SCA effects for grain yield were highly significant ($P < 0.001$) across low N, optimum and across all test environments. It was however not significant under random drought stress site.

GCA of lines were significant at Gwebi low N and Harare A ($P < 0.05$); and highly significant at Gwebi, ART, Ivordale, Mpongwe, Lusaka, Cedara 1 and Cedara 2 (all optimum test environments) and at Potchefstroom (random drought stress) (Table 3.4). Tester GCA effects for grain yield were significant at Gwebi and highly significant at Potchefstroom (low N stress test environments); and highly significant at all optimum test environments except at Ivordale. SCA effects for grain yield at individual sites were significant ($P < 0.05$) at Gwebi, ART and

Lusaka (optimum test environments); and highly significant (P < 0.01) at Harare A (low N stress) and at Cedara 2 (optimum test environment). The calculated GCA/SCA ratios for individual test environments were all above 1 except at Ivordale optimum environment with a value of 0.74. Across management levels and in combined analysis, GCA/SCA ratios were also above 1 indicating the predominance of additive gene action.

3.3.2 Genotype by environment interactions

There were highly significant (P < 0.001) hybrid x environment interactions across low N, optimum and across combined test environments (Table 3.3). Both GCA line x E and GCA tester x E effects were highly significant (P < 0.001) across low N, optimum and across combined test environments. SCA x E was significant across combined and for low N test environments and was not significant across optimum environments.

Table 3.3 Mean squares for early line by tester crosses under low N, optimum, combined and random drought environments during the 2014/15 growing season

	Low N		Optimum		Combined		Random drought	
Source	df	MS	df	MS	df	MS	df	MS
Rep(site)	4	11.29***	7	4.88***	13	8.84***	1	-
Environment	3	474.51***	6	430.10***	12	1135.54***	-	-
Hybrid	108	2.08***	108	5.89***	108	6.45***	108	-
GCA line	11	3.02***	11	10.42***	11	10.44***	11	6.00***
GCA tester	9	2.65***	9	22.29***	9	23.47***	9	5.31**
SCA	87	1.90***	87	3.64***	87	4.26***	87	1.90
Hybrid x E	324	1.37***	648	1.74***	1296	1.77***	-	-
GCA line x E	33	1.82***	66	3.30***	132	3.35***	-	-
GCA tester x E	27	1.49***	54	2.19**	108	2.47***	-	-
SCA x E	261	1.31***	522	1.50	1044	1.50**	-	-
Residuals	435	1.18	763	1.33	1416	1.38	109	1.94
GCA/SCA		1.59		2.86		2.451		3.16

***P < 0.001; **P < 0.01, *P < 0.05, df degrees of freedom, GCA general combining ability; SCA specific combining ability; E environment; MS mean squares

Table 3.4 Mean squares for grain yield (t ha^{-1}) of early line by tester crosses at 12 individual environments

SOV	df	1	2	3	4	5	6
Rep	1	0.13	10.49***	24.01***	10.47*	3.08	1.9
Hybrid	108	0.70**	1.09***	1.86	2.54	1.98***	2.24***
GCA Line	11	1.08*	1.12*	2.52	3.76	3.72***	5.50***
GCA Tester	9	1.15*	1.09	0.89	4.02	5.22***	5.37***
SCA	87	0.58	1.08**	1.9	2.26	1.44*	1.52*
Residual	109	0.47	0.6	1.57	2.1	0.98	1.04
GCA/SCA ratio		1.87	1.04	1.33	1.67	2.58	3.62
SOV	**Df**	**7**	**8**	**9**	**10**	**11**	**12**
Rep	1	11.23	0.2	3.78	13.58***	0.42	17.67**
Hybrid	108	4.13	2.65***	2.33***	1.51***	1.48***	2.58
GCA Line	11	3.05	6.32***	4.12***	3.77***	3.75***	6.00**
GCA Tester	9	6.1	7.55***	4.51***	2.67***	4.00***	5.31**
SCA	87	4.11	1.69	1.90*	1.11*	0.91**	1.9
Residual	109	3.36	1.36	1.26	0.78	0.54	1.94
GCA/SCA ratio		0.74	3.75	2.17	2.41	4.14	3.16

***P < 0.001; **P < 0.01, *P < 0.05; GCA general combining ability; SCA specific combining ability; SOV source of variation, df degrees of freedom; 1 Gwebi Low N; 2 Harare A Low N; 3 Harare B Low N; 4 Potchefstroom Low N; 5 Gwebi Opt; 6 Art Opt; 7 Ivordale Opt; 8 Mpongwe Opt; 9 Lusaka; Opt; 10 Cedara 1 Optimum; 11 Cedara 2 Optimum; 12 Potchefstroom random drought

3.3.3 Analysis of variance for yield and agronomic characteristics across all environments

Hybrid effects were highly significant ($P < 0.001$) for yield for all environments except for Harare B and Potchefstroom (low N) and Ivordale (optimum) (Table 3.4). GCA line effects were significant for the same environments. GCA tester effects were significant for the same environments as mentioned above, with the exception of Harare A low N. SCA effects were significant for Harare A low N; and Gwebi, ART, Mpongwe, Lusaka, Cedara 1 and 2 optimal,

Hybrid effects were highly significant ($P < 0.001$) for days to 50% anthesis, ASI, plant and ear height, ear position and for number of ears per plant (Table 3.5). Environment effect was also highly significant ($P < 0.001$) for all the characteristics. GCA effects for lines and testers were all highly significant ($P < 0.001$) for all the characteristics. SCA was significant ($P < 0.05$) for all the characteristics. Hybrid x environment interaction was only significant for days to 50% anthesis ($P < 0.05$) and number of ears per plant ($P < 0.001$). GCA line x environment interaction was highly significant ($P < 0.001$) for all the characteristics. GCA tester x environment interaction was significant for all the characteristics except ASI and plant height. The calculated ratios of

GCA/SCA for the agronomic characteristics were higher than 1 indicating the predominance of additive gene action, and thus selection can be done effective inearly generations (Lal et al., 2006).

Table 3.5 Mean squares for agronomic characteristics of early line by tester crosses across all test environments during the 2014/15 growing season

SOV	df	AD	ASI	PH	EH	EPO	EPP
Rep(Site)	13	27.56***	0.04	2954.53***	1019.72***	0.02***	0.13***
Environment	12	11670.12***	1.34***	296165.75***	127327.68***	2.00***	3.23***
Hybrids	108	101.26***	0.07***	1896.30***	1321.02***	0.01***	0.12***
GCA line	11	436.90***	0.21***	8735.64***	3204.97***	0.02***	0.56***
GCA tester	9	504.73***	0.17***	7385.25***	9589.49***	0.07***	0.24***
SCA	87	17.97***	0.04**	479.03***	241.86*	0.00***	0.05***
Hybrid x E	1296	6.48*	0.03	302.72	198.59	0.00	0.023**
GCA Line x E	132	13.81***	0.05***	427.60**	321.86***	0.00***	0.04***
GCA tester x E	108	9.14***	0.03	254.16	250.11*	0.00**	0.04***
SCA x E	1044	5.31	0.03	290.01	178.10	0.00	0.02
Residuals	1416	5.77	0.03	301.96	187.29	0.00	0.02
GCA/SCA ratio		24.32	4.93	18.24	13.25	5.33	11.85

***P < 0.001; **P < 0.01, *P < 0.05; GCA general combining ability; SCA specific combining ability; E environment; AD days to 50% anthesis; ASI anthesis silking interval; PH plant height (cm); EH ear height (cm); EPO ear position; EPP number of ears per plant

3.3.4 The line GCA effect on grain yield and agronomic characteristics for separate and across management levels

Lines 1, 3, 5, 6 and 12 had positive GCA effects for yield under random drought; lines 2, 3, 4, 10 and 11 had positive GCA effects across low N test environments (Table 3.6). GCA effects for yield were also positive for lines 1, 3, 4, 6, 10 and 11 across optimum test environments and lines 1, 3, 4, 6, 10 and 11 were positive across all test environments. Line 3 showed positive GCA across all the management levels. Lines 5 and 6 were positive and had significant GCA effects while line 7 was negative but had significant GCA effects for grain yield under random drought stress. Line 6 recorded significant GCA effects across combined test environments. Lines 7, 8 and 9 had negative GCA across all the test environments, indicating that they are poor combiners for grain yield across stress and non-stress test environments. Lines with negative GCA effects indicate that they took fewer days to reach 50% anthesis, and thus were desirable. Lines 3, 4, 5, 6 and 7 had negative GCA effects for days to 50% anthesis across all test environments, indicating their usefulness as early maturity hybrids. Lines 8 and 9 were also desirable under random drought stress. Line 7 had negative and significant GCA effects (P <

0.05) for days to 50% anthesis across optimum environments and highly significant GCA effects ($P < 0.001$) under random drought and low N stress. Lines 1, 2 and 11 were positive and significant for days to 50% anthesis under random drought stress and across low N stress environments. Lines 6, 8 and 9 had positive GCA effects for ASI across all test environments (Table 3.6). Line 6 showed positive and significant GCA effects for ASI across all test environments. Plants with negative GCA effects for plant height showed reduced plant height, and were therefore desirable. Reduced plant height is required for short season varieties, which will help escape periodic droughts that are common in southern Africa. Lines 2, 7, 8 and 9 had negative GCA effects for plant height across all management levels, and across test environments. Lines 1 and 10 had negative GCA effects for plant height under random drought stress. The following lines showed significant GCA effects for plant height: lines 2 and 12 (random drought stress and low N stress); 7 ($P < 0.001$), 8 ($P < 0.01$), 10, 11 and 12 ($P < 0.05$) across low N stress environments and line 7 ($P < 0.05$) under optimum environments. Line 7 showed negative and significant GCA effects for ear height ($P < 0.05$). Lines 2 and 8 had negative GCA effects for ear height across all management levels. Line 9 had positive and significant ($P < 0.05$) effects for ear position across low N stress, optimum and across all test environments. Lines 3, 5, 6, 10, 11 and 12 had positive GCA effects for number of ears per plant.

Table 3.6 General combining ability effects of lines for grain yield and agronomic characteristics across test environments

	Grain yield (t ha^{-1})				Days to anthesis			
Line	Random	low N	Opt	Combined	Random	low N	Opt	Combined
1	0.25	-0.16	0.19	0.03	1.40	1.07*	0.23	0.75
2	-0.04	0.07	-0.18	-0.09	2.40*	0.99	1.01	1.35
3	0.24	0.01	0.42	0.28	-1.92*	-0.74	-1.14	-1.32
4	-0.39	0.09	0.01	0.01	-1.13	-1.23*	-0.68	-1.00
5	0.77*	-0.05	-0.16	-0.04	-2.02*	-0.39	-0.32	-0.64
6	0.71*	0.00	0.50	0.47**	-0.83	-0.89	-0.26	-0.48
7	-0.58*	-0.05	-0.33	-0.33	-4.54***	-2.54***	-2.22*	-2.84
8	-0.46	-0.03	-0.22	-0.16	-0.14	0.60	0.49	0.30
9	-0.01	-0.03	-0.37	-0.19	-0.74	0.63	0.22	0.05
10	-0.53	0.12	0.25	0.09	1.31	-0.1	0.11	0.32
11	-0.15	0.10	0.21	0.16	2.67**	0.74	0.86	1.15
12	0.17	-0.06	-0.12	-0.07	3.53***	1.90***	1.56	2.16

	Anthesis silking interval				Plant height (cm)			
Line	Random	low N	Opt	Combined	Random	low N	Opt	Combined
1	0.07	0.02	-0.02	0.01	-0.44	2.79	5.21	3.16
2	-0.04	-0.01	-0.03	-0.03	-9.82*	-8.58***	-6.51	-9.00
3	-0.08	-0.01	0.01	-0.02	3.98	2.72	0.24	2.45
4	-0.04	-0.01	0.00	-0.02	0.88	2.10	4.93	3.04
5	-0.04	0.00	0.02	0.00	2.34	0.06	1.52	0.55
6	0.05	0.04	0.04	0.06*	2.26	3.74	3.58	4.37
7	0.02	-0.01	0.02	0.01	-5.61	-9.56***	-	-10.67
8	0.02	0.01	0.00	0.01	-5.48	-5.89**	-4.02	-5.23
9	0.08	0.03	0.03	0.05	-0.21	-4.02	-6.65	-3.91
10	0.07	-0.02	-0.04	-0.02	-1.44	5.20*	4.40	2.76
11	-0.06	-0.01	-0.03	-0.04	2.69	5.58*	5.72	6.63
12	-0.04	-0.02	0.01	-0.01	10.84*	5.81*	6.30	8.16

	Ear height (cm)				Ear position			
Line	Random	low N	Opt	Combined	Random	low N	Opt	Combined
1	2.21	4.19*	5.26	3.42	0.01	0.00	0.01	0.01
2	-2.65	-4.30*	-5.59	-5.95	0.01	-0.01	-0.01	0.00
3	2.21	1.93	3.38	3.98	0.00	0.01	0.01	0.01
4	0.40	1.99	1.33	0.57	0.00	0.00	-0.01	-0.01
5	0.78	0.94	0.99	0.44	0.00	0.00	0.00	0.00
6	1.19	-0.27	0.96	1.68	0.00	0.00	0.00	0.00
7	-2.89	-	-9.13*	-6.62*	0.00	0.00	-0.01	0.00
8	-3.51	-1.27	-2.42	-3.31	0.00	0.00	0.00	0.00
9	0.10	0.78	0.92	1.76	0.00	0.02**	0.02*	0.02*
10	-2.19	0.09	-0.25	-1.13	-0.01	-0.01	-0.01	-0.01
11	0.28	0.71	2.00	2.50	0.00	0.00	0.00	-0.01
12	4.08	2.25	3.82	4.02	-0.01	-0.01	0.00	-0.01

				Number of ears per plant					
Line	Random	low N	Opt	Combined	Line	Random	low N	Opt	Combined
1	-0.04	-0.05**	-0.06	-0.06	**7**	-0.12	-0.04*	-0.05	-0.07
2	0.018*	0.00	-0.04	-0.02	**8**	-0.03	0.00	-0.02	-0.01
3	0.02	0.00	0.03	0.02	**9**	-0.03	0.00	-0.04	-0.03
4	-0.04	0.00	-0.05	-0.03	**10**	0.00	0.02	0.02	0.02
5	0.12	0.02	0.11*	0.10	**11**	0.03	0.03	0.04	0.04
6	0.02	0.00	0.04	0.03	**12**	0.05	0.01	0.03	0.03

***P < 0.001, **P < 0.1, *P < 0.05; Opt optimum; random random drought stress

3.3.5 The tester GCA effects on grain yield and agronomic characteristics

Grain yield is the most important component for breeders and farmers and hence testers with good GCA indicate their potential and usefulness for making valuable hybrids. Testers 1, 2, 3, 7 and 10 showed positive GCA effects for grain yield across all test environments (Table 3.7). Together with tester 9 across optimum environments and tester 8 across low N environments; these lines showed potential to produce better hybrids across the test environments. Testers 4 and 6 were poor combiners for grain yield across all the management levels. The GCA effects of testers for grain yield were not significant across the test environments.

Testers 5, 6, 8 and 9 had negative GCA effects for days to 50% anthesis across all the test environments and across combined test environments (Table 3.7). Tester 7 exhibited positive GCA effects across low N conditions. Tester 8 had negative GCA effects for days to 50% anthesis that were significant ($P < 0.001$) across random drought stress and low N stress environments, indicating their earliness across these environments. Tester 5 had positive GCA effects for ASI across all test environments. The same tester had significant GCA effects across both optimum ($P < 0.05$) and combined environments ($P < 0.01$). Testers 5, 8 and 9 had negative GCA effects for plant height across all test environments, including combined, which indicates their height reducing effects on hybrid combinations. Testers 5, 8 and 9 had significant ($P < 0.001$) GCA effects across low N stress environments. Testers 4, 5, 6, 8 and 9 had negative and significant GCA effects for ear height across low N stress environments. Tester 7 (positive); 5 and 8 (negative) had significant ($P < 0.05$) GCA effects for ear position across low N environments. Fifty percent of the testers had positive GCA effects for ear position across all test environments. Testers 1, 2, 3 and 9 had positive GCA effects for ear position across all test environments.

Table 3.7 General combining ability of testers for grain yield and agronomic characteristics across test environments

	Grain yield (t ha^{-1})				Days to 50% anthesis				Anthesis silking interval			
Tester	Random	low N	Optimum	Combined	Random	low N	Optimum	Combined	Random	low N	Optimum	Combined
1	0.20	0.09	0.25	0.23	0.42	0.35	0.14	0.30	-0.02	-0.02	-0.03	-0.04
2	-0.06	0.10	0.44	0.27	2.38**	1.81***	1.46	1.86	-0.01	0.00	0.00	0.00
3	0.36	-0.07	0.39	0.24	2.50**	1.25**	0.68	1.18	-0.03	0.02	-0.01	0.00
4	-0.47	-0.17	-0.65	-0.56	1.76*	1.54**	1.31	1.47	0.00	0.00	0.00	0.00
5	0.11	-0.09	-0.18	-0.13	-1.93*	-1.34**	-1.23	-1.55	0.05	0.02	0.04*	0.05**
6	-0.40	-0.05	-0.61	-0.43	-0.30	-0.71	-0.34	-0.53	-0.01	0.00	0.00	-0.01
7	0.18	0.17	0.24	0.27	-0.30	0.19	-0.16	-0.05	0.01	-0.02	-0.01	-0.02
8	0.20	0.07	-0.26	-0.07	-3.23***	-2.19***	-1.70	-2.27	0.03	0.00	0.03	0.03
9	-0.32	-0.03	0.10	-0.05	-1.51	-1.33**	-1.00	-1.31	0.01	-0.01	-0.01	-0.01
10	0.20	-0.02	0.17	0.15	0.20	0.43	0.58	0.52	-0.04	0.01	0.00	0.00

	Plant height (cm)				Ear height (cm)				Ear position				Number of ears per plant			
Tester	Random	low N	Opt	Comb	Random	low N	Opt	Comb	Random	low N	Opt	Comb	Random	low N	Opt	Comb
1	4.52	2.71	1.25	2.12	7.18*	5.13**	5.67	5.48	0.01	0.01	0.02	0.02	0.04	0.01	0.05	0.05
2	5.06	7.23**	7.92	7.47	5.55*	7.45***	8.00	6.45	0.01	0.01	0.01	0.01	0.03	-0.02	-0.01	-0.01
3	3.68	3.34	4.97	4.58	6.68*	4.65**	4.87	4.83	0.01	0.01	0.01	0.01	-0.01	-0.03	0.04	0.01
4	0.83	1.81	-0.06	0.44	-5.2	-5.10**	-5.87	-4.08	-0.02	0.00	-0.02	-0.02	-0.05	-0.04*	0.02	-0.02
5	-3.68	-6.78***	-6.41	-6.91	-5.69*	-8.88***	-9.40	-8.59	-0.01	-0.02*	-0.02	-0.02	0.00	0.02	0.00	0.01
6	-5.65	0.75	-4.58	-3.05	-5.83*	-3.46*	-3.70	-3.40	0.00	-0.01	0.00	-0.01	-0.03	-0.01	-0.07	-0.05
7	3.03	1.71	1.29	1.68	4.34	4.76**	5.19	5.17	0.01	0.02**	0.02	0.02	0.04	0.03*	0.05	0.05
8	-6.37	-6.90***	-6.31	-7.44	-6.02*	-6.97***	-7.99	-7.83	0.00	-0.02*	-0.02	-0.02	0.01	0.03	-0.03	0.00
9	-7.77	-7.54***	-3.99	-5.15	-4.87	-2.41	-2.48	-3.19	0.01	0.00	0.00	0.00	-0.05	-0.01	-0.02	-0.03
10	6.35	3.69	4.37	4.89	3.84	4.81**	4.37	3.92	-0.01	0.00	0.01	0.00	0.03	0.00	-0.04	-0.02

***P < 0.001; **P < 0.01, *P < 0.05; Random = random drought stress; Opt = optimum environments; Comb = Combined environments

3.3.6 Specific combining ability for testcross hybrids under random drought stress

Positive SCA often leads to heterotic effects, causing increased vigour and grain yield. A cross between line 7 and tester 8 recorded the highest positive and significant ($P < 0.05$) SCA effect (1.82) and one of the parents (line 7) had a negative GCA effect (-0.79) for grain yield (Table 3.8). The second best hybrid was a cross between line 8 and tester 8 (L8 x T8) with SCA of 1.58, and one of its parents (line 8 GCA of -0.36) had a negative GCA effect. A total of 50% of the evaluated 109 testcross hybrids exhibited positive SCA, which indicates their potential as good combiners for grain yield. There were negative and highly significant ($P < 0.01$) SCA effects for testcross hybrid L7 x T9 (-2.36); and significant ($P < 0.05$) effects for testcross hybrid L5 x T6 and L10 x T5 (-2.00). Line 8 (1. 58) also showed positive SCA effects when it was crossed with T8. It also produced one of the lowest recorded SCA when it was crossed with testers T7 (-1.58) and T3 (-1.64). Hybrids L4 x T4; L10 x T9 and L7 x T3 produced positive SCA effects, even though all their parents had negative GCA effects. Fourteen hybrids (L1 x T7; L1 x T5; L1 x T1; L3 x T8; L3 x T3; L3 x T1; L5 x T3; L5 x T8; L6 x T10; L6 x T1; L9 x T8; L9 x T3; L12 x T5 and L12 x T1) recorded negative SCA effects while all their parents had positive GCA effects for grain yield.

3.3.7 Specific combining ability for testcross hybrids under low N environments

The testcross hybrids with the highest SCA effects for grain yield were L1 x T6 (1.39) followed by L2 x T5 (1.36) both of which had a parent with negative GCA effects (Table 3.9). Out of the 109 testcross hybrids evaluated, 47.22% had positive SCA effects. Four hybrids showed positive and significant SCA effects; L1 x T6 and L2 x T5 ($P < 0.01$); L9 x T7 and L4 x T4 ($P < 0.05$) while hybrids L3 x T1 and L1 x T2 had negative and significant ($P < 0.05$) SCA effects for grain yield across combined low N environments. Testcross hybrid L3 x T1 had both parents with positive GCA effects.

Table 3.8 Specific combining ability effects for grain yield under random drought stress

	Lines												
Testers	1	2	3	4	5	6	7	8	9	10	11	12	GCA tester
1	-0.82	-0.47	-0.54	0.04	1.31	-1.27	0.84	-	0.65	-0.06	-0.21	-0.05	0.43
2	0.57	0.93	-0.45	-0.47	-0.18	-0.39	0.66	-1.21	-0.23	-0.32	0.38	0.47	-0.02
3	1.55	0.24	0.00	0.23	-0.98	0.05	0.95	-1.64	-0.14	0.56	-1.45	0.40	0.62
4	-0.32	-0.56	-	1.31	0.68	0.18	-0.96	0.23	-0.36	-0.58	1.29	-0.73	-0.73
5	-1.28	0.55	0.99	-1.00	0.21	0.23	1.13	0.79	0.57	-1.98*	-	-0.84	0.07
6	0.94	-0.20	-0.76	1.07	-2.00*	-	-0.58	-	0.28	1.44	0.50	-0.16	-0.70
7	-0.86	0.09	0.24	-	0.50	0.42	-0.50	-1.58	0.72	0.11	0.25	0.15	0.40
8	0.77	0.19	-0.42	-0.43	-0.58	-	1.82	1.58	-0.33	-1.12	-1.56	-	0.16
9	-1.38	-		0.12	0.86	1.29	-2.36*	-0.11	-1.05	1.04	1.02	0.55	-0.68
10	0.98	-1.30	-	-	0.33	-0.90	-0.85	0.08	0.05	1.04	0.01	0.52	0.31
GCA line	0.30	-0.21	0.40	-0.23	0.76	1.13	-0.79	-0.36	0.06	-0.68	-0.41	0.24	

***P < 0.001; **P < 0.01 and *P < 0.05 respectively; SCA specific combining ability

Table 3.9 Specific combining ability effects for grain yield across low N environments

	Lines												
Tester	1	2	3	4	5	6	7	8	9	10	11	12	GCA tester
1	0.03	0.08	-0.95	-0.52	0.48	-0.66	0.18	-	0.27	-0.13	0.79	0.42	0.11
2	-0.92	-0.74	0.06	-0.19	-0.02	0.18	0.55	-0.29	0.59	0.79	-0.01	-0.05	0.08
3	-0.07	-0.38	-0.35	0.51	-0.59	-0.08	0.27	-0.12	-0.04	0.57	0.02	0.20	-0.20
4	0.17	0.06	-	0.91	-0.39	0.24	0.33	-0.64	-0.39	-0.39	-0.08	0.10	-0.30
5	0.17	1.36	-0.18	-0.54	0.44	-0.13	-0.53	0.51	-0.79	0.09	-	-0.12	-0.13
6	1.39	-0.01	0.35	0.16	-0.68	-	-0.72	-	-0.39	-0.20	-0.30	0.43	0.01
7	-0.15	0.11	0.00	-	0.00	0.22	-0.42	-0.13	0.91	0.20	-0.07	-0.60	0.27
8	0.09	-0.29	0.78	-0.10	-0.18	-	0.12	-0.12	0.00	-0.08	-0.30	-	0.15
9	-0.68	-	-	0.05	0.60	0.30	0.04	0.39	-0.29	-0.20	-0.14	-0.04	0.01
10	-0.04	-0.19	-	-	0.33	0.12	0.16	0.47	0.11	-0.66	-0.06	-0.21	0.02
GCA line	-0.40	0.12	-0.02	0.13	-0.21	0.05	-0.09	0.06	0.00	0.19	0.36	-0.13	

***P < 0.001; **P < 0.01 and *P < 0.05 respectively; SCA specific combining ability

3.3.8 Specific combining ability for testcross hybrids across optimum conditions

There was no SCA x environment interaction for grain yield among the evaluated maize genotypes under optimum environments, indicating that selection of testcross hybrids can be done at any location (Table 3.5). SCA was, however, highly significant ($P < 0.001$), indicating differential responses and performance existing among the hybrids. Hybrid L4 x T6 had the highest SCA effect of 1.24, followed by L4 x T4 with 1.11 (Table 3.10). These two testcross hybrids had positive and highly significant ($P < 0.01$) GCA effects under optimum conditions, though they all had one parent with negative GCA. Testcross hybrids L1 x T6 (0.89) and L2 x T6 (1.00) had positive and significant ($P < 0.05$) SCA effects. Testcross hybrids with the lowest SCA effects included L2 x T10 (-1.17); L9 x T6 (-1.29) and L5 x T6 (-0.81). Tester 6 was unique in producing the highest SCA effects in hybrids, and also the weakest GCA effects; and had a negative GCA of -0.61. Fifty four of 109 testcross hybrids exhibited positive SCA effects, indicating their usefulness as potential heterotic hybrids. Line 3 and line 1 had positive GCA effects but produced testcross hybrids with the most negative SCA effects.

3.3.9 Specific combining ability for testcross hybrids across all environments

The SCA estimates for yield of testcross hybrids evaluated across all 12 environments (Table 3.11) showed that testcross hybrid L4 x T4 had the highest SCA effect, followed by L1 x T6, and all shared a negative tester parent. Testcross hybrid L5 x T6 and L7 x T6 were among the hybrids with the lowest SCA effect. Some testcrosses had parents with positive GCA effects but had negative SCA effects (L1 x T1; L3 x T7; L6 x T10; L6 x T7; L11 x T3; and L11 x T1). Tester 9 produced several hybrids with negative SCA effects. Out of the 109 testcross hybrids developed, 50% showed positive SCA effects.

Table 3.10 Specific combining ability effects for grain yield in optimum environments

	Lines											
Testers	1	2	3	4	5	6	7	8	9	10	11	12	GCA tester
1	-0.03	-0.12	-0.23	-0.44	0.17	0.14	0.67	-	0.15	0.28	-0.48	-0.53	0.25
2	-0.01	-0.58	0.03	-0.40	-0.05	0.36	0.20	-0.18	0.07	0.39	-0.08	0.06	0.44
3	-0.33	-0.59	-0.30	0.01	0.62	-0.24	0.31	0.02	0.25	-0.15	0.26	-0.05	0.39
4	-0.33	0.15	-	1.09*	0.14	-0.14	-0.12	-1.03*	-0.08	0.43	0.24	-0.14	-0.65
5	0.06	0.86	-0.33	-0.54	0.29	0.10	-0.89	0.07	-0.07	0.03	-	0.44	-0.18
6	0.89	1.00*	0.90*	1.24**	-0.81	-	-1.14	-	-1.29*	-0.50	-0.41	0.18	-0.61
7	0.23	0.36	-0.31		-0.22	-0.71	-0.09	0.42	-0.10	0.03	0.12	0.08	0.24
8	-0.23	0.28	-0.03	-0.32	-0.62	-	0.17	0.09	0.43	-0.09	0.64	-	-0.26
9	0.04	-	-	-0.12	0.65	0.08	0.28	0.25	0.29	-0.30	-0.71	-0.41	0.10
10	-0.19	-1.17**	-	-	-0.07	-0.35	0.71	0.29	0.46	-0.01	0.34	0.21	0.17
GCA line	0.19	-0.18	0.42	0.01	-0.16	0.50	-0.33	-0.22	-0.37	0.25	0.21	-0.12	

***P < 0.001; **P < 0.01, *P < 0.05 respectively; GCA general combining ability; SCA specific combining ability

Table 3.11 Specific combining ability effects for grain yield across all environments

	Lines												
Tester	1	2	3	4	5	6	7	8	9	10	11	12	GCA tester
1	-0.13	-0.11	-0.50	-0.39	0.44	-0.34	0.55	-	0.27	0.10	-0.05	-0.16	0.23
2	-0.21	-0.4	-0.04	-0.36	-0.07	0.29	0.37	-0.38	0.18	0.39	0.00	0.08	0.27
3	0.04	-0.40	-0.27	0.20	0.00	-0.16	0.40	-0.28	0.10	0.18	-0.08	0.09	0.24
4	-0.17	0.01	-	1.07**	0.60	0.02	-0.11	-0.72*	-0.22	0.03	0.30	-0.15	-0.56
5	-0.11	0.97*	-0.08	-0.61	0.32	0.04	-0.47	0.32	-0.19	-0.26	-	0.07	-0.13
6	1.05*	0.51	0.48	0.88*	-0.95**	-	-0.92*	-	-0.77*	-0.11	-0.23	0.21	-0.43
7	-0.06	0.24	-0.13	-	-0.04	-0.27	-0.25	-0.06	0.34	0.10	0.08	-0.12	0.27
8	0.03	0.09	0.16	-0.28	-0.48	-	0.41	0.26	0.18	-0.25	0.01	-	-0.07
9	-0.40	-	-	-0.03	0.67	0.32	-0.20	0.24	-0.10	-0.06	-0.27	-0.15	-0.05
10	0.04	-0.88	-	-	0.11	-0.30	0.30	0.32	0.29	-0.05	0.17	0.13	0.15
GCA lines	0.03	-0.09	0.28	0.01	-0.04	0.47	-0.33	-0.16	-0.19	0.09	0.16	-0.07	

***P < 0.001, **P < 0.1, *P < 0.05; SCA specific combining ability; GCA general combining ability

3.3.10 Estimates of variance components and heritability for grain yield and agronomic characteristics in individual environments and across management levels

Estimates of variance components and heritability based on grain yield at individual environments and across environments are presented in Table 3.12. Genotype variance across combined and for optimum environments were higher than environmental variances, and lower than both across low N and random drought stress environments. Broad sense heritability estimates across all management levels (combined, optimum, random drought and low N) were high (0.61-0.95). Narrow sense heritability was moderate for grain yield across these management levels at a range of 0.55-0.63. Additive variance was higher than dominance variance for all individual environments, and across management levels. Genotype variance was highest at Mpongwe, followed by Art Farm and Lusaka, all optimum environments, while lowest for all stress (random drought and low N) environments. Narrow sense heritability estimates ranged between 0.42-0.71, with the highest estimates observed under individual stressed locations.

For most characteristics, genotype variance was higher than environmental variance (Table 3.13). High broad sense and narrow sense heritability was observed for the recorded characteristics at a range of 0.87-0.99 and 0.66-0.93 respectively. For days to 50% anthesis and ear height, tester variance was better than live variance, while lower for plant height and ASI. Line x tester variances was low for all characteristics across all the management levels. All the variance components for both ear position and the number of ears per plant were very low across all the management levels. Both broad sense and narrow sense heritability was high under random drought stress for days to 50% anthesis, ear and plant height, ear position and the number of ears per plant except for ASI.

Table 3.12 Estimates of grain yield variance components and heritability at individual and combined environments

Location	Management/ Environment	Line variance	Tester variance	Line x Tester variance	Genotype Variance	Additive variance	Dominance variance	Environmental variance	H^2	h^2
Gwebi	Low N	0.07	0.05	0.00	0.08	0.32	0.00	0.13	0.71	0.71
Harare A	Low N	0.08	0.05	0.13	0.26	1.05	0.52	0.25	0.86	0.58
Harare B	Low N	0.01	0.03	0.21	0.26	1.03	0.85	0.14	0.93	0.51
Potchefstroom	Low N	0.16	0.12	0.08	0.36	1.44	0.34	0.41	0.81	0.66
Gwebi	Optimum	0.11	0.18	0.23	0.51	2.04	0.93	0.46	0.87	0.59
Art Farm	Optimum	0.26	0.19	0.18	0.58	2.31	0.72	0.28	0.92	0.70
Ivordale	Optimum	0.00	0.16	0.33	0.47	1.90	1.34	1.29	0.71	0.42
Mpongwe	Optimum	0.24	0.28	0.15	0.64	2.57	0.62	0.68	0.82	0.66
Lusaka	Optimum	0.11	0.10	0.37	0.56	2.24	1.49	0.42	0.90	0.54
Cedara1	Optimum	0.14	0.08	0.18	0.37	1.49	0.71	0.31	0.88	0.59
Cedara2	Optimum	0.14	0.15	0.18	0.46	1.82	0.72	0.27	0.90	0.65
Potchefstroom	Random	0.27	0.13	0.00	0.24	0.96	0.00	0.62	0.61	0.61
Across	All	0.01	0.07	0.10	0.18	0.74	0.41	0.06	0.95	0.61
Across	Low N	0.02	0.02	0.05	0.09	0.37	0.20	0.10	0.86	0.55
Across	Opt	0.03	0.13	0.17	0.32	1.28	0.66	0.10	0.95	0.63
Across	Random	0.27	0.13	0.00	0.24	0.96	0.00	0.62	0.61	0.61

H^2 broad sense heritability; h^2 narrow sense heritability; random random drought stress

Table 3.13 Variance components and broad sense and narrow sense heritability estimates for characteristics across environments

Trait	Line variance	Tester variance	Line x Tester variance	Genotype variance	Additive variance	Dominance variance	Environmental variance	H^2	h^2
AD	1.33	1.48	0.46	3.20	12.82	1.85	0.20	0.99	0.86
ASI	0.07	0.04	0.05	0.15	0.62	0.19	0.12	0.87	0.66
PH	32.52	22.91	5.38	58.40	233.60	21.53	7.41	0.97	0.89
EH	9.51	31.42	1.41	39.83	159.33	5.64	5.96	0.97	0.93
EPO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.94	0.85
EPP	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.94	0.77

AD days to 50% anthesis, ASI anthesis silking interval, PH plant height, EH ear height, EPO ear position, EPP ears per plant, H^2 broad sense heritability; h^2 narrow sense heritability

The contribution of line x tester variance was very low for most of the characteristics (Table 3.14). Variances due to dominance effects were also insignificant, leading to similar values for broad and narrow sense heritability estimates for most of the characteristics. Environmental variance was larger than variances due to genotypes for most characteristics across the management levels. Both broad sense and narrow sense heritability estimates were high for days to 50% anthesis, ear height and the number of ears per plant for the random drought stress management level. Observed broad sense and narrow sense heritability for most other characteristics across the management levels were low, with some cases indicating heritability estimates of zero.

Table 3.14 Estimates of variance and heritability for characteristics across management levels

Trait	Management	Line var	Tester var	L x T var	Gen. var	Add. var	Dom. var	Env. var	H^2	h^2
AD	LN	1.56	2.00	0.00	1.55	6.19	0.00	13.32	0.32	0.32
	Opt	0.37	0.59	0.00	0.00	0.00	0.00	41.10	0.00	0.00
	RS	5.77	3.80	0.00	8.88	35.54	0.00	2.99	0.92	0.92
ASI	LN	0.18	0.07	0.00	0.13	0.53	0.00	2.85	0.16	0.16
	Opt	0.04	0.03	0.00	0.05	0.20	0.00	1.09	0.16	0.16
	RS	0.65	0.21	0.00	0.00	0.00	0.00	2.96	0.00	0.00
PH	LN	30.45	20.46	0.00	17.98	71.90	0.00	295.42	0.20	0.20
	Opt	34.72	21.85	0.00	45.49	181.96	0.00	225.69	0.45	0.45
	RS	40.65	39.02	0.00	67.57	270.27	0.00	135.79	0.67	0.67
EH	LN	3.78	17.45	0.00	0.00	0.00	0.00	272.07	0.00	0.00
	Opt	12.51	38.21	0.00	30.70	122.80	0.00	237.70	0.34	0.34
	RS	9.63	39.93	8.70	57.12	228.48	34.82	47.14	0.85	0.74
EPO	LN	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
	Opt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22	0.22
	RS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.31	0.31
EPP	LN	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.39	0.38
	Opt	0.00	0.00	0.00	0.00	0.01	0.00	0.02	0.44	0.44
	RS	0.00	0.00	0.00	0.01	0.05	0.02	0.01	0.86	0.61

AD days to 50% anthesis, ASI anthesis silking interval, PH plant height, EH ear height, EPO ear position, EPP ears per plant, L x T line by tester; Gen genotype; Add additive; Dom dominance; H^2 broad sense heritability; h^2 narrow sense heritability; var variance; LN low N; Opt Optimum; RS random drought stress; E environment

3.3.11 Variance components and genotypic and phenotypic coefficients of variation under random drought stress

The variance components and genotypic and phenotypic coefficients of variation for grain yield and agronomic characteristics are presented in Table 3.15. The genetic coefficient of variation (GCV) was lower than the phenotypic coefficient of variation (PCV) for all measured characteristics under random drought stress environments. All values for both genotypic and phenotypic coefficients of variation were lower for all the measured characteristics except for plant height which recorded higher values across all the management levels. Genotypic variances for grain yield, ASI, ear position, number of ears per plant ear rots, and ear aspect were generally low under both random drought and low N environments. This means that the stress environments had a larger effect on these characteristics than the genotypic effects. Though variances due to locations (environments) were generally high for individual management levels, there was a greater contribution across all the combined test environments.

Table 3.15 Variance components and genotypic and phenotypic coefficients of variation for measured characteristics under different management levels

Trait	GY	AD	ASI	PH	EH	EPO	EPP
Under random drought stress							
Genotypic mean	0.10	0.59	0.04	0.14	0.30	0.08	0.26
GCV (%)	20.93	1.04	8.35	0.22	0.46	40.21	55.64
Phenotypic variance	0.40	0.80	0.51	0.41	0.56	0.48	0.52
PCV (%)	29.19	1.21	28.81	0.36	0.62	97.11	79.31
Across low N environments							
Genotypic variance	0.09	4.29	0.00	58.84	27.49	3 E-04	0.00
GCV (%)	16.19	24.81	2.28	55.06	53.07	2.44	4.30
Phenotypic variance	0.18	4.84	0.01	79.09	42.29	0.00	0.00
PCV (%)	23.44	26.36	4.78	63.83	65.83	3.42	6.26
G x E variance	0.15	0.68	0.00	11.13	10.57	2 E-04	0.00
Location variance	2.17	26.09	0.01	268.89	405.90	0.01	0.00
Error variance	0.47	3.08	0.03	140.07	99.15	0.00	0.01
Across optimum environments							
Genotypic variance	0.33	2.24	0.00	57.35	50.43	0.00	0.00
GCV (%)	7.72	2.05	1.11	3.03	5.21	3.19	5.90
Phenotypic variance	0.43	2.55	0.00	69.87	62.34	0.00	0.01
PCV (%)	8.86	2.18	1.93	3.34	5.79	3.76	6.94
G x E variance	0.21	0.15	0.00	0.00	4.33	0.00	0.00
Location variance	1.97	87.79	0.00	248.88	322.13	0.00	0.02
Error variance	1.04	4.01	0.02	175.37	158.13	0.00	0.02
Across all combined environments							
Genotypic variance	0.18	3.84	0.00	59.42	43.36	0.00	0.00
GCV (%)	17.75	23.06	2.64	51.92	59.66	2.32	5.83
Phenotypic variance	0.23	4.04	0.00	66.49	48.73	0.00	0.02
PCV (%)	20.17	23.66	3.39	54.92	63.24	6.57	14.56
G x E variance	0.21	0.46	0.00	1.77	4.99	0.00	0.00
Location variance	5.19	53.55	0.01	1355.81	581.39	0.01	0.01
Error variance	0.93	4.35	0.03	180.30	129.60	0.00	0.02

GCV genotypic coefficient of variation; PCV phenotypic coefficient of variation; G x E genotype by environment; GY grain yield (t ha^{-1}); AD days to 50% anthesis; ASI anthesis silking interval, PH plant height (cm), EH ear height (cm), EPO ear position; EPP number of ears per plant

3.4 Discussion

The significant differences for different characteristics among hybrids developed from 10 testers and 12 lines indicated the presence of large variability among the parents. This makes selection for improved grain yield and agronomic characteristics under random drought and low N stress environments possible. Several authors have also identified large variability in hybrids under stressed and non-stressed environments (Bänziger and Lafitte, 1997; Betrán et al., 2003; Diallo et al., 2004; Bänziger and Diallo, 2004; Mosisa et al., 2007; Gissa, 2008). The parents used in this investigation have been developed by CIMMYT to increase the levels of tolerance to major yield limiting factors in SSA, such as drought and low N fertility. The existence of genetic variability in maize evaluated under different levels of management was reported by several investigators (Bolaños and Edmeades, 1993; 1996; Bänziger et al., 1997; 1999; Gissa et al., 2007; Derera et al., 2008; Umar et al., 2015).

Breeding for drought and low N tolerance at CIMMYT started in the early 1970's and since then, several hybrids have been released to farmers. The ongoing challenge faced by breeders is that drought and low N tolerance are governed by multi-genes/QTLs with smaller effects (Cairns et al., 2013). Hence efforts were put in place to increase levels of tolerance of maize hybrids, with the view of reducing yield losses to drought and low N conditions in SSA. Sub-optimal environments reduce the potential yields compared to yields under optimum conditions. Yield decreases of 52.33% (low N vs optimum); 33.24% (random drought vs optimum) and 28.6% (random drought vs low N) environments were observed in this study. Though differential genotypic responses across locations were observed, maize hybrids developed for drought and low N tolerance used in this study were better performing than several checks, implying that they can be better hybrids under those environments.

Maize yields in Africa range between 0.6 to 4 t ha^{-1} (Pingali and Pandey, 2000; Weber et al., 2012). This can be reduced by over 80% under drought and low N conditions (Betrán et al., 1997; Bänziger et al., 1997; 2006; Weber et al., 2012). The results observed for yield decreases in this study were in line with these observations and conclusions.

ANOVA indicated significant differences in mean grain yields across management levels and within environments, indicating the differential responses of genotypes to varying levels of stress. The screening of inbred lines under contrasting environments in maize breeding programmes has been reported to lead to better selection of parents for use in hybrid development programmes (Badu-Apraku et al., 2013; 2015). The results indicated highly significant SCA x E interactions for grain yield across low N test environments, indicating differential performance of these hybrids across these environments. The differential performance of genotypes leads to better selection of consistent genotypes across multiple environments, and helps to identify suitable parents (both lines and testers) to use for hybrid development across diverse environments. Contrasting environments play a significant role in determining how characteristics are expressed under a specific stress management level, and can be used for improving genetic gains. Similar results were indicated by Akinwale et al. (2014) and Badu-Apraku et al. (2015). The effect of environment across sites was highly significant, indicating the differential potential of the environments. Optimum environments (7.07 t ha^{-1}) out-yielded both random drought (5.74 t ha^{-1}) and low N stress environments (4.34 t ha^{-1}). Similar results have been previously reported by Bolaños and Edmeades (1993; 1996); Bänziger et al. (1997); Bänziger and Lafitte (1997); Bänziger et al. (1999); Gissa et al. (2007); Derera et al. (2008); Gissa (2008) and Umar et al. (2015), among others.

Location contributed largely to variation in yield under low N conditions as indicated by high contributions to the total sum of squares. These results can be explained by different levels of N depletion for each site. Harare A was depleted of N for the past seven years, as compared to other locations like Gwebi which had been depleted of N for only two years. The line x tester crossing design for identifying suitable parents for hybridization was successful in this study because it allowed differentiation between good and poor combiners for hybrid development. The success of a breeding programme, according to Legesse et al. (2009), often depends on the selection of a good mating design and the existence of genetic diversity among genotypes.

Line GCA, tester GCA, and their interactions with the environments were highly significant, indicating the differential responses of the evaluated lines and testers with the environments. SCA was highly significant for grain yield, indicating the presence of heterotic effects among the lines and testers used. SCA x environment was significant for both combined and low N environments indicating that selection based on better SCA effects can be performed across these test environments. SCA x environment interaction was however, not significant under optimum environments. This also means the breeding programme for drought and low N tolerance was effective, since the genotypes performed similarly under varied stress and optimal environments. The high GCA/SCA ratio of 3.16 indicates the importance of additive gene action for grain yield under random drought stress. Khodarahmpour (2011) reported high GCA/SCA ratios under heat stress environments in maize. Karaya et al. (2014) reported high

GCA/SCA ratios for grain yield when evaluating maize hybrids for *Striga* resistance. The large contribution of hybrid sum of squares to total sum of squares indicates that hybrid variability was due to their intrinsic genetic differences *per se*.

Lines 1, 3, 4, 6, 10 and 11 were the best combiners across all locations, and can thus be effectively used to produce good hybrid combinations across varied environments (drought and low N environments or optimum). Lines 2, 3, 4, 10 and 11 were important under low N environments and had high positive GCA values for grain yield. Lines 1 and 6 showed poor GCA effects under low N environments, and contributed much to reduced yields. Under random drought stress, lines 1, 3, 5, 6 and 12 were important. Line 3 had positive GCA across all the individual environments, which indicates that it had better average GCA effects compared to others. Lines, 3, 4, 5, 6 and 7 contributed much to earliness across all environments. Apart from these lines; line 10 (under low N stress) and lines 8 and 9 (under random drought) also contributed to earliness. Lines 1, 5, 6, 7, 8 and 9 were good combiners for ASI and they contributed to better synchronization. Lines 2, 7, 8 and 9 contributed to reduced plant stature across all the environments. Lines contributing to shortness are essential for the development of early and extra early maturity maize varieties. These hybrids will mature early, before the onset of drought, especially during the mid-season, which occurs sporadically in SSA. The increasing importance of climate variability and seasonal drought caused by the ENSO effects (Dilley and Heyman, 1995; Singh, 2006; Jury, 2000; Shiferaw et al., 2014) are likely to increase and genotypes with good tolerance to drought and extra early attributes will be beneficial for smallholder farmers in the region (Janowiak, 1988; Singh, 2006; Shiferaw et al., 2014).

The best testcross hybrid (L2 x T6) with the highest SCA was a cross between two parents with negative GCA, and the increased grain yield can be a result of heterotic and epistatic gene effects. Significant GCA and SCA effects in the experiments for most characteristics across locations indicated that selection of good inbred lines and hybrids can be effective under drought and low N stress environments. These genotypes can be advanced to regional trials and subsequently released as hybrids if their performance is consistent.

Grain yield in maize is a complex trait, under the influence of multi-genes which interact with the environment differently (Zhang et al., 2014). To make informed inferences about the behaviour of genes in a sample population, information about the heritability, genotypic and phenotypic variations, genotypic and phenotypic coefficient of variation and genetic advance are important in explaining the patterns of responses and gene actions. Broad sense heritability estimates for grain yield were relatively lower under both random drought and low N environments, and higher under optimum environments. Lafitte and Bänziger (1995), Piepho (2000) and Cattivelli et al. (2008) observed low broad sense heritability estimates in maize under stress environments. Grain yield under stress is characterised by low broad sense heritability, polygenic control, epistasis, and significant G x E interaction and QTL x E interactions (Piepho, 2000) that reduces response to selection for grain yield under stress environments. This has led to the selection of secondary characteristics with higher heritability that are highly correlated to grain yield for yield improvement.

High heritability values indicate that characteristics studied were not masked by the environmental variations, which will lead to an increased response to selection. Differential heritability estimates observed under varied test environments can be attributed to the choice of lines used which created structured populations of highly tolerant/susceptible groups that showed more repeatable differentiation under their respective stresses. Characteristics with high heritability estimates have been indicated to improve genetic gains in plants and selection can be done based on these results (Singh and Ceccarelli, 2000). Low heritability estimates, on the other hand, reduce genetic advance and selection (Singh, 2005), and the combined use of heritability estimates and genotypic coefficients will improve selection efficiency (Assefa et al., 1999). High broad sense and narrow sense heritability for most characteristics across the management levels indicates that the characters like grain yield can be improved under these conditions. Some characteristics showed low broad sense and narrow sense heritability across management levels, while higher estimates were obtained under random drought stress conditions. In this case, there is potential to improve genetic gains across sub-optimal conditions. Campos et al. (2006) and Masuka (2014) indicated high heritability for ASI and the number of ears per plant under drought stress and this can increase selection efficiency in breeding programmes for drought tolerance. From the current study it can be seen that there is potential for improved selection gains for yield under drought stress.

The results indicated low genotypic and phenotypic coefficients of variation for grain yield at all locations, including across all locations. This can be a result of the increased influence of different environments on the performance of the evaluated genotypes. Similar results were reported by Nelson and Sommers (1973) and Bello et al. (2012). Low genotypic coefficient of variation often indicates low variability within a sampled population. Johnson et al. (1955)

reiterated that heritability alone cannot describe the amount of genetic progress expected through selection of better genotypes, but should be aided by other measures of variation, especially genotypic and phenotypic coefficients of variation. Apart from aiding in selecting the best genotypes at individual environments, or across environments, the proportion of genotypic and phenotypic coefficients of variation are also helpful for measuring the impacts of environmental influences on specific characteristics of a particular genotype. Plant height and ear height had higher genotypic coefficients of variation, especially across locations and under optimum conditions, indicating that these characteristics were under the influence of additive gene action. Magashi et al. (2013) also reported lower genotypic coefficients of variation for several agronomic characteristics.

3.5 Conclusions

Maize in the SSA region is rain-fed and is prone to climate variability, especially increasingly infrequent and low precipitation and the occurrence of heat stress conditions, making maize more vulnerable to climatic change. Soils, on the other hand, are intrinsically low in N, as organic fertilisers to boost their production, are out of the reach of small scale farmers. Nitrogen and water are important factors in the growth and development of maize genotypes and their shortage singly or combined, always occurs with yield penalties. The ongoing climate variability could have other effects such as increasing susceptibility to pathogens and increasing virulence of pathogens. This will continue to decrease the profitability of maize-based cropping systems and could cause significant food insecurity in the region. Significant yield reductions as a result of random drought and low N were apparent in this investigation. Smallholder farmers will depend heavily on the success of breeding programmes that are targeted at improving the water use and N use efficiency of maize in the presence of reduced moisture and N levels. This study was aimed at estimating the combining ability of maize genotypes that were developed for tropical and sub-tropical drought and low N stress tolerance. The identified lines with good combining ability effects can be utilized for efficient hybrid production, and as sources of drought and low N tolerance genes for future improvements.

The investigation was successful in identifying suitable parents with good GCA and SCA for use in hybrid development. High heritability estimates observed for grain yield across stress environments indicated the utility of stress test environments for increasing selection gains of maize. Low heritability estimates observed for other characteristics usually are undesirable as they lower the selection precision of a system. The use of genotypic and phenotypic coefficients of variation has enabled easy inferences about the behaviour of genes in the target population, where scenarios of low heritability are encountered. Hybrids with good combining ability for grain yield those that give early attributes to hybrids in terms of flowering and those with short plant stature can be easily selected and recommended for use in hybrid programmes aimed at reducing the impacts of drought and low N fertility in the SSA region.

The line x tester mating design was efficient in identifying better parents and parent combinations for the formation of hybrids. The high heterotic responses and positively significant GCA and SCA effects observed indicated the importance of additive and non-additive gene action. In maize, heterosis is often a result of mating two parents that are unrelated (originating from different heterotic groups) and the heterotic effects depend on the combining ability of these unrelated parents. Parents with significant GCA are a result of additive gene action for the observed characteristics and are good combiners. They can be successfully used as parents in hybrid development. The presence of significant SCA effects confirms the presence of non-additive gene action and potentially good hybrid combinations. The inbred lines used in this investigation had enough genetic variability that can be used for successful hybrid breeding for drought and low N fertility stress prone environments. The study confirms that CIMMYT was effective in breeding quality sources of drought and low N tolerance genes for use in the SSA region.

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CHAPTER 4

Combining ability and heritability estimates of elite late maturity maize inbred lines and hybrids under optimal, drought and low N stress environments in southern Africa

Abstract

Maize cropping systems in southern Africa are exposed to droughts and low soil fertility, causing hunger, starvation and food insecurity. The use of drought and low N tolerant maize hybrids have improved the livelihoods of millions of people in eastern and southern Africa, who depend mostly on maize based diets as their staple food. This study aimed to estimate the GCA, SCA and heritability of late maturing hybrids generated from a line x tester design during the 2014/2015 summer season. Twenty six inbred lines were crossed to six broadly adapted CIMMYT testers to produce 156 three-way hybrids. These hybrids were evaluated across 15 test environments that included optimum, low N and random drought stress sites. The treatments were arranged in an alpha-lattice design with two replications. There was large variability among the selected maize inbred lines for drought and low N tolerance, as shown by significant GCA for lines and testers, and their interactions with the environment. The results indicated the presence of both additive and non-additive gene action for the measured characteristics. Heritability was high for several characteristics, indicating their potential for selection for drought and low N tolerance. SCA can be effectively used with information about the GCA for both lines and testers as poor and good genotypes combine to produce good hybrids. Yield reductions ranged between 60.53% (low N environments) and 79.55% (random drought stress environments), indicating the importance of these stresses in southern Africa. Lines 1, 2, 5, 15, 21, 22, 23, 25 and 26 showed positive GCA effects for grain yield across all the environments, and can be successfully utilized as potential sources for hybrid breeding programmes across optimum, low N and random drought stress environments, or in areas where drought and low N stresses is a challenge. Hybrids and inbred lines had intrinsically higher tolerance to drought and low N stresses. The holistic approach can be continued as a way of combating food insecurity in the region. Though stresses can reduce yields significantly, there is high potential of boosting maize productivity by the use of the novel gene sources from the CIMMYT breeding pool, where these inbred lines evaluated, were selected from. Varied performance of hybrids is an indication of the responsiveness of maize to stressful environments, which can be used as way of producing well-adapted genotypes.

4.1 Introduction

There has been an increased output of breeding materials from CIMMYT and other private and public breeding institutions, and a relative good adoption of these improved maize (*Zea mays* L.) varieties with drought and low soil fertility tolerance in southern Africa (Zimbabwe, Zambia and South Africa). The smallholder farmers have indeed benefitted from stress tolerance research, where grain yields for the improved varieties out-yielded local commercial checks under stress conditions by 20-30% (Kassie et al., 2013). Drought and low N fertility have continued to limit grain yield in eastern and southern Africa. In the light of these challenges, CIMMYT and other collaborators developed and disseminated hundreds of improved varieties to smallholder farmers. There have been different initiatives, carried on for the past 40 years that were geared at improving yield productivity across Africa. Such initiatives included; the drought tolerant maize for Africa (DTMA), the improved maize for African soils (IMAS) and the water efficient maize for Africa (WEMA), among other projects. Maize hybrids were improved for water use efficiency (WUE), nitrogen use efficiency (NUE), drought tolerance among other objectives, all with some great success stories across the SSA (Mueller et al., 2012).

Drought is a widespread phenomenon, which is estimated at 22% in mid-altitude/subtropical and 25% in lowland tropical maize growing regions annually, due to inadequate water supply during the growing season (Heisey and Mwangi, 1996). Yield losses are quite high in tropical and sub-tropical regions due to the unpredictability of rain during the growing season, with other places suffering from mid-season droughts, which severely reduce the grain yields per unit area. The use of improved varieties together with improved management options have been shown to offset yield losses by up to 40% (Thornton et al., 2009). The general implications of utilizing tolerant genotypes will likely benefit farmers in environments which are getting hotter and drier. In addition to the benefits of drought tolerance in improved germplasm, the development of WUE and improved NUE and low N tolerant varieties will boost maize productivity in the tropical regions. The need for irrigation and N fertilization costs and the negative impact of excessive N on the environment will be reduced (IPCC, 2001; Tilman et al., 2002).

The use of inbred lines with tolerance mechanisms can bring about hybrids that are better than their parents, and can undergo developmental transitions better than their inbred parents (Schnable and Springer, 2013). So the agronomic and genetic knowledge will improve the understanding on how to combine maize for hybrid vigour with both drought and N stress tolerance and provide new strategies to address drought and N related issues. Le Gouis et al.

(2002) emphasized the use of combining ability as key to understanding and enhancing maize NUE characteristics when assessing genetic variation for low N stress tolerance.

Combining ability estimates have been successful to help plant breeders to identify and select best performing genotypes based on the nature of gene action, either additive or dominance gene effects (Ali et al., 2013). Furthermore, the performance of hybrids generated across different agro-ecologies/environments also needs to be assessed. Because maize genotypes differ in their adaptation to environments, understanding the magnitude of G x E interaction would lead to identification of specifically adapted and also stable hybrids across environments (Nyombayire, 2011). GCA is defined as the average performance of a line in hybrid combinations and SCA refers to the deviation of a particular cross from performance predicted on the basis of general combining ability (Sprague and Tatum, 1942; Schlegel, 2010). The GCA effect is due to additive gene action and that of SCA is largely dependent on genes with dominance and/or epistatic effects. Comstock and Robinson (1948) introduced the line by tester mating scheme to study the combining ability of lines. In the line by tester design a set of female parents are crossed with a genetically different set of male parents in all possible combinations.

GCA and SCA have been indicated to interact with environments, usually with observable changes in parental combining ability across test environments (Pixley and Bjarnason, 1993). Therefore, to obtain precise combining ability estimates, it is necessary to evaluate parents in more than one environment. Betrán et al. (2003) reported significant combining ability interactions under both low and high N environments. In their study, additive gene effects were most pronounced under low N conditions while dominance gene effects were reported under drought stress test environments. Each recurrent selection cycle includes multiple years where the selected candidates are crossed to several tester lines from the opposite pool and evaluated as testcrosses in multi-environment trials to assess their genetic potential and GCA. After several selection steps, hybrid performance is evaluated in factorial crosses either by a diallel cross or a line x tester method to assess the SCA of possible hybrid parents. The selected lines will be used as parental lines for a new generation of new lines and form the next recurrent selection cycle.

Testers can be used in the assessment of combining ability and breeding values of genotypes for population improvement (Falconer, 1981; Hallauer and Miranda, 1988). The overall principle is to find a genotype (tester) that discriminates genotypes (low performers vs high performers) and this aids plant breeders to identify superior candidates for selection, across diverse environments. A tester can be described as desirable when it combines better discrimination, and can classify genotypes in terms of their relative merits, while maximising on genetic gains (Hallauer, 1975).

The use of the line x tester and diallel methods have been reliably adopted to evaluate maize hybrids based on their GCA and SCA performance (Kaushik et al., 2004). As drought and low N fertility challenges are a common cause of yield failure in southern Africa, the use of elite germplasm with good characteristics of tolerance to these challenges will boost food productivity in the region. The objective of this study was to identify the breeding value of CIMMYT-developed late maturity elite maize inbred lines as potential parents for hybridization programmes across randomly occurring drought and low N stress and optimal conditions in southern Africa.

4.2 Materials and methods

4.2.1 Plant materials

One hundred and fifty-six three-way late maturity hybrids were developed from 26 CIMMYT elite lines crossed with six CIMMYT testers following a line x tester mating design and the testcrosses were evaluated across 15 test environments in southern Africa during the 2015 summer season. The lines and testers were developed by CIMMYT specifically for drought and low N tolerance, which is why they were included in this study. The detailed characteristics of the germplasm used are shown in Table 4.1.

4.2.2 Data collection

Data was collected as described in Chapter 3 (Section 3.2.5).

4.2.3 Test environments and trial management

Trials were grown at 15 test locations across southern Africa (South Africa, Zimbabwe and Zambia) as described in Chapter 3 (Section 3.2.2). Three additional trials were conducted in the following sites in Zimbabwe:

(i) Gwebi (low N) 17°40;60” S, 30°52’0” E, 1438 masl;
(ii) Kaguvi (random drought) (19°11’ S; 29°48’E, 1440 masl); and
(iii) Rattrey Arnold Research Station (optimum) (17°40’ S; 31°05’ E, 1369 masl).

Trials were grown under managed drought conditions, N depleted soil, optimum and random drought stress environments as described in Chapter 3 (Section 3.2.2).

Table 4.1 Information on late maturity maize inbred lines and testers used for crosses in the combining ability studies

Line/Tester code	Pedigree	Description
1	CML444/CML546	Tester
2	CML543/CKDHL0089	Tester
3	CML543/VL05420	Tester
4	CML536/CML312	Tester
5	CKDHL0228/CZL99017	Tester
6	CML312/CML444	Tester
1	(CML536/DTPWC9-F109-2-6-1-1-B)DH-0013-B-B-B	Line
2	(CML509/[INTA-2-1-3/INTA-60-1-2]-X-11-6-3-BBB)F2-216-1-1-B-B-B	Line
3	(CML509/[INTA-2-1-3/INTA-60-1-2]-X-11-6-3-BBB)F2-188-1-1-B-B-B	Line
4	(CML509/[INTA-2-1-3/INTA-60-1-2]-X-11-6-3-BBB)F2-41-1-1-B-B-B	Line
5	(CML312IR/[(CLQRCWQ50/CML312SR//CML312SR)-3-1-B/(CLQRCWQ50/CML312SR)-2-2-1-BB]-BB)F2-B-4-1-1-B	Line
6	(La Posta Seq C7-F71-1-2-1-2-B-B-B/*CML395) DH-5-B-B-B-B	Line
7	(La Posta Seq C7-F96-1-2-1-1-B-B-B/*CML395) DH-74-B-B-B	Line
8	(La Posta Seq C7-F96-1-2-1-1-B-B-B/*CML395) DH-60-B-B-B-B-B	Line
9	(La Posta Seq C7-F96-1-2-1-1-B-B-B/*CML395) DH-19-B-B-B-B-B	Line
10	(La Posta Seq C7-F71-1-2-1-2-B-B-B/*CML444) DH-56-B-B-B-B	Line
11	(La Posta Seq C7-F71-1-2-1-2-B-B-B/*CML444) DH-118-B-B-B-B	Line
12	(La Posta Seq C7-F96-1-2-1-1-B-B-B/*CML444) DH-16-B-B-B-B-B	Line
13	(La Posta Seq C7-F71-1-2-1-2-B-B-B/*CML539) DH-20-B-B-B-B-B	Line
14	(CML395/CML444)DH-3008-B-B-B	Line
15	(CML442*/DTPWC9-F109-2-6-1-1-B)DH-3004-B-B-B	Line
16	(CML202/CML204)DH-3018-B-B-B	Line
17	(CML444*/OFP23)-6-3-1-1-1-B	Line
18	(CML444*/OFP14)-2-2-4-2-2-B	Line
19	(CML444*/OFP14)-3-2-4-1-2-B	Line
20	(CML444*/OFP14)-3-3-1-1-2-B	Line
21	(CML491*/OFP9)-10-2-3-2-2-B	Line
22	(CML491*/OFP106/)-4-1-2-2-1-B	Line
23	(CML495*/OFP9)-1-1-2-2-1-B	Line
24	(CML495*/OFP14)-1-6-1-1-1-B	Line
25	(CML495*/OFP14)-7-1-2-1-2-B	Line
26	(CML495*/OFP14)-7-1-5-1-1-B	Line

4.2.4 Statistical analysis

The data was subjected to ANOVA based on the R-software, AGD-R developed by CIMMYT to estimate both GCA (lines and testers) and SCA for the lines and testers evaluated. Checks used in the experiments were not included. The GCA effects for lines and testers, and the SCA, and their respective interactions were estimated using the model described by Hallauer and Miranda (1988).

$$Y_{ijk} = \mu + g_i + g_j + S_{ij} + e_k + (ge)_{ik} + (ge)_{jk} + (se)_{ijk}$$

Where; Y_{ijk} is the performance of the hybrid made with i^{th} inbred line, and the j^{th} tester, in the k^{th} location; μ is the overall mean; g_i is the effect of the i^{th} inbred line; g_j is the effect of the j^{th} tester; s_{ij} is the interaction of the i^{th} inbred line with the j^{th} tester; e_k is the effect of the k^{th} environment; $(ge)_{ik}$ is the interaction of the g_i and e_k; $(ge)_{jk}$ is the interaction of the g_j and e_k; $(se)_{ijk}$ is the interaction of s_{ij} and e_k

The relative importance of GCA and SCA was computed as a ratio of GCA/SCA. When the ratio is higher than 1, additive effects are more important that dominance effects, and vice versa. The significance of GCA F ratios for both lines and testers per site were determined using line x tester interaction as the error term while the significance of SCA was determined using the error mean square as the error term. Error mean squares calculated for crosses were used to test the significance of GCA and SCA interactions with site (Singh and Choudhary, 1985; Sharma, 1998; Dabholkar, 1999).

4.3 Results

4.3.1 Analysis of variance

Analysis of variance was conducted for single sites and across sites for different management levels for the 15 test environments (Table 4.2). There were highly significant effects ($P < 0.001$) for environments and hybrids across the combined and for separate management levels, except hybrids under random drought stress, which was not significant. There were highly significant ($P < 0.001$) GCA line and tester effects on combined sites, as well as under low N and optimum management levels. Both GCA lines and testers were not significant for random drought stress test environments. Highly significant ($P < 0.001$) SCA effects and G x E interactions were observed on combined, low N and under optimum management levels. The GCA line x E interactions were highly significant across combined and optimum sites, and significant ($P < 0.05$) across low N management levels. GCA tester effects were highly significant ($P < 0.001$)

across combined, low N and optimum management levels. SCA x E interaction was highly significant across all sites ($P < 0.001$) and for optimum sites ($P < 0.01$), and significant ($P < 0.05$) across low N sites. GCA/SCA ratio was larger than 1 across sites, low N and under optimum management levels, and below 1 for the random drought stress sites.

Table 4.2 Mean squares for grain yield (t ha^{-1}) across combined, low N, optimum and random drought stress environments

Source	df	Combined	df	Low N	df	Opt	df	Random
Rep (E)	15	9.96***	6	6.88***	7	7.36***	2	28.26***
Environment	14	1266.86***	5	170.32***	6	400.94***	1	86.67***
Entry (Hybrid)	77	20.98***	77	7.20***	77	18.77***	77	1.05
GCA line	25	27.47***	25	10.36***	25	22.12***	25	0.70
GCA tester	2	125.78***	2	41.25***	2	113.94***	2	0.24
SCA	50	13.54***	50	4.25***	50	13.29***	50	1.26
Entry (Hybrid) x E	1078	1.77***	385	1.35***	462	1.83***	77	0.93
GCA line x E	350	1.90***	125	1.27*	150	2.34***	25	0.54
GCA tester x E	28	5.97***	10	6.34***	12	3.67***	2	0.26
SCA x E	700	1.53***	250	1.19*	300	1.51**	50	1.15
Residuals	1155	1.07***	462	0.97	539	1.20	154	0.89
GCA/SCA ratio		2.23		2.44		1.66		0.56

***$P < 0.001$; **$P < 0.01$, *$P < 0.05$; df degrees of freedom; Low N low Nitrogen stress; E Environment; random random drought stress; GCA general combining ability; SCA specific combining ability; Opt optimum

Table 4.3 shows the GCA and SCA effects at individual test environments. There were highly significant ($P < 0.001$) differences among the hybrids (entries) at all test environments except at Kaguvi and Potchefstroom (random drought stress sites) and at Rattrey Arnold where there were significant differences ($P < 0.05$). Hybrid effects were significant ($P < 0.05$ and $P < 0.01$) also at Kaguvi (random drought) and Lusaka (optimum), respectively. GCA line effects were significant ($P < 0.05$) at Rattrey Arnold Research station and highly significant ($P < 0.001$) at all other test sites except at Cedara and Kaguvi (random drought sites). GCA tester effects were also highly significant for all sites except at Gwebi (low N), Cedara and Kaguvi (random drought) sites. SCA effects were significant ($P < 0.05$) for Cedara (optimum), Gwebi and Harare Low N1 (low N sites), highly significant for low N sites Cedara and Harare low N2, and optimum sites; Gwebi, Ivordale, Mpongwe and Rattrey Arnold Research station. GCA/SCA was larger than 1 at all sites except for optimum site Ivordale (0.88) and random drought stress environments, Kaguvi and Potchefstroom (0.65 and 0.48), respectively.

Table 4.3 Mean squares for grain yield (t ha^{-1}) of late maturity line x tester crosses at 15 individual sites in southern Africa

Source	df	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Rep	1	19.44***	0.03	11.50***	3.15	2.22	22.37***	10.54***	4.77	2.68*	7.74**	0.20	6.12***	53.84***	0.02	4.72***
Entry	77	6.40***	3.43***	2.64***	4.40***	1.12***	2.10***	4.36***	5.13***	0.43	4.18***	4.07***	0.38**	1.56	2.56*	2.96***
GCA lines	25	8.75***	4.06***	4.57***	4.35***	1.42***	2.92***	4.97***	4.12***	0.32	4.93***	6.09***	0.66***	0.92	2.70*	3.36***
GCA testers	2	15.69***	20.68***	9.28***	28.32***	0.64	10.03***	30.16***	28.75***	0.06	11.98***	15.00***	0.13	0.44	11.31***	26.94***
SCA	50	4.85***	2.43**	1.41*	3.48***	0.99*	1.38*	3.03***	4.69***	0.49	3.48***	2.62***	0.26	1.92	2.14	1.79***
Residuals	77	2.08	1.31	0.92	1.19	0.61	0.88	1.21	1.62	0.45	0.93	1.17	0.23	1.33	1.59	0.51
GCA/SCA		1.80	1.67	3.24	1.25	1.43	2.12	1.64	0.88	0.65	1.42	2.32	2.54	0.48	1.26	1.88

***P < 0.001; **P < 0.01, *P < 0.05; df degrees of freedom; L line; T tester; 1 = ART Farm Opt; 2 = Cedara Low N; 3 = Cedara Opt; 4 = Gwebi Opt; 5 = Gwebi Low N; 6 = Harare Low N1; 7 = Harare Low N2; 8 = Ivordale Opt; 9 = Kaguvi Random drought stress;10 = Lusaka Opt; 11 = Mpongwe Opt; 12 = Potchefstroom Low N; 13 = Potchefstroom Random drought stress; 14 = Rattrey Arnold Low N; 15 = Rattrey Arnold Optimum

4.3.2 General combining ability of lines for grain yield

Under combined test environments (Figure 4.1), line 4 recorded the highest GCA effect of 0.32, followed by line 1 (0.27) and line 24 (0.26). A total of 53.84% of the lines had positive GCA across all the test environments, including lines 2, 3, 5, 15, 16, 21, 22, 23, 25 and 26. Lines 7, 9, 13 and 14 recorded the lowest GCA effects for grain yield across combined test environments. A total of 42.3% of the lines showed positive GCA effects across random drought environments. Line15 (0.36**) was the highest combiner and had highly significant ($P < 0.01$) GCA effects for grain yield across random drought stress test environments (Figure 4.2). Lines 1, 2 and 4 had the highest positive GCA effects for grain yield across optimum environments (Figure 4.3). A total of 46.15% of the lines showed positive GCA effects for grain yield across optimum test environments. Under low N test environments (Figure 4.4), lines 1, 2, 3 and 4 recorded positive and significant GCA effects for grain yield. They were among the 50% inbred lines that had positive GCA effects for grain yield, while lines 7 and 14 were among the inbred lines with the lowest GCA effects for grain yield. Lines 7 and 14 had negative and significant GCA effects for grain yield across low N test environments.

4.3.3 General combining ability line effects on agronomic characteristics

Late maturity and taller plants are useful in regions with a prolonged growing season. This means more time for biomass accumulation, and will increase plant and yield productivity. The lines which showed lateness and increased plant stature in this investigation will be preferred. Across combined test environments 15 inbred lines had positive GCA for days to 50% anthesis, including lines 1, 2, 6, 7, 10, 11, 12, 13, 14, 16, 17, 19, 20, 21 and 22 (Table 4.4). Breeding maize tolerant to drought and low N also targets specific regions, and thus also those with negative GCA for days to 50% anthesis will be useful for their earliness. Lines 3, 4, 5, 8, 9, 15, 18, 23, 24, 25 and 26; recorded negative GCA effects for days to 50% anthesis across combined test environments, indicating their importance for earliness. Fifty percent of the inbred lines showed negative GCA for days to 50% anthesis under low N management levels, including lines 3, 23, 25, 26 ($P < 0.001$) and 15 ($P < 0.01$) and lines 1, 4, 5, 8, 9, 13, 18 and 24 at a GCA range of -3.59 to -0.11. Twelve lines showed negative GCA effect for ASI across combined sites, including lines 1, 7, 8, 10, 11, 12, 15, 19, 20, 24, 25 and 26 at a GCA range of -0.48 to -0.0. These inbred lines were desirable for synchronization between anthesis and silking, reducing the effects of barrenness and infertility among hybrids.

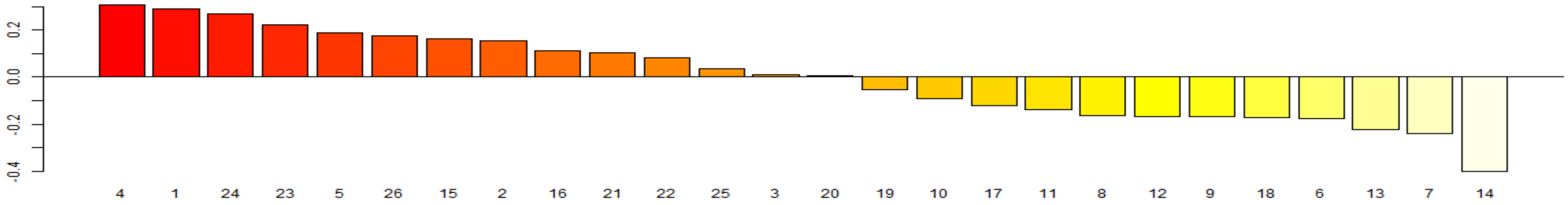

Figure 4.1 General combining ability effects of lines for grain yield across combined test environments for the 26 elite drought and low N stress tolerant maize inbred lines. Increased red (good GCA) and gold-yellow (poor GCA) colour intensity corresponds with the magnitude of GCA effects

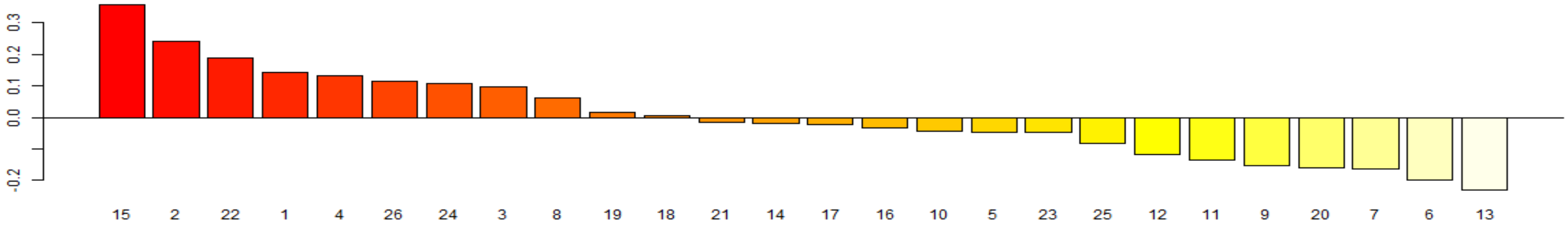

Figure 4.2 General combining ability effects of lines for grain yield across random drought stress environments for 26 drought and low N tolerant maize lines. Increased red (good GCA) and gold-yellow (poor GCA) colour intensity corresponds with the magnitude of GCA effects

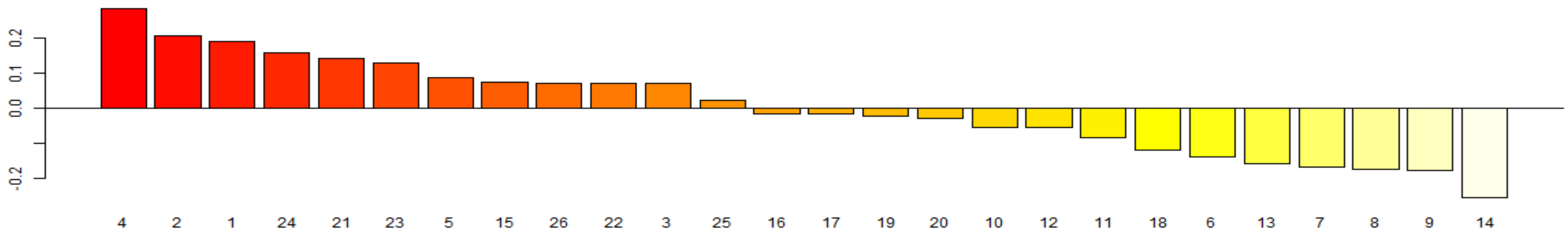

Figure 4.3 General combining ability effects of lines for grain yield across optimum test environments for 26 drought and low N stress tolerant maize inbred lines. Increased red (good GCA) and gold-yellow (poor GCA) colour intensity corresponds with the magnitude of GCA effects

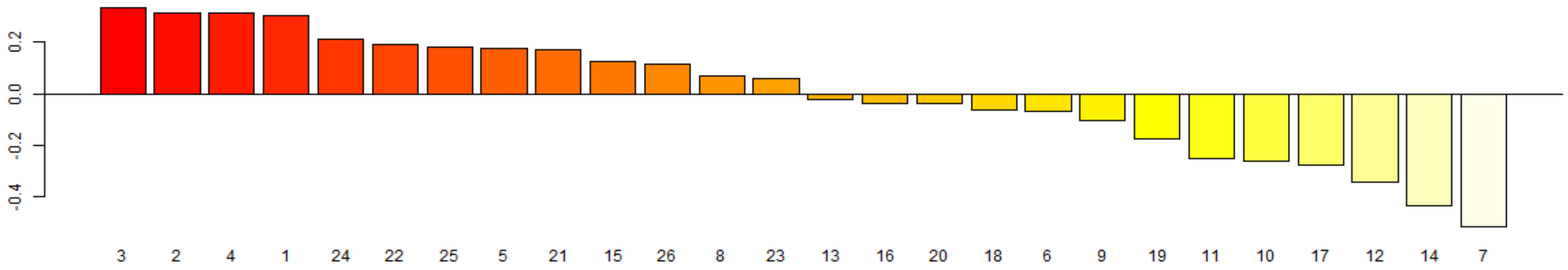

Figure 4.4 General combining ability effects of lines for grain yield across low N test environments for 26 drought and low N stress tolerant maize inbred lines. Increased red (good GCA) and gold-yellow (poor GCA) colour intensity corresponds with the magnitude of GCA effects

Across drought and low N conditions, lines 1, 3, 7, 8, 10, 15, 20 and 24 had negative GCA indicating their potential usefulness under these stress conditions (Table 4.4). Apart from these, lines 5, 11, 12, 17 and 19 were important under low N conditions while lines 2, 13, 21 and 26 were important under random drought conditions. Six lines had consistent negative GCA values across all the test environments, including the combined 15 test environments.

Lines 1, 4, 5, 7, 9, 10, 12, 17, 20, 21, 22, 23 and 24 showed positive GCA for plant stature across the combined test environments (Table 4.4). Lines 1, 4, 7, 9, 20, 21, 23 and 24 consistently showed positive GCA for plant height across combined test environments and across different management levels. Lines 2, 3, 6, 8, 11, 13, 14, 15, 16, 19, 25 and 26, had negative GCA effects for plant height, indicating their usefulness for reduced plant stature across drought-prone regions. Short and early maturity characteristics are important for drought escape mechanisms in regions characterised by mid-season droughts.

Results for combined test environments indicated that lines 1, 5, 13 and 24 showed positive and significant GCA effects for prolificacy, while lines 6, 7, 9, 12 and 14 showed negative and significant GCA effects for the same trait (Table 4.5). Fifteen lines showed positive GCA effects for ear height, and among these, lines 4, 7 and 16 were significant. Lines 26, 25, 23 and 3 were negative and significant for ear height. Lines 1, 10, 11, 16, 18, 19 and 21 showed positive and significant GCA for ear position. Lines 3, 23, 24, 25 and 26 had negative and significant GCA effects for this trait across the combined test environments. Lines 12 and 14 had positive and significant GCA effects for stalk and root lodging, respectively. Lines 2, 4, 11, 15 and 19 showed positive and highly significant GCA effects for grain texture. Out of the 16 lines that were negative for grain texture, lines 8, 16, 21 and 22 were highly significant. Fifty percent of the lines showed negative GCA effects for ear aspect, with lines 2 and 4 being the only significant ones. Two lines 13 and 19 had positive and significant GCA for ear aspect. GCA for senescence was significant for lines 24 (negative) and 16 (positive). For disease reactions, PS, GLS, ET and ear rot, line 2 had negative and significant GCA effects for GLS and ET; line 4, 15 and 21 for GLS. Lines 11, 12 and 13 had positive and significant GCA effects for ET.

.

Table 4.4 General combining ability effects on earliness, synchronization and tallness of 26 elite maize inbred lines under different management levels

	Combined			Low N			Optimum			Random drought	
Line	AD	ASI	PH	AD	ASI	PH	AD	ASI	PH	AD	ASI
1	0.16	-0.48**	2.82	-0.11	-0.62**	1.00	0.01	-0.33**	1.38	-0.11	-0.13
2	0.72	0.30	-2.06	0.21	0.50*	-0.45	0.48	0.38**	0.63	-0.11	-0.01
3	-3.03***	0.00	-4.35*	-3.59***	-0.06	-1.51	-2.33***	0.14	-3.03	-1.28	-0.01
4	-1.01	0.30	4.95*	-0.88	0.34	3.44	-0.98*	0.32*	4.84*	-0.39	0.05
5	-0.93	0.02	0.09	-0.81	-0.15	1.73	-0.89	-0.13	-0.68	-0.42	0.02
6	0.57	0.34	-2.51	1.06*	0.35	0.54	0.52	0.16	-1.45	0.32	0.11
7	1.75***	-0.24	5.40**	1.81***	-0.21	2.60	1.52***	-0.11	4.48*	0.73	-0.07
8	-0.77	-0.16	-1.04	-0.78	-0.31	-0.96	0.03	-0.08	-1.61	-1.49*	-0.08
9	-0.08	0.28	3.21	-0.35	0.43	2.38	0.06	0.13	1.21	-0.35	0.06
10	1.00	-0.10	1.27	1.40**	-0.24	-1.75	1.00*	-0.07	0.20	0.30	-0.05
11	1.20*	-0.06	-3.99	1.82***	-0.01	-1.88	0.66	0.01	-2.87	0.74	0.01
12	2.17***	-0.07	1.58	2.38***	-0.45	0.40	1.89***	-0.26*	1.23	0.96	0.03
13	0.14	0.03	-2.34	-0.67	0.17	-1.43	0.01	0.21	-2.12	0.21	-0.02
14	1.00	0.00	-2.28	1.14*	0.22	-1.08	0.62	0.12	-3.53	0.68	0.00
15	-1.06	-0.01	-2.08	-1.45**	-0.12	-0.98	-0.89	0.08	-1.98	-0.84	-0.02
16	0.56	0.20	-0.05	0.76	0.30	2.06	0.60	0.02	1.87	0.43	0.05
17	0.08	0.11	2.29	0.79	-0.05	2.57	0.17	-0.05	1.83	0.05	0.06
18	-0.55	0.26	-5.95**	-0.74	0.40	-3.67	-0.62	0.28*	-6.62***	-0.28	0.05
19	1.33**	-0.07	-0.28	1.78***	-0.50*	-2.16	0.93*	-0.24	0.47	0.27	0.04
20	1.54**	-0.27	1.31	2.37***	-0.38	0.04	1.07*	-0.33*	0.70	1.33	-0.06
21	0.61	0.10	2.94	0.87	0.33	0.60	0.45	0.31*	1.89	0.52	-0.01
22	0.95	0.05	0.67	0.17	0.13	-0.12	0.55	0.25	0.26	0.33	0.00
23	-2.20***	0.10	3.76	-2.47***	0.19	1.27	-1.41***	0.00	3.67	-0.84	0.04
24	-0.5	-0.44**	3.36	-0.70	-0.31	0.61	-0.65	-0.49***	3.38	0.46	-0.07
25	-2.09***	-0.02	-1.98	-2.00***	0.01	-0.43	-1.70***	-0.02	-2.14	-0.55	0.01
26	-1.55***	-0.18	-4.73*	-2.01***	0.06	-2.81	-1.12**	-0.30*	-2.01	-0.69	-0.01

***P < 0.001; **P < 0.01, *P < 0.05; AD days to 50% anthesis; ASI anthesis silking date; PH plant height (cm)

Table 4.5 General combining ability effects of lines for agronomic characteristics and disease reaction for 26 maize inbred lines across 15 test environments

Line	EPP	EH	EPO	RL	SL	TEX	EA	HC	SEN	PS	GLS	ET	ER
1	0.10***	2.64	0.01*	1.46	-1.53	-0.06	0.05	0.13	0.01	0.02	-0.06	-0.06	-0.17
2	0.00	1.39	0.01	0.20	-0.02	0.55***	-0.16*	-0.19	0.03	0.00	-0.15**	-0.12**	-0.26
3	0.02	-3.04*	-0.01*	0.22	0.49	0.10	-0.14	0.14	0.13	-0.02	-0.04	-0.05	0.68
4	-0.01	3.84**	0.00	0.38	-0.44	0.39***	-0.22**	0.03	-0.03	-0.02	-0.14*	-0.07	0.03
5	0.06***	-0.53	0.00	-0.98	-1.54	-0.17	0.07	0.03	-0.03	0.01	-0.03	0.04	0.4
6	-0.04*	-1.57	-0.01	0.14	0.85	-0.08	-0.08	-0.05	0.1	-0.05	-0.03	0.01	-0.37
7	-0.09***	2.85*	0.00	-0.01	1.53	0.02	0.10	-0.15	0.06	0.06	0.03	0.01	0.67
8	0.00	1.12	0.01	0.30	-0.45	-0.35**	-0.04	-0.29	0.05	-0.02	0.00	0.02	-0.27
9	-0.06***	0.96	0.00	-0.45	0.37	-0.16	-0.01	-0.04	-0.17	0.03	0.00	0.08	-0.89
10	-0.04	2.24	0.01***	-0.15	-1.25	0.10	-0.06	-0.11	0.03	0.03	-0.02	0.00	-0.39
11	-0.03	1.59	0.02***	-0.96	0.93	0.32**	0.05	-0.01	0.02	0.01	0.07	0.11*	0.46
12	-0.05**	1.36	0.01	0.37	2.16*	-0.01	0.02	-0.11	0.05	0.02	-0.01	0.12**	0.48
13	0.07***	-1.67	0.00	-0.25	-1.18	-0.02	0.17*	0.20	0.00	-0.03	-0.06	0.15***	0.52
14	-0.04*	-0.63	0.01	2.68***	1.63	-0.18	0.12	-0.08	0.14	-0.04	-0.06	0.07	0.34
15	0.00	-1.16	0.00	1.16	1.53	0.48***	-0.01	0.13	-0.01	-0.06	-0.13*	-0.03	-0.09
16	0.01	3.03*	0.01*	-0.06	0.12	-0.40***	-0.06	-0.06	0.21*	-0.04	0.08	-0.06	0.04
17	-0.02	0.91	0.00	0.28	0.76	-0.10	0.05	-0.07	0.12	-0.03	0.23***	0.02	0.69
18	-0.02	-2.68	0.01**	0.26	-1.14	-0.07	-0.03	-0.02	0.04	0.05	0.07	-0.07	-0.25
19	0.01	1.02	0.01**	-0.80	0.42	0.78***	0.16*	0.05	0.04	-0.01	0.10	0.02	0.19
20	-0.03	0.27	0.00	-0.13	1.71	0.02	0.09	0.29	-0.04	0.03	0.09	0.04	-0.08
21	0.03	2.82	0.01*	-0.62	-1.40	-0.44***	-0.09	0.17	-0.1	-0.02	-0.05	-0.10*	-0.26
22	0.03	0.21	0.00	-0.79	-0.05	-0.67***	-0.10	0.02	-0.04	-0.06	0.00	-0.09	0.30
23	0.02	-3.27*	-0.03***	-0.17	-1.16	-0.03	-0.01	-0.12	-0.13	-0.04	0.01	-0.01	-0.50
24	0.04*	-2.80	-0.02***	-0.59	-0.74	-0.10	0.04	0.22	-0.25**	0.06	0.07	0.05	-0.47
25	0.01	-3.85**	-0.02***	-1.29	-0.81	-0.08	0.04	0.01	-0.07	0.03	0.00	-0.04	-0.39
26	0.03	-5.07***	-0.02***	-0.21	-0.81	0.15	0.05	-0.13	-0.14	0.08	0.02	-0.04	-0.39

***P < 0.001; **P < 0.01, *P < 0.05; EPP number of ears per plant; EH ear height; EPO ear position; RL root lodging; SL Stalk lodging; TEX texture; EA ear aspect;; HC husk cover; SEN senescence; PS *Puccinia sorghi;* GLS Grey leaf spot; ET *Exserohilum turcicum*; ER ear rot

4.3.4 The GCA tester effects across the test environments

Table 4.6 presents the GCA effects of testers across all test environments. Two testers had positive GCA for grain yield; tester 3 and tester 4. Tester 1 had negative and significant GCA for grain yield across the combined test environments. Three testers (2, 3 and 4) showed positive GCA for days to 50% anthesis. Line 6 had negative and significant GCA and line 5 also had negative and highly significant GCA for days to 50% anthesis across the 15 test sites. Lines 1 and 5 had negative and highly significant GCA for plant stature; while lines 4 and 3 had positive and significant GCA. Line 5 showed negative and significant GCA for GLS and ET indicating their significance in reducing disease susceptibility. Line 2 showed positive and highly significant GCA for root lodging, indicating its proneness to root lodging.

4.3.5 Specific combining ability effects

A total of 60.53% of the hybrids had positive SCA effects for grain yield across the combined test environments (Table 4.7). The following hybrids had positive SCA effects for grain yield; L5 x T1, L1 x T1, L19 x T4, L3 x T2, L4 x T2, L1 x T2, and L20 x T4. Twenty-three hybrids had positive and significant ($P < 0.05$) SCA effects ranging between 0.54 and 0.73; including crosses L10 x T4; L4 x T1; L2 x T1; L13 x T2; L11 x T4; L5 x T2; L3 x T1; L4 x T6; L1 x T6; L19 x T5; L12 x T3; L2 x T2; L7 x T3; L17 x T5; L10 x T5; L19 x T3; L12 x T5; L20 x T3; L7 x T5; L20 x T5; L22 x T1; L16 x T2 and L6 x T6. Cross 13 x 5 had the lowest SCA effect for grain yield, followed by crosses 12 x 2; 3 x 5; 20 x 1; 7 x 2 and 10 x 1.

Table 4.6 General combining ability effects of testers for grain yield, agronomic characteristics, and disease reactions for six testers across 15 test environments

Tester	GY	AD	ASI	EH	PH	EPO	EPP	TEX	EA	HC	RL	SL	PS	GLS	ET	ER
1	-0.27*	-0.21	-0.31***	-0.07	-5.64***	0.01***	0.01	-0.04	0.16*	-0.22	0.41	0.24	0.02	0.02	0.11***	-0.19
2	-0.16	1.81***	-0.05	3.06***	0.84	0.01***	-0.02*	0.06	-0.05	-0.12	0.05	4.14***	0.01	0.01	0.05	0.08
3	0.19	0.48	0.05	3.20***	3.26*	0.01*	0.01	0.03	-0.06	-0.25	0.32	2.07	-0.01	0.07*	-0.03	0.13
4	0.35**	0.02	-0.06	0.20	6.07***	-0.01***	0.01	-0.06	-0.16*	-0.10	-0.60	-2.50*	-0.01	-0.05	-0.04	-0.70
5	-0.01	-1.48***	0.40***	-5.65***	-3.88**	-0.02***	0.00	0.10	0.09	0.88***	-0.15	-1.80	-0.02	-0.08**	-0.07*	0.77
6	-0.10	-0.62*	-0.03	-0.74	-0.66	0.00	-0.02	-0.09	0.02	-0.19	-0.03	-2.15	0.02	0.03	-0.02	-0.09

***P < 0.001; **P < 0.01, *P < 0.05; GY grain yield; AD anthesis date; ASI anthesis silking interval; EH ear height; PH plant height; EPO ear position; EPP number of ears per plant; TEX texture; EA ear aspect;; HC husk cover; RL root lodging; SL Stalk lodging; PS *Puccinia sorghi;* GLS Grey leaf spot; ET *Exserohilum turcicum*; ER ear rot.

Table 4.7 Specific combining ability effects for grain yield across combined test environments

	Lines												
Tester	1	2	3	4	5	6	7	8	9	10	11	12	13
1	0.83***	0.68*	0.65*	0.72**	0.87***	0.17	-0.90	0.31	0.07	-1.15	-1.07	-0.81	0.46
2	0.77**	0.61*	0.80***	0.78**	0.66*	-0.60	-1.27	-0.63	-0.41	-0.56	-0.58	-1.43	0.68*
3	-0.01	0.24	0.19	0.37	0.16	-1.09	0.60*	-0.62	-0.91	0.37	0.07	0.62*	0.28
4	-1.13	0.20	0.28	0.33	-0.50	0.07	-0.03	0.16	0.09	0.73*	0.67*	0.44	-0.46
5	0.46	-0.39	-1.29	-0.94	-	0.03	0.58*	0.01	-0.36	0.59*	0.44	0.59*	-1.94*
6	0.63*	0.31	0.32	0.65*	-0.57	0.54*	-0.76	0.13	0.42	-0.58	-0.46	-0.36	0.04
Tester	14	15	16	17	18	19	20	21	22	23	24	25	26
1	-0.52	0.40	0.25	-1.00	-0.81	-1.14	-1.28***	0.43	0.55*	0.23	0.34	0.08	0.07
2	-0.86	0.45	0.55*	-0.33	-0.35	-0.51	-0.96	0.53	0.44	0.13	0.27	0.54	0.34*
3	-0.53	-0.11	-0.51	0.35	0.46	0.59*	0.59*	-	-0.01	-0.19	0.09	0.11	0.02
4	0.29	-0.39	-0.32	0.46	-0.03	0.81***	0.74**	0.09	-0.15	-0.11*	0.15	-0.24	-0.13*
5	-	-	-0.22	0.60*	0.45	0.62*	0.58*	-0.35	-0.16	0.20	0.11	0.03	0.30
6	-0.35	0.46	0.09	-0.66	-0.35	-0.78	-	0.22	0.09	0.42	0.17	-0.15	-0.03

***P < 0.001; **P < 0.01, *P < 0.05

4.3.6 Grain yield characteristics across all test environments and management levels

Consistently higher yields were observed across optimum test environments with yields ranging between 5.01 and 9.29 t ha^{-1} with a mean of 7.48 t ha^{-1} (Table 4.8). The combined test environments recorded yield averages between 3.04-6.08 t ha^{-1} with a mean of 4.86 t ha^{-1}. Low N test environments recorded 60.58% lower yields than the optimum test environments with mean yields ranging between 1.09-4.26 t ha^{-1} and a mean of 2.95 t ha^{-1}. However, random drought stress test environments were the most affected, with 79.55% lower yields compared to the optimum sites with a mean yields for hybrids ranging between 0.56 to 2.77 t ha^{-1} and an average of 1.53 t ha^{-1}. The cross L19 x T4 recorded the highest mean yields across combined test environments (6.08 t ha^{-1}), followed by L20 x T4 (6.04 t ha^{-1}); L4 x T4 (5.99 t ha^{-1}) and L11 x T4 (5.91 t ha^{-1}). Lowest observed yields were for L12 x T2 (3.04 t ha^{-1}); L7 x T2 (3.11 t ha^{-1}) and L20 x T1 (3.19 t ha^{-1}). Under optimum test environments, crosses L19 x T4 and L4 x T2 (both with 9.29 t ha^{-1}); L14 x T4 (9.26 t ha^{-1}); L11 x T4 (9.18 t ha^{-1}) and L20 x T4 (8.93 t ha^{-1}) were among the highest yielding hybrids. Across low N test environments, crosses L20 x T4 (4.26 t ha^{-1}); L21 x T4 (4.18 t ha^{-1}); L2 x T1 (4.06 t ha^{-1}) and L3 x T4; L4 x T1 (4.03 t ha^{-1}) were among the highest yielders, while L7 x T2 (1.21 t ha^{-1}) and L12 x T2 (1.09 t ha^{-1}) were among the lowest. Grain yields under random drought stress were the lowest, with the highest yielding crosses L4 x T2 (2.77 t ha^{-1}); L8 x T4 (2.43 t ha^{-1}); L11 x T1 (2.44) and L14 x T2 (2.38 t ha^{-1}) while among the lowest were crosses L8 x T2 (0.56 t ha^{-1}); L23 x T2 (0.64 t ha^{-1}) and L9 x T1 (0.71 t ha^{-1}).

Table 4.8 Line x tester mean grain yield (t ha^{-1}) across management levels

L x T	Combined	Random drought	Low N	Opt	L x T	Combined	Random drought	Low N	Opt	L x T	Combined	Random drought	Low N	Opt
19 x 4	6.08	1.72	3.79	9.29	13 x 2	5.33	2.14	3.10	8.15	17 x 2	4.41	1.45	2.28	7.08
4 x 2	5.87	2.77	2.91	9.29	22 x 2	5.31	2.07	3.12	8.12	6 x 1	4.67	1.08	3.08	7.07
4 x 4	5.99	1.15	3.80	9.26	21 x 4	5.66	1.56	4.18	8.11	26 x 1	4.69	1.64	2.98	7.04
11 x 4	5.91	1.51	3.57	9.18	25 x 2	5.48	1.18	3.86	8.11	9 x 1	4.45	0.71	2.71	7.01
20 x 4	6.04	1.31	4.26	8.93	15 x 2	5.36	2.22	3.28	8.04	13 x 4	4.54	0.76	3.22	6.76
1 x 1	5.90	1.53	3.87	8.88	2 x 1	5.67	2.32	4.06	8.02	19 x 2	4.18	1.68	2.06	6.71
1 x 2	5.87	1.63	3.80	8.85	24 x 2	5.21	1.93	3.09	7.96	9 x 2	4.20	1.20	2.38	6.62
17 x 4	5.63	2.03	3.08	8.84	22 x 1	5.38	2.20	3.48	7.92	18 x 2	4.29	1.34	2.65	6.54
4 x 1	5.80	0.77	4.03	8.76	14 x 4	5.23	1.34	3.43	7.88	1 x 4	4.35	1.90	2.67	6.48
21 x 2	5.50	0.98	3.28	8.68	9 x 4	5.11	1.17	3.18	7.88	11 x 2	4.03	0.79	2.27	6.46
5 x 1	5.73	1.50	3.83	8.57	15 x 4	5.09	1.27	3.15	7.86	10 x 2	4.03	1.10	2.27	6.38
21 x 1	5.33	1.89	2.68	8.57	15 x 1	5.19	2.03	3.12	7.86	8 x 2	3.93	0.56	2.22	6.36
3 x 2	5.74	2.22	3.65	8.53	16 x 4	4.77	0.91	2.59	7.74	6 x 2	3.95	1.19	2.26	6.20
2 x 4	5.75	2.04	3.79	8.50	23 x 2	5.02	0.64	3.32	7.72	12 x 1	3.67	1.34	1.77	5.97
3 x 4	5.67	2.12	3.55	8.50	22 x 4	5.07	1.55	3.16	7.72	14 x 1	3.79	1.45	2.06	5.94
10 x 4	5.54	1.45	3.47	8.49	6 x 4	5.12	1.35	3.37	7.71	20x 2	3.80	2.35	1.78	5.94
12 x 4	5.43	1.24	3.26	8.49	26 x 2	5.21	2.10	3.37	7.69	14 x 2	3.62	2.38	1.52	5.78
2 x 2	5.59	1.75	3.60	8.39	13 x 1	5.05	0.97	3.34	7.68	18 x 1	3.64	1.12	2.20	5.60
23x 4	5.32	2.00	2.87	8.36	18 x 4	5.30	2.36	3.52	7.67	7 x 1	3.33	1.30	1.47	5.51
7 x 4	4.97	0.95	2.43	8.31	23 x 1	4.87	1.54	2.81	7.58	17 x 1	3.34	1.23	1.60	5.44
24 x 4	5.60	1.35	3.88	8.30	8 x 4	5.27	2.45	3.56	7.54	11 x 1	3.34	2.44	1.34	5.32
24 x 1	5.19	1.07	2.95	8.28	5 x 4	4.91	1.37	3.18	7.40	12 x 2	3.04	1.12	1.09	5.27
16 x 2	5.24	0.89	3.18	8.24	25 x 4	4.95	1.29	3.35	7.38	20 x 1	3.19	0.84	1.63	5.20
5 x 2	5.60	1.98	3.75	8.23	8 x 1	4.89	1.83	3.04	7.35	7 x 2	3.11	1.55	1.21	5.19
3 x 4	5.63	1.46	4.03	8.20	16 x 1	4.80	2.21	2.70	7.34	19 x 1	3.27	1.05	1.83	5.13
26 x 4	5.27	1.04	3.32	8.15	25 x 1	4.73	2.05	2.72	7.22	10 x 1	3.27	1.38	1.87	5.01

L x T line x tester; opt optimum

4.3.7 Estimation of variances for characteristics across and at individual test environments

Variances due to lines were higher than variances due to testers for days to 50% anthesis, ASI, ear rot, GLS, root lodging and grain texture (Table 4.9). The effects of lines and testers were the same for *ET* and grain yield, which had variances due to lines being equal to variances due to testers. Variances due to line x tester were less than those due to both variances due to lines and due to testers all traits except ear rots, GLS, grain yield, husk cover, plant height; for days to 50% anthesis, ET*,* root lodging and grain texture and were higher for ASI, ear height, ear rot, grain yield, husk cover, plant height and ear aspect. Variances due to additive gene action were consistently higher than those for dominance effects for all the characteristics. Variances due to the environment were all lower than both additive and dominance effects for most characteristics. Variances due to lines were higher than variances due to testers at most sites with the exceptions of Gwebi, Lusaka, Ivordale and Rattrey Arnorld Research Station (all optimum test environments). Line x tester variances were higher than variances due to both lines and testers for grain yield for all test environments, except at Potchefstroom under low N stress. Additive effects were, however, higher than dominance effects across all the test localities. Heritability for grain yield was high across all the test environments used in this study. Narrow sense heritability estimates for grain yield were also high across all combined test environments with the ear aspect ($h^2 = 0.41$) being the lowest while days to 50% anthesis had the highest ($h^2 = 0.85$). Narrow sense heritability estimates were higher for low N stressed sites, and lowest for random drought stress environments.

4.3.8 Estimation of variance components and heritability estimates based on the management level

Line, tester and line x tester variances were very low for most of the recorded characteristics, and in most cases was zero (Table 4.10). In most instances, environmental variances were larger than genotype variances. For grain yield, additive variance was higher than dominance variance at all management levels. Broad sense heritability estimates for grain yield were high across low N and optimum environments, while it was mostly zero under random drought stress. Narrow sense heritability ranged between 0 and 58% for grain yield. For days to 50% anthesis, dominance variance was zero, leading to broad sense and narrow sense heritability estimates being the same ranging between 0 (optimum and random drought) and 0.26 at low N environments.

Table 4.9 Estimation of variance components and heritability estimates for measured characteristics across, and at individual test environments

Trait	Line variance	Tester variance	L x T variance	Gen. variance	Additive variance	Dom. variance	Env. variance	H^2	h^2
AD	1.76	1.27	0.52	3.29	13.17	2.09	0.18	0.99	0.85
ASI	0.11	0.06	0.02	0.18	0.70	0.06	0.08	0.90	0.83
EH	7.74	11.13	8.84	25.30	101.20	35.35	3.97	0.97	0.72
EPO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.96	0.89
EPP	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.95	0.75
ER	0.57	0.39	0.98	1.87	7.48	3.92	2.12	0.84	0.55
ET	0.01	0.01	0.00	0.01	0.05	0.00	0.01	0.86	0.84
GLS	0.01	0.00	0.01	0.02	0.07	0.02	0.01	0.92	0.71
GY	0.07	0.07	0.41	0.53	2.14	1.64	0.05	0.99	0.56
HC	0.07	0.24	0.26	0.48	1.93	1.06	0.35	0.90	0.58
PH	9.38	20.64	26.53	53.47	213.88	106.14	5.64	0.98	0.66
SL	2.38	8.49	3.31	10.89	43.58	13.24	4.35	0.93	0.71
EA	0.01	0.01	0.03	0.05	0.21	0.11	0.20	0.61	0.41
RL	1.47	0.28	0.31	1.69	6.75	1.23	3.64	0.69	0.58
Tex	0.11	0.01	0.06	0.18	0.71	0.24	0.28	0.77	0.57
Site					Yield				
ART Farm Opt	0.36	0.17	1.10	1.62	6.5	4.42	0.71	0.94	0.56
Cedara low N	0.17	0.14	0.68	0.97	3.9	2.71	0.41	0.94	0.56
Cedara Opt	0.23	0.15	0.57	0.93	3.72	2.28	0.27	0.96	0.59
Gwebi Opt	0.16	0.19	0.84	1.15	4.58	3.34	0.63	0.93	0.54
Gwebi low N	0.05	0.00	0.17	0.22	0.89	0.68	0.21	0.88	0.50
Harare low N1	0.15	0.10	0.18	0.41	1.63	0.72	0.26	0.90	0.62
Harare low N2	0.17	0.17	0.86	1.17	4.68	3.45	0.24	0.97	0.56
Ivordale Opt	0.10	0.36	0.95	1.34	5.37	3.78	0.83	0.92	0.54
Kaguvi random	0.01	0.00	0.04	0.06	0.23	0.17	0.06	0.86	0.49
Lusaka Opt	0.03	0.06	1.09	1.17	4.67	4.36	0.46	0.95	0.49
Mpongwe Opt	0.40	0.32	1.00	1.66	6.63	4.01	0.53	0.95	0.59
Potch low N	0.04	0.00	0.02	0.06	0.25	0.08	0.07	0.82	0.61
Potch random	0.06	0.00	0.12	0.18	0.71	0.46	0.34	0.78	0.47
Rattrey low N	0.13	0.06	0.19	0.37	1.47	0.77	0.42	0.84	0.55
Rattrey Opt	0.17	0.24	0.85	1.23	4.91	3.42	0.15	0.98	0.58

L x T line x tester, Gen variance genotypic variance; Dom variance dominance variance; Env variance environmental variance; H^2 broad sense heritability; h^2 narrow sense heritability; Opt optimum; random random drought stress; AD anthesis date; ASI anthesis silking interval; EH ear height; EPO ear position; EPP number of ears per plant; ER ear rot; ET *Exserohilum turcicum*; GLS Grey leaf spot; GY grain yield; HC husk cover; PH plant height; PS *Puccinia sorghi;* SL Stalk lodging; EA ear aspect; RL root lodging; TEX texture;

Anthesis silking interval also had low heritability estimates (0-0.28). Analysis based on all experimental data showed that ear aspect had high broad sense and narrow sense heritability estimates across all management levels. Broad sense heritability was high for grain yield across low N and optimum conditions, while zero under random drought conditions. Narrow sense heritability for grain yield was also moderate under both low N (0.40) and optimum conditions (0.43). Dominance variance for days to 50% anthesis, ASI, the number of ears per plant was zero, leading to the same broad sense and narrow sense heritability estimates. Ear height had lower heritability estimates (< 50%) across the management levels. Ear aspect had high broad sense heritability estimates across both optimum and random drought stress sites. Narrow sense heritability estimates was also higher under optimum conditions. Higher heritability estimates indicate that selection can be done under these smanagement levels during early stages of development as they are not affected by environmental variations.

Table 4.10 Variance components and heritability estimates for grain yield and agronomic characteristics at different management levels

	SITE	Line Variance	Tester Variance	L x T Variance	Gen. Variance	Add. Variance	Dom. Variance	Env. Variance	H^2	h^2
GY	LN	0.08	0.05	0.15	0.27	1.07	0.60	1.02	0.62	0.40
	Opt	0.10	0.15	0.61	0.83	3.33	2.43	1.96	0.75	0.43
	RS	0.02	0.00	0.00	0.00	0.00	0.00	0.59	0.00	0.00
AD	LN	2.23	1.60	0.00	1.63	6.51	0.00	18.27	0.26	0.26
	Opt	0.44	0.96	0.00	0.00	0.00	0.00	41.23	0.00	0.00
	RS	0.00	0.54	0.00	0.00	0.00	0.00	23.76	0.00	0.00
ASI	LN	0.18	0.09	0.00	0.15	0.58	0.00	2.44	0.19	0.19
	Opt	0.07	0.02	0.00	0.07	0.30	0.00	0.77	0.28	0.28
	RS	0.00	0.18	0.00	0.00	0.00	0.00	4.71	0.00	0.00
EPP	LN	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.48	0.43
	Opt	0.00	0.00	0.00	0.00	0.02	0.00	0.01	0.54	0.54
	RS	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.00	0.00
PH	LN	1.78	23.91	0.00	0.00	0.00	0.00	552.14	0.00	0.00
	Opt	13.12	27.39	19.19	54.44	217.76	76.75	180.74	0.62	0.46
	RS	18.31	10.81	0.00	27.50	110.02	0.00	84.74	0.56	0.56
EH	LN	8.59	7.22	0.00	4.43	17.70	0.00	214.45	0.08	0.08
	Opt	11.36	19.29	0.97	26.68	106.70	3.87	148.38	0.43	0.41
	RS	1.43	0.00	2.85	4.22	16.86	11.40	34.59	0.45	0.27
EA	LN	0.02	0.02	0.00	0.04	0.16	0.01	0.25	0.41	0.38
	Opt	0.02	0.02	0.04	0.08	0.31	0.17	0.05	0.91	0.58
	RS	0.00	0.01	0.07	0.08	0.31	0.30	0.10	0.86	0.44

L x T line x tester; Gen genotype; Add additive; Dom dominance; Env environment; H^2 broad sense heritability; h^2 narrow sense heritability; GY grain yield, AD days to 50% anthesis; ASI anthesis-silking interval; EPP number of ears per plant; PH plant height; EH ear height; EPO ear position; EA ear aspect; LN low N; Opt Optimum environment; RS random drought stress;

4.4 Discussion

Breeding for combined drought and low N stress tolerant hybrids is an integral component of wider efforts aimed at increasing maize productivity in changing environments in the face of climate change, which is expected to have adverse effects on cropping systems. Characterisation of lines developed for these objectives is a requirement for the success of hybrid programmes aimed at reducing the compound effects of drought and low N fertility. The knowledge of germplasm and target environments is vital for the success of hybrid development programmes. This study was conducted to identify the best combiners out of the selected drought and low N tolerant maize inbred lines developed by CIMMYT, across optimum, low N and random drought stress environments.

There was large variability in performance of the selected inbred lines and testers, and large variability in test environments. This indicated the uniqueness of the test environments, and large potential variability among the inbred lines and testers that allows for selection for improvement of different characteristics (Badu-Apraku et al., 2011; 2016; Akinwale et al., 2014). The observed line and tester GCA for combined test sites and across low N and under optimum test environments indicates the potential of these inbred lines in hybrid development for optimum and low N stress environments. The significant GCA and SCA interactions with the environment indicate the relative changes in the combining ability effects across management levels. Betrán et al. (2003) and Gissa (2008) reported large variability among maize hybrids developed for drought and low N stress environments.

The GCA/SCA ratios across the combined test localities and across optimum and low N stress environments were larger than unity for yield indicating the predominance of additive gene action for grain yield. However, GCA/SCA ratios for grain yield across random drought stress environments were less than one, indicating the importance of non-additive gene action. Analysis of variance at individual localities indicated large variability in the response of hybrids (entries) at all sites for grain yield except at Gwebi and Potchefstroom (random drought stress) environments.

Makumbi et al. (2011) reported the importance of additive gene effects for grain yield under stress and non-stress environments. Derera et al. (2008) reported that non-additive gene action was more important under drought stress environments, results that agree with the findings of the current research. Significant GCA and SCA variances indicate the importance of both additive and non-additive gene action in the expression and control of a given trait. Mutimaamba (2015) also reported both additive and non-additive gene action in the control and expression of grain yield. From this investigation, it can be concluded that both additive and non-additive gene action are important for grain yield across optimum, low N and random drought stress environments. The knowledge of gene action for the selected inbred lines and testers is vital for the formulation of breeding programmes whose objective is to develop hybrids suitable for optimum, low N and random drought stress environments.

Lines 4, 2, 1, 21, 3, 21, 15, 22, 23, 5, 26 and 25 showed positive GCA effects for grain yield across all the environments, and can be successfully utilized as potential sources for hybrid breeding programmes across optimum, low N and random stress environments, or in areas where drought and low N stress is prevalent. Lines that can be of potential value across random drought stress environments include lines 15, 2, 22, 1, 4, 26, 24, 3, 8, 19 and 18 as they recorded positive GCA effects for grain yield under these conditions. Lines 3, 2, 4, 1, 24, 22, 25, 5, 21, 15, 26, 8 and 23 had positive GCA for grain yield across low N environments and can potentially be utilized as genetic sources for hybridization targeting these environments. Breeding for drought and low N tolerance has been a major breeding goal for scientists at CIMMYT, and they have developed several varieties with good tolerance to stress and non-stress environments. However, since the changing climate is becoming more of a problem, rainfall patterns, distribution, intensity and occurrence are all unpredictable, and continued research into better drought and low N resilience will remain a key objective.

For late maturity selection, lines that showed late maturity characteristics included; 1, 2, 6, 7, 10, 11, 12, 13, 14, 16, 17, 19, 21 and 22. Late maturing varieties tend to produce more biomass than their counterparts, and in regions with a prolonged rainy season, they have a large yield advantage. However due to the shorter rainy seasons in most parts of SSA, the lines which show earliness can also help to escape mid-season droughts, hence can be useful for hybrid breeding programmes targeting environments where droughts occur more randomly. Lines 1, 4, 5, 7, 9, 10, 12, 17, 20, 21, 23 and 24 showed increased plant stature. Shorter plants can be of importance in random drought stress environments. Prolificacy can also be used as a secondary trait for selection across stress and non-stress environments (Mhike et al., 2012). Lines 1, 5, 13 and 24 showed positive and highly significant GCA for ears per plant, and hence can be used as potential sources of improved genotypes across drought and low N environments. Lines 2 and 5 showed negative GCA effects for both GLS and ET across combined test environments indicating their potentials as sources of resistance to those diseases.

Testers 3 and 4 showed significant and positive GCA effects for grain yield and could be ideal donor parents in hybrid programmes as well as for introgression of desired alleles for drought and low N tolerance into local germplasm lacking one or more desired genes. These testers had comparatively good GCA effects for grain yield which compares very well with what was reported by Ali et al. (2013) and Mutimaamba (2015).

Positive and significant SCA effects were observed in 20.51% of the crosses, while 17.95% showed negative SCA effects. Ceyhan et al. (2008) reported significant positive SCA effects for grain yield for some of the crosses, which indicated the importance of non-additive gene action for the trait. Hybrid crosses with the highest SCA included L5 x T1, L1 x T1, L19 x T4, L3 x T2, L4 x T2, L1 x T2, L20 x T4 and L4 x T1. All these hybrids had positive SCA effects for grain yield, though some of their parents had negative GCA effects for grain yield. Most crosses involving testers 1, 2 and 4 had significantly higher SCA effects, indicating that they had better heterotic effects with most of the lines used. Selection of inbred lines based on GCA and SCA is a good hybrid development technique. According to Gowda et al. (2013), the occurrence of a superior hybrid with positive SCA is a result of the interaction between positive genes from parents with good combining ability and those with negative genes from those with poor combining ability. The effective utilization of this is through heterosis breeding where different inbred lines that are genetically unrelated are crossed. Selection of good inbred lines and hybrids for drought tolerance, low N stress and for optimum test environments is possible, since GCA and SCA mean squares were significant.

The results indicated a wide range of both broad sense and narrow sense heritability estimates for the different characteristics, indicating that these characteristics responded differently based on the environment (stress level). Characteristics with high heritability estimates are better, as selection for improvement can be done more easily (Lu et al., 2011). Complex characteristics (quantitatively inherited) are usually difficult to improve as they are prone to environmental plasticity, which is often linked to low heritability estimates. Plant height and ear aspect, which had high heritability estimates under random drought stress, can be improved under such conditions while grain yield, days to 50% anthesis and the number of ears per plant can be better improved across low N environments. Campos et al. (2006) and Masuka (2014) indicated that both ASI and the number of ears per plant usually have high heritability estimates under random drought stress environments, and thus can be improved, as secondary characteristics to grain yield (Bänziger et al., 2000; Ribaut et al., 2009).

The observed significant differences in the mean yields for genotypes across the combined environments, and at individual sites indicate the differential responses of the selected inbred lines across the varied levels of stress effects. Mean yields for optimum test environments (7.48 t ha^{-1}), were 60.58% and 79.55% higher than for both low N and random drought stress environments, respectively. The results are in line with previous findings by Betrán et al. (1997);

Bänziger et al. (1997; 2006) and Weber et al. (2012), who concluded that maize yield reductions can reach up to 80% in drought and low N environments.

4.5 Conclusions

Maize cropping systems in southern Africa are rain-fed and highly prone to droughts due to erratic rainfall; that is also highly unpredictable. The interactions of El Niño and the ITCZ have been causing drying of the southern hemisphere, often causing serious droughts in the region. The declining soil fertility is also of increasing importance in maize-based cropping systems. This has been due to the low fertiliser inputs into the soil, and continuous nutrient mining every season without replacements. Smallholder farmer communities in southern Africa cannot afford the high priced-fertiliser costs and hence low soil fertility has been named a major cause of hunger, starvation and food insecurity. The use of drought and low N tolerant maize hybrids has improved the livelihoods of millions of people in eastern and southern Africa, who depend mostly on maize based diets as their staple food. The objective of this study was to identify the breeding value of CIMMYT-developed elite maize lines as potential parents for hybrid development programmes across randomly occurring drought, low N stress and optimal conditions in southern Africa.

The differential breeding value of the selected late maize inbred lines can be beneficial for the hybrid breeding programmes in southern Africa. Several inbred lines showed positive GCA values for grain yield, indicating their potential as parents across the varied experimental conditions. They can also be potential sources of genes for random drought and low N stress tolerance for future breeding programmes. With the increasing importance of drought and the declining soil fertility status, they can be useful in maize improvement in the region. This research has indicated that yields were reduced the most under random drought stress and to a lesser extent under low soil N fertility. It can also be concluded that GCA alone is not enough to select maize inbred lines with improved breeding value, but rather both SCA and GCA should be utilized to identify good lines for hybridization. This is because some lines which showed negative GCA values showed good SCA when hybridized with other testers. The line x tester method that was used was effective for identifying the potential parents for hybridization, and can thus be recommended for future maize breeding programmes. The high heritability estimates for grain yield across all the test environments indicated the potential of improving maize under random drought, low N stress and optimum conditions. The research was effective in identifying the breeding values of the selected maize lines developed by CIMMYT for drought and low N stress tolerance in southern Africa.

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CHAPTER 5

Performance of maize hybrids developed from elite early maturity maize inbred lines under optimal, drought and low N stress environments

Abstract

Maize occupies the most important role globally as a food grain crop. Despite its importance, yields in southern Africa remain far lower than the global average as a result of mainly drought and low soil fertility, especially low N. This study was conducted in South Africa, Zimbabwe, and Zambia to assess the testcross performance of early maturity hybrids under low N, random drought stress and optimum conditions. A line x tester method was used to evaluate inbred lines and testers developed by CIMMYT for drought and low N stress tolerance for SSA. Sixty-eight testcross hybrids yielded better (9.53 to 27.5%) than the best commercial hybrid, P2859W. Grain yield was significantly ($P < 0.05$) correlated with secondary characteristics like number of ears per plant, plant height and ear height. Grain yield and anthesis-silking interval were negatively correlated both at individual and combined environments. Low N stress conditions increased anthesis silking interval by 5%, while it decreased prolificacy and plant stature by 14% and 22.34% respectively. The highest yielding testcross hybrids included entries 100 and 84 (6.36 ton ha^{-1}), 97 and 30 (6.38 ton ha^{-1}), 43 and 21 (6.40 ton ha^{-1}), 52 and 6 (6.50 ton ha^{-1}), 15 (6.61 ton ha^{-1}), 83 (6.70 ton ha^{-1}) and 46 (7.20 ton ha^{-1}). These ten testcross hybrids, together with the other 68 testcross hybrids that were significantly better than the highest commercial check across environments, warrants further evaluation for stability and consistency, and can be recommended for use as cultivars across varied environments in southern Africa. Observed high yielding cultivars can be efficient to stabilise farmers' yields in SSA where droughts and low N fertility are common challenges.

5.1 Introduction

Maize is a cereal of global importance belonging to the grass family, Poaceae and tribe, Maydeae. Its global significance is due to its use as human food, animal feed and numerous industrial products. It is important in the production of mixed feed, and other maize products like maize starch, maize oil syrups, maltodextrins and other fermentation and distilling industrial products (Troyer, 2004). Though a diverse utility, its gross influence is as the most important African staple food. With its origin in Mexico and Central America it has spread to different geographical regions and it has evolved to grow under different environments, which makes it a preferred crop. It was introduced into Africa by the Portuguese between the 15th and 16th centuries, where white maize is predominantly preferred to yellow maize (Dowswell et al., 1996).

The use of improved technologies and varieties has been increasing since the 1950s. Improved varieties are preferred for their high yielding and stress tolerance characteristics. Though the adoption rate for improved germplasm has been high, research shows that smallholder farmers, who constitute the greater part of maize producers in SSA, record less than 1.5 t ha^{-1} yield on average, which is far less than the 4.9 t ha^{-1} global average and the above 5 t ha^{-1} average for countries like the USA, China and Brazil (Smale et al., 2011; AGRA, 2013; 2014; Mutegi and Zingore, 2014; FAOSTAT, 2015). The key factors to low production in SSA have been linked to the poor adoption of improved technologies, shortage of high yielding varieties, biotic and abiotic stresses and limited financial capital to sustain their agricultural projects (Mosisa et al., 2011). There are also global increases of greenhouse gases and temperatures, seasonal droughts, and the increased challenges of pests and diseases, which will further weaken maize production systems.

In the light of this, scientists, many of them from CIMMYT and other NARS, have embarked on the production of maize inbred lines which are stress tolerant, as a way to combat food insecurity in the tropics. The inbred lines are produced objective-specific, and with a target environment in mind. Plant breeders objectively select better parents for further improvement, while discarding inferior lines.

Drought and low N stresses are the major challenges affecting maize productivity in the tropics. Breeding for tolerance to these challenges will help in the improvement of maize yields under these conditions. This study aimed to evaluate the testcross performance of the 12 CIMMYT maize elite lines crossed to 10 CIMMYT common testers specifically for maturity characteristics, and drought and low N stress tolerance across the SSA region. Apart from obtaining vital information which speeds up the delivery of higher yielding seeds to farmers, it also provides detailed scientific knowledge vital for maize improvement.

The success of maize breeding depends on the performance of inbred lines developed for specific objectives. There has been major limitations in establishing the parental relationship with its hybrid progeny (Buckler et al., 2009), and this has limited hybrid development in breeding programmes. This is because the yield trials are required to be tested under multi-environments, which may be very costly. The use of testcrosses however, was shown to reduce these costs, since the performance of these inbred lines can be established through their specific hybrid performance using testers, which can be inbred lines themselves or single cross hybrids, thereby reducing the need to conduct extensive yield trials (Hallauer et al., 2010). Testcrosses will establish the transmissibility and expressivity of parental characteristics to their hybrids. The use of secondary characteristics, which are relatively easy to improve genetically, has improved the ultimate goal of research and crop improvement – higher yields per unit area. Grain yield, drought tolerance and low soil N stress tolerance are genetically complex characteristics; hence the use of the secondary yield related characteristics in order to indirectly improve yields and other tolerance levels of maize (Buckler et al., 2009; Hallauer et al., 2010). Studies by Dudley and Johnson (2009) and Ali et al. (2011), among others, have indicated the relationship between parents and their progeny, though the prediction of performance remains challenging.

There are different ways to evaluate testcross performances of parental lines in maize. The first one involves visual selection of the preferred genotypes, in an ‘ear to row’ method, done for several selfing generations. This method is repeated for several generations of selection, until lines are nearly homozygous (Hallauer, 1990). The second method involves early generation testing of genotypes. The higher performing genotypes are selected based on their performance in hybrid combinations (testcross performance). The genotypes that perform below given standards are discarded, thus allowing the use of resources for the promising inbred lines (Hallauer, 1990). This is done on lines which show high levels of homozygosity, and thus combining ability of these lines do not change with continued inbreeding. This study was conducted in South Africa, Zimbabwe, and Zambia to assess the testcross performance of early maturity hybrids under low N, random drought stress and optimum conditions.

5.2 Materials and methods

5.2.1 Plant materials

One hundred and twenty three-way hybrids generated from a 12 x 10 line x tester design, together with six local commercial checks (SC403, SC513, SC627, PAN53, PAN4M-21 and P2859W) were used in this study (the same material as used in Chapter 3).

5.2.2 Experimental design and trial management

The trials were planted in an alpha-lattice design, according to Patterson and Williams (1976), with two replicates as described in section 3.2.3.

5.2.3 Data collection

Data was collected for agro-morphological characteristics as described in section 3.2.4.

5.2.4 Statistical analysis

Combined ANOVA across environments was computed using Genstat 17th Edition statistical software (VSN-International, 2015). Genotypes were considered as fixed effects and replications and blocks as random effects. Analysis of variance for genotypes, environments and G x E interaction was performed. Mean separation was conducted using least significant differences (LSDs) at $P < 0.05$. Multiple test correlations were calculated using R based software (Rodríguez et al., 2015; Schwarzer et al., 2016).

5.3 Results

5.3.1 Analysis of variance for grain yield and agronomic characteristics across and on individual management levels

Under the combined test environments, G x E interactions were highly significant for grain yield, days to 50% anthesis, plant and ear height, ear position, number of ears per plant, root lodging and stalk lodging (Table 5.1). The effects of environment were highly significant ($P < 0.001$) for all the characteristics. Blocking within locations was significant, except for anthesis-silking interval. There were highly significant differences among testcross hybrids and commercial checks evaluated for all characteristics. Coefficients of variation were low (below 14%) for all characteristics except for grain yield (19.94%).

ANOVA across the four low N environments showed significant ($P < 0.05$) G x E interaction for grain yield and ear height (Table 5.1). There were highly significant ($P < 0.001$) differences for grain yield, days to 50% anthesis, anthesis silking interval, plant and ear height, ear position, number of ears per plant and root lodging among the evaluated testcross hybrids. Stalk lodging was significant ($P < 0.05$). Low N test environments were not significantly different ($P < 0.05$) from each other for all the measured characteristics.

Under random drought stress environments (Table 5.1) significant differences were only observed for days to 50% anthesis, ear height ($P < 0.001$) and number of ears per plant ($P < 0.01$)

ANOVA for individual and across optimum environments showed significant differences among testcross hybrids for all characteristics (Table 5.1). There was significant G x E interactions for all characteristics, except for anthesis-silking interval. There were significant differences for environments for all characteristics. Blocking within environment was significant, except for ear position and number of ears per plant. Genotypes were significantly different ($P < 0.001$) for grain yield, days to 50% anthesis, anthesis-silking interval, plant height, ear height and ear position, number of ears per plant, root ($P < 0.01$) and stalk lodging.

5.3.2 Grain yield and agronomic performance of the hybrids

5.3.2.1 Mean grain yield performance of maize testcross hybrids across individual test environments and across management levels

Mean grain yields were lowest at Gwebi (low N), recording a mean of 1.73 t ha^{-1} (range 0.37-3. 83 t ha^{-1}) and highest at Mpongwe, Zambia with a mean of 9.94 t ha^{-1} (range of 4.69-14.13 t ha^{-1}) (Figure 5.1). Across management levels analysis indicated that low N management levels recorded the lowest grain yield of 3.37 t ha^{-1} (Figure 5.2), followed by random drought stress (4.72 t ha^{-1}) and optimum environments with the highest mean yield of 7.07 t ha^{-1}. Of the evaluated testcross hybrids, 73% of the entries had higher yield than the mean of the checks. The highest yielding testcross hybrids included entries 46, 83; 52 and 35 with grain yields of 6.64, 6.35, 6.28 and 6.28 t ha^{-1}, respectively. These hybrids did not differ significantly for yield. Test cross hybrids 59, 40, 77 and 66 recorded the lowest grain yield across environments. There were significant correlations for grain yield among the pooled management levels (Table 5.2). Positive and highly significant correlations were observed between the grain yield of combined environments and random drought stress ($r = 0.72^{***}$) and optimum conditions($r = 0.57^{***}$). Negative correlations were observed between low N and random drought stress ($r = -0.33^{***}$).

Table 5.1 Mean squares for grain yield and agronomic characteristics of early maturing hybrids across all environments

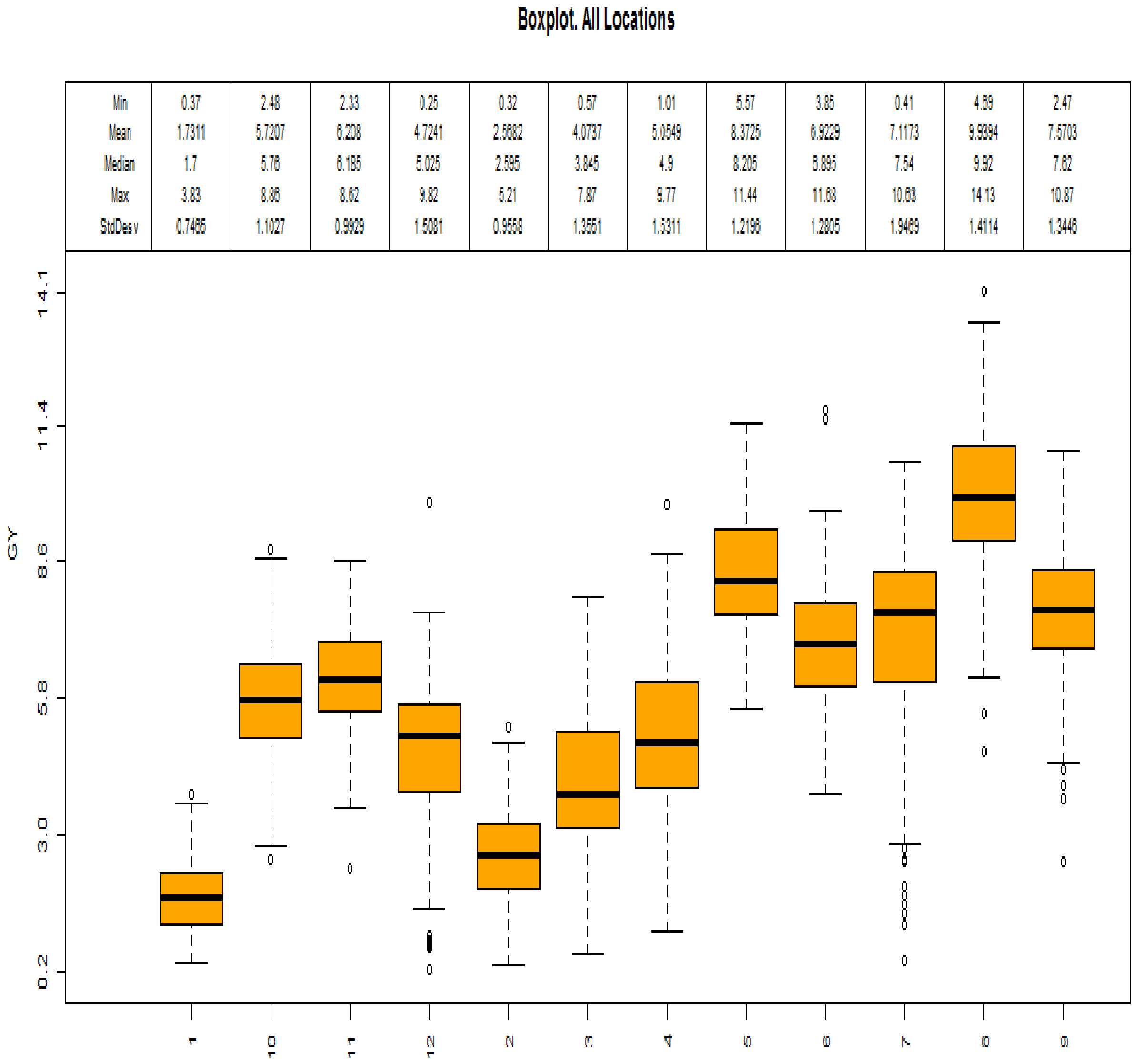
					Combined test environments					
Source	**df**	**GY**	**AD**	**ASI**	**PH**	**EH**	**EPO**	**EPP**	**RL**	**SL**
Environments	11	1215.54***	13141.50***	1.36***	263131***	143723***	1.72***	3.20***	17.18***	45.51***
Bloc(env)	12	8.80***	30.68***	0.05	2606.31***	1103.32***	0.02***	0.10***	0.68***	0.14*
Hybrids	114	7.80***	88.14***	0.07***	2961.62***	1301.85***	0.02***	0.10***	0.14***	0.03***
G x E	1254	2.01***	7.69***	0.27	498.54***	219.44***	0.00***	0.02***	0.12***	0.13***
MSE	1368	1.33	5.96	0.03	298.07	190.98	0	0.02	0.09	0.08
Grand mean		5.78	72.1	2.43	223.18	121.82	0.55	1	2.58	2.7
R squared		0.9	0.95	0.62	0.91	0.89	0.89	0.76	0.75	0.87
CV (%)		19.94	3.39	6.61	7.74	11.34	8.51	13.5	11.43	10.32
					Low N test environments					
Environment	3	0.78	17.28	0.06	125.08	97.98	0.01	0.02	0.15	0.04
Bloc(env)	4	1.51	8.51	0.08	176.48	133.63	0.01	0.01	0.29	0.06
Testcross	114	13.27***	115.66***	0.08***	1836.30***	1995.06***	0.05***	0.05***	0.41***	0.08*
G x E	342	1.83*	18.09	0.04	561.49	413.26*	0.01	0.02	0.17	0.06
MSE	456	1.49	18.16	0.04	490.61	348.99	0.01	0.02	0.17	0.06
Grand mean		3.37	69.61	2.5	194.11	97.6	0.5	0.92	2.49	2.42
R-squared		0.76	0.7	0.59	0.64	0.7	0.72	0.62	0.58	0.52
LSD		1.01	3.51	0.16	18.25	15.4	0.07	0.1	0.34	0.2
SED		0.61	2.13	0.1	11.07	9.34	0.04	0.63	0.21	0.12
					Random drought stress test environments					
Bloc	1	19.18*	0.35	0.02	7658.52*	270.44	0.08***	0.59***	0.05	0.05
Testcross	114	2.5	24.84***	0.05	537.36	236.79***	0.01	0.05**	0.02	0.09
MSE	114	1.9	6.45	0.44	434.82	131.68	0.01	0.03	0.02	0.07
Grand mean		4.72	73.55	2.48	169.58	119.55	0.71	0.91	2.34	2.5
LSD (0.05)		2.28	4.21	0.35	34.58	19.03	0.1	0.28	0.25	0.44
SED		1.38	2.54	0.217	2.85	11.48	0.06	0.17	0.15	0.27
R-squared		0.59	0.79	0.51	0.58	0.64	0.59	0.66	0.47	0.56
					Optimum test environments					
Environment	6	403.06***	19644.9***	0.34***	54068.20***	71644.90***	0.47***	3.02***	19.92***	57.58***
Bloc(env)	7	4.67***	20.70***	0.05*	1560.75***	501.49**	0	0.01	1.06***	0.21*
Hybrid	114	8.46***	39.64***	0.05***	2963.26***	1019.08***	0.02***	0.09***	0.10**	0.43***
G x E	684	2.04***	7.55***	0.02	457.84***	214.52*	0.01***	0.02***	0.10***	0.17***
MSE	798	1.31	5.87	0.02	225.17	185.08	0.01	0.02	0.07	0.09
Grand mean		7.31	73.29	2.39	247.39	135.97	0.55	1.07	2.66	2.91
LSD (0.05)		0.71	1.51	0.09	9.34	8.47	0.03	0.08	0.17	0.19
SED		0.43	0.92	0.05	5.67	5.14	0.02	0.05	0.1	0.12
R-squared		0.82	0.96	0.58	0.85	0.83	0.82	0.76	0.78	0.87

***P < 0.001; **P < 0.01; *P < 0.05; df degrees of freedom; GY grain yield (t ha^{-1}); AD days to 50% anthesis; ASI anthesis silking interval; PH plant height (cm); EH ear height (cm); EPO ear position; EPP number of ears per plant; RL root lodging; SL stalk lodging; G x E genotype x environment; MSE mean square error; LSD least significant (0.05); SED standard error of the difference

Table 5.2 Grain yield correlations between management levels

	Combined	Low N	Optimum
Low N	0.20*		
Optimum	0.57***	0.21*	
Random drought	0.72***	-0.33***	0.03

***P < 0.001; **P < 0.01; *P < 0.05



Min	0.37	2.48	2.33	0.25	0.32	0.57	1.01	5.57	3.85	0.41	4.69	2.47
Mean	1.7311	5.7207	6.208	4.7241	2.5682	4.0737	5.0549	8.3725	6.9229	7.1173	9.9394	7.5703
Median	1.7	5.76	6.185	5.025	2.595	3.845	4.9	8.205	6.895	7.54	9.92	7.62
Max	3.83	8.88	8.62	9.82	5.21	7.87	9.77	11.44	11.68	10.63	14.13	10.87
StdDesv	0.7465	1.1027	0.9929	1.5081	0.9558	1.3551	1.5311	1.2196	1.2805	1.9469	1.4114	1.3446

Figure 5.1 Mean yields of early maturing hybrids at each individual environment; 1=Gwebi Low N; 2=Harare A Low N; 3 Harare B Low N; 4 Potchefstroom Low N; 5 Gwebi Opt; 6 Art Opt; 7 Ivordale Opt; 8 Mpongwe Opt; 9 Lusaka; Opt; 10 Cedara 1 optimum; 11 Cedara 2 Optimum; 12 Potchefstroom Random drought

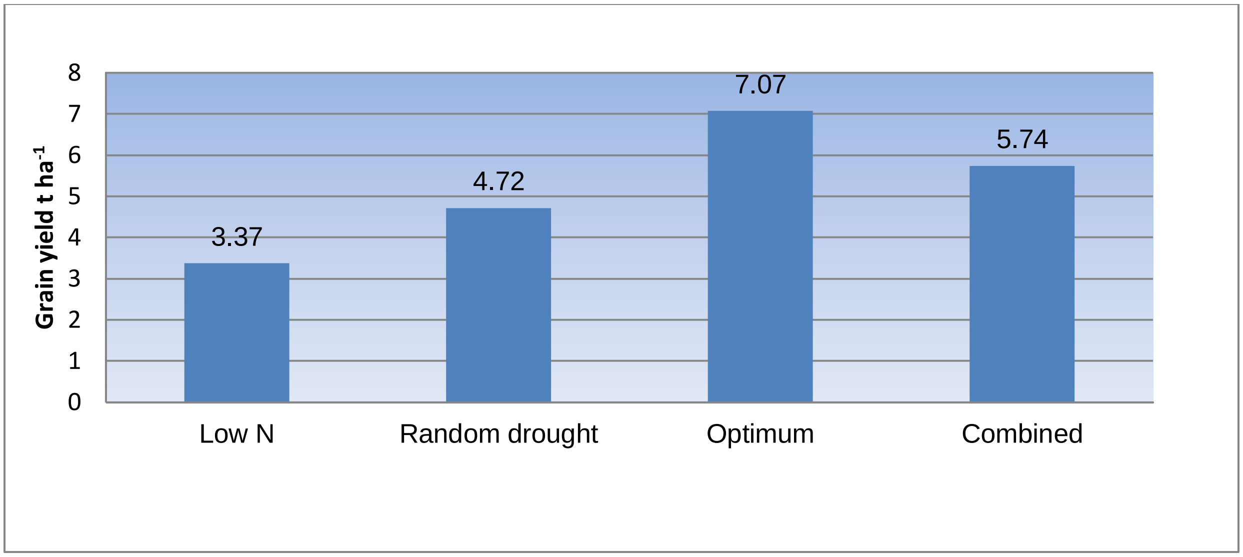


Figure 5.2 Mean grain yield of early maturing hybrids across management levels (LSD = 0.55)

5.3.2.2 Grain yield and agronomic testcross performance across all environments

The top 15 highest yielding, five lowest yielding and six local commercial checks are presented in Tables 5.3 and 5.4. Tester 2 had the highest heterotic effects when combined with line 6 and line 10, giving the highest mean yields. The highest yielding genotype across all test environments was entry 46 (L6 x T2) with 7.2 t ha^{-1}, followed by entry 83 (L10 x T2) with 6.74 t ha^{-1}. These two hybrids did not differ significantly. These two hybrids took 74 and 72 days to reach anthesis, respectively. They were very tall and recorded numbers of ears per plant above 1 (1.07 and 1.01 respectively). The lowest yielding testcross hybrids were entries 59 (L7 x T6), 66 (L8 x T4), 77 (L9 x T6), 40 (L5 x T6) and 58 (L7 x T5) with 4.2 t ha^{-1}, 4.36 t ha^{-1}, 4.37 t ha^{-1}, 4.47 t ha^{-1} and 4.81 t ha^{-1} , respectively (Table 5.3). All the commercial checks yielded below the trial mean of 5.78 t ha^{-1}, with P2859W having the highest (5.22 t ha^{-1}) and SC513 the lowest mean yields (3.96 t ha^{-1}). Of the testcross hybrids evaluated, 58.26% recorded higher yields than the trial mean of 5.78 t ha^{-1}, while 83.48% had relatively better yields than the highest commercial check, P2859W. Tester 6 and line 7 were common parents among the lowest yielding hybrids. Line 7 and tester 8 contributed much to earliness while tester 8 contributed to lateness of the hybrids. For the plant stature, especially shortness, line 7 and tester 5 contributed the most (Table 5.3). Line 5 and line 10 contributed much to prolificacy, with hybrids scoring higher than 1 for every cross they were involved in, while tester 9 and line 7 showed negative heterotic effects for prolificacy.

Table 5.3 Mean grain yield, flowering and plant and ear height of the 15 best and poorest five hybrids across all environments, with six checks

Rank	Entry	Testcross	GY	Entry	Testcross	AD	Entry	Testcross	ASI	Entry	Testcross	PH	Entry	Testcross	EH
1	46	L6 x T2	7.20	58	L7 x T5	67.13	82	L10 x T1	2.31	61	L7 x T8	203.39	58	L7 x T5	103.34
2	83	L10 x T2	6.74	61	L7 x T8	67.17	88	L10 x T7	2.32	58	L7 x T5	203.87	15	L2 x T5	103.8
3	15	L2 x T5	6.61	62	L7 x T9	68.42	17	L2 x T7	2.33	62	L7 x T9	209.21	61	L7 x T8	104.66
4	52	L6 x T9	6.50	60	L7 x T7	68.75	97	L11 x T7	2.33	59	L7 x T6	209.33	42	L5 x T8	108.18
5	6	L1 x T6	6.50	34	L4 x T9	69.00	92	L11 x T1	2.34	70	L8 x T9	209.72	31	L4 x T5	110.44
6	43	L5 x T9	6.40	26	L3 x T8	69.04	1	L1 x T1	2.35	15	L2 x T5	210.55	67	L8 x T5	111.39
7	21	L3 x T2	6.40	59	L7 x T6	69.17	6	L1 x T6	2.35	77	L9 x T6	211.38	62	L7 x T9	112.47
8	97	L11 x T7	6.38	33	L4 x T8	69.33	99	L11 x T9	2.36	42	L5 x T8	211.88	86	L10 x T5	112.78
9	30	L4 x T4	6.38	8	L1 x T8	69.33	70	L8 x T9	2.36	60	L7 x T7	212.23	69	L8 x T8	113.31
10	100	L11 x T10	6.36	42	L5 x T8	69.42	30	L4 x T4	2.37	67	L8 x T5	212.32	14	L2 x T4	113.34
11	84	L10 x T3	6.36	23	L3 x T5	69.54	96	L11 x T6	2.37	79	L9 x T8	212.78	89	L10 x T8	113.54
12	88	L10 x T7	6.35	63	L7 x T10	69.71	91	L10 x T10	2.38	18	L2 x T8	213.10	66	L8 x T4	113.6
13	32	L4 x T6	6.33	51	L8 x T8	69.75	4	L1 x T4	2.38	76	L9 x T5	213.94	77	L9 x T6	114.32
14	82	L10 x T1	6.33	39	L5 x T5	69.88	104	L12 x T4	2.38	31	L4 x T5	214.23	57	L7 x T4	114.69
15	35	L5 x T1	6.32	43	L5 x T9	70.08	18	L2 x T8	2.38	80	L9 x T9	214.40	51	L8 x T8	114.88
105	58	L7 x T5	4.81	64	L8 x T2	75.00	50	L6 x T7	2.51	83	L10 x T2	237.5	2	L1 x T2	132.98
106	40	L5 x T6	4.47	107	L12 x T7	75.13	49	L6 x T5	2.52	103	L12 x T3	238.32	101	L12 x T1	133.01
107	77	L9 x T6	4.37	12	L2 x T2	75.17	105	L12 x T5	2.52	46	L6 x T2	238.47	103	L12 x T3	133.52
108	66	L8 x T4	4.36	2	L1 x T2	75.17	10	L1 x T10	2.53	28	L4 x T2	239.15	74	L9 x T3	133.53
109	59	L7 x T6	4.2	102	L12 x T2	75.21	76	L9 x T5	2.53	93	L11 x T2	240.37	25	L3 x T7	134.02
1	115		5.22	110		67.50	110		2.38	112		207.57	115		105.55
2	110		4.79	111		69.38	113		2.44	110		201.30	110		107.75
3	113		4.76	114		71.29	112		2.54	113		195.23	114		108.28
4	112		4.51	115		71.33	115		2.58	115		191.63	111		112.19
5	114		4.34	112		72.25	114		2.60	111		186.25	112		127.25
6	111		3.96	113		74.54	111		2.61	114		175.94	113		122.42

GY grain yield (t ha^{-1}); AD days to 50% anthesis; ASI anthesis-silking interval; PH plant height (cm); EH ear height (cm); Entry 110= SC403; Entry 111= SC513; Entry 112= SC627; Entry 113= PAN53; Entry 114= PAN4M-21 and Entry 115= P2859W

Table 5.4 Agronomic performance of the 15 best and poorest five testcross hybrids across all environments, with six checks

Rank	Entry	Testcross	EPO	Entry	Testcross	EPP	Entry	Testcross	RL	Entry	Testcross	SL
1	15	L2 x T5	0.50	35	L5 x T1	1.22	57	L7 x T4	2.43	22	L3 x T3	2.48
2	89	L10 x T8	0.50	41	L5 x T7	1.17	106	L12 x T6	2.45	95	L11 x T4	2.50
3	58	L7 x T5	0.50	39	L5 x T5	1.14	61	L7 x T8	2.45	23	L3 x T5	2.51
4	39	L5 x T5	0.51	92	L11 x T1	1.13	60	L7 x T7	2.46	35	L5 x T1	2.52
5	85	L10 x T4	0.51	97	L11 x T7	1.12	79	L9 x T8	2.47	54	L7 x T1	2.52
6	42	L5 x T8	0.51	37	L5 x T3	1.11	69	L8 x T8	2.47	96	L11 x T6	2.53
7	51	L8 x T8	0.51	82	L10 x T1	1.11	17	L2 x T7	2.48	101	L12 x T1	2.54
8	86	L10 x T5	0.51	44	L6 x T7	1.11	39	L5 x T5	2.48	39	L5 x T5	2.55
9	14	L2 x T4	0.51	36	L5 x T2	1.10	31	L4 x T5	2.48	5	L1 x T5	2.56
10	31	L4 x T5	0.51	107	L12 x T7	1.10	16	L2 x T6	2.48	86	L10 x T5	2.58
11	61	L7 x T8	0.51	105	L12 x T5	1.10	55	L7 x T2	2.48	24	L3 x T6	2.58
12	104	L12 x T4	0.51	88	L10 x T7	1.10	18	L2 x T8	2.49	78	L9 x T7	2.58
13	95	L11 x T4	0.52	49	L6 x T5	1.09	53	L6 x T10	2.49	72	L9 x T1	2.58
14	105	L12 x T5	0.52	43	L5 x T9	1.08	76	L9 x T5	2.49	84	L10 x T3	2.58
15	48	L6 x T4	0.52	84	L10 x T3	1.08	59	L7 x T6	2.49	85	L10 x T4	2.58
105	73	L9 x T2	0.58	80	L9 x T9	0.91	91	L10 x T10	2.71	29	L4 x T3	2.92
106	25	L3 x T7	0.58	62	L7 x T9	0.90	93	L11 x T2	2.71	102	L12 T2	2.93
107	20	L3 x T1	0.58	9	L1 x T9	0.89	6	L1 x T6	2.74	18	L2 x T8	2.97
108	74	L9 x T3	0.58	57	L7 x T4	0.88	94	L11 x T3	2.77	28	L4 x T2	2.99
109	72	L9 x T1	0.59	59	L7 x T6	0.87	29	L4 x T3	2.78	51	L8 x T8	3.01
1	110		0.53	110		0.96	115		2.41	115		2.46
2	115		0.56	114		0.93	111		2.41	110		2.50
3	112		0.61	111		0.91	114		2.42	112		2.61
4	111		0.62	113		0.91	110		2.46	111		2.71
5	114		0.63	112		0.88	112		2.51	114		2.85
6	113		0.65	115		0.88	113		2.60	113		2.88

EPO ear position; EPP number of ears per plant; RL root lodging; SL stalk lodging; Entry 110=SC403; Entry 111=SC513; Entry 112=SC627; Entry 113=PAN53; Entry 114=PAN4M-21 and Entry 115=P2859W

5.3.2.3 Grain yield and agronomic testcross performance across low N environments

Grain yield and agronomic testcross performances for the hybrids that were evaluated across low N environments are presented in Table 5.5 and Table 5.6. Entry 46 (L6 x T2) recorded the highest yield of 4.98 t ha^{-1} across low N environments, followed by entry 15 (L2 x T5) with 4.72 t ha^{-1}. Entry 2 had the lowest yield (2.14 t ha^{-1}) followed by entry 9 (L1 x T9) with 2.31 t ha^{-1}. Hybrid combinations with line 1 (entry 2 and 9) and line 5 (entry 38 and 37) were among the lowest yielding genotypes. Genotypes with line 10 as parent had the highest frequency in the top yielding hybrids under low N environments. The lowest yielding testcross hybrid was characterised by late maturity (72 days), medium cob placement (0.55) and moderate plant height (197.95 cm). Hybrids with line 7 and tester 8 as parents were very early maturing while those with line 12 and line 1 were late maturing. Hybrids with line 7 and testers 5 and 8 as parents had reduced plant height, while those with line 12 had increased plant height (Table 5.8).

Table 5.5 Grain yield and agronomic performance of the 15 best and poorest five hybrids across low N environments, with six checks

Rank	Entry	Testcross	GY	Entry	Testcross	AD	Ent	Testcross	ASI	Entry	Testcross	PH
1	46	L6 x T2	4.98	61	L7 x T8	64.00	76	L9 x T5	2.66	58	L7 x T5	169.63
2	15	L2 x T5	4.72	58	L7 x T5	64.38	10	L1 x T10	2.66	61	L7 x T8	170.48
3	92	L11 x T1	4.64	59	L7 x T6	65.63	73	L9 x T2	2.65	11	L2 x T1	174.93
4	78	L9 x T7	4.55	34	L4 x T9	65.63	105	L12 x T5	2.64	18	L2 x T8	175.20
5	83	L10 x T2	4.42	60	L7 x T7	65.63	53	L6 x T10	2.64	31	L4 x T5	176.63
6	6	L1 x T6	4.37	26	L3 x T8	65.75	67	L8 x T5	2.38	17	L2 x T7	176.68
7	26	L3 x T6	4.29	8	L1 x T8	66.13	63	L7 x T10	2.38	42	L5 x T8	176.80
8	30	L4 x T4	4.11	62	L7 x T9	66.13	26	L3 x T8	2.37	62	L7 x T9	179.08
9	73	L9 x T2	4.04	52	L6 x T9	66.38	97	L11 x T7	2.36	67	L8 x T5	179.28
10	88	L10 x T6	4.03	42	L5 x T8	66.63	104	L12 x T4	2.35	76	L9 x T5	179.43
11	84	L10 x T3	3.93	51	L6 x T8	66.75	6	L1 x T6	2.35	51	L6 x T8	180.40
12	97	L11 x T7	3.93	23	L3 x T4	66.75	88	L10 x T7	2.31	70	L8 x T9	181.03
13	71	L8 x T10	3.92	98	L11 x T8	66.75	61	L7 x T8	2.41	56	L7 x T3	181.63
14	69	L8 x T8	3.91	39	L5 x T5	66.88	72	L9 x T1	2.41	82	L10 x T1	182.25
15	55	L7 x T2	3.91	43	L5 x T9	66.88	101	L12 x T1	2.41	68	L8 x T7	183.78
105	38	L5 x T4	2.46	4	L1 x T4	72.88	108	L12 x T8	2.41	45	L6 x T1	210.95
106	76	L9 x T5	2.46	107	L12 x T7	73.25	83	L10 x T2	2.40	109	L12 x T9	211.20
107	37	L5 x T3	2.37	12	L2 x T2	73.63	99	L11 x T9	2.40	100	L11 x T10	212.80
108	9	L1 x T9	2.31	102	L12 x T2	74.00	82	L10 x T1	2.40	102	L12 x T2	213.15
109	2	L1 x T1	2.14	2	L1 x T2	75.13	29	L4 x T3	2.39	46	L6 x T2	217.73
1	112		3.77	110		65.50	111		2.43	114		177.83
2	111		3.52	111		66.75	114		2.48	110		182.03
3	114		3.03	115		67.88	110		2.49	112		186.20
4	110		2.87	114		68.63	112		2.52	115		191.25
5	115		2.63	112		68.75	113		2.55	111		192.13
6	113		2.56	113		70.50	115		2.58	113		202.18

GY grain yield, AD days to 50% anthesis, ASI anthesis silking interval, PH plant height (cm); Entry 110=SC403; Entry 111=SC513; Entry 112=SC627; Entry 113=PAN53; Entry 114=PAN4M-21 and Entry 115=P2859W

Table 5.6 Ear characteristics of the 15 best and poorest five hybrids across low N test environments, with six checks

Rank	Entry	Testcross	EH	Entry	Testcross	EPO	Entry	Testcross	EPP
1	78	L9 x T7	81.25	15	L2 x T5	0.43	98	L11 x T8	1.06
2	31	L4 x T5	81.68	89	L10 x T8	0.44	107	L12 x T7	1.06
3	67	L8 x T5	82.03	67	L8 x T5	0.45	82	L10 x T1	1.05
4	15	L2 x T5	83.50	8	L1 x T8	0.46	39	L5 x T5	1.04
5	42	L5 x T8	83.75	16	L2 x T6	0.46	44	L5 x T10	1.04
6	58	L7 x T5	83.85	31	L4 x T5	0.46	35	L5 x T10	1.03
7	61	L7 x T8	84.68	39	L5 x T5	0.46	78	L9 x T7	1.02
8	89	L10 x T8	86.13	42	L4 x T8	0.46	52	L6 x T9	1.01
9	51	L6 x T8	87.83	19	L2 x T9	0.47	67	L8 x T5	1.01
10	62	L7 x T9	87.95	86	L10 x T5	0.47	18	L2 x T8	1.01
11	18	L2 x T8	88.73	33	L4 x T8	0.48	17	L2 x T7	1.00
12	11	L2 x T1	88.75	46	L6 x T2	0.48	105	L12 x T5	1.00
13	56	L7 x T3	89.25	51	L6 x T8	0.48	50	L6 x T7	1.00
14	16	L2 x T6	89.63	85	L10 x T4	0.48	32	L4 x T6	0.99
15	33	L4 x T8	89.80	105	L12 x T5	0.48	83	L10 x T2	0.99
105	8	L1 x T8	90.10	25	L3 x T7	0.55	3	L1 x T3	0.80
106	29	L4 x T3	108.85	60	L7 x T7	0.55	9	L1 x T9	0.80
107	1	L1 x T1	108.98	72	L9 x T1	0.55	2	L1 x T2	0.80
108	25	L3 x T7	110.63	78	L9 x T7	0.55	59	L7 x T6	0.79
109	74	L9 x T3	112.40	74	L9 x T3	0.56	57	L7 x T4	0.77
1	110		83.75	110		0.45	110		0.97
2	115		89.15	115		0.46	114		0.91
3	114		91.20	111		0.49	115		0.9
4	111		93.70	114		0.5	111		0.89
5	112		99.13	113		0.51	113		0.87
6	113		102.75	112		0.53	112		0.85

EH ear height (cm), EPO ear position, EPP number of ears per plant; Entry 110=SC403; Entry 111=SC513; Entry 112=SC627; Entry 113=PAN53; Entry 114=PAN4M-21 and Entry 115=P2859W

5.3.2.4 Grain yield and agronomic testcross performance of hybrids under random drought stress environment

The testcross performances for maize hybrids grown under random drought stress are presented in Table 5.7 and Table 5.8. Entry 35 (L5 x T1) had the highest mean yield of 7.22 t ha^{-1} and was followed by entry 3 (L1 x T3) with 7.19 t ha^{-1}. The lowest yielding genotype was entry 62 (L7 x T9) with 0.89 t ha^{-1} and was followed by entry 86 (L10 x T5) with 2.13 t ha^{-1}. The best genotype yielded 17.86% and 41.97% better than the best commercial check cultivar SC403 (5.93 t ha^{-1}) and the poorest commercial check, PAN4M-21 (4.19 t ha^{-1}), respectively.

Sixty two hybrids had mean yields above the trial mean (4.72 t ha^{-1}). The 55 highest yielding hybrids did not differ significantly. Among the highest yielding testcross hybrids, line 1 had high heterotic effects in most hybrid combinations it was involved in. These hybrids include entry 3 (L1 x T3, 7.19 t ha^{-1}), entry 10 (L1 x T10, 6.31 t ha^{-1}) and entry 8 (L1 x T8, 5.95 t ha^{-1}). Line 6 was also high yielding in most of the hybrid combinations it was involved in, including entries 50 (L6 x T7, 6.67 t ha^{-1}), 47 (L6 x T3, 6.52 t ha^{-1}), 52 (L6 x T9, 6.46 t ha^{-1}) and 49 (L6 x T4, 6.15 t ha^{-1}). Testers 8 and 3 also contributed much to the high yield occurring in many high yielding hybrid combinations under random drought stress. Line 7 and tester 8 contributed much to earliness, as observed in all the hybrid combinations they were involved in, while line 12 was involved in most late maturing testcross hybrids. Five of the top 15 testcross hybrids of the highly prolific (high number of ears per plant) testcross hybrids had line 5 as one of the parents, while line 10 and line 7 were parents for hybrids with lower numbers of ears per plant.

Table 5.7 Grain yield and agronomic performance of the 15 best and poorest five early maturing hybrids under random drought stress, with six checks

Rank	Entry	Testcross	GY	Entry	Testcross	AD	Entry	Testcross	ASI
1	35	L5 x T1	7.22	58	L7 x T5	66.00	21	L3 x T2	2.13
2	3	L1 x T3	7.19	61	L7 x T8	66.50	100	L10 x T11	2.18
3	50	L6 x T7	6.67	63	L7 x T10	66.50	34	L4 x T9	2.19
4	47	L6 x T3	6.52	59	L7 x T6	67.00	17	L2 x T7	2.19
5	52	L6 x T9	6.46	62	L7 x T9	67.00	35	L5 x T1	2.19
6	41	L5 x T7	6.38	42	L5 x T8	67.50	70	L8 x T9	2.24
7	10	L1 x T10	6.31	39	L5 x T5	68.00	103	L12 x T3	2.24
8	69	L8 x T8	6.26	34	L5x T4	68.00	19	L2 x T9	2.28
9	23	L3 x T4	6.18	60	L7 x T7	68.00	93	L11 x T2	2.30
10	49	L6 x T4	6.15	33	L4 x T8	68.00	59	L7 x T6	2.30
11	44	L5 x T10	6.12	69	L8 x T8	68.00	24	L3 x T5	2.30
12	103	L12 x T3	5.98	51	L8 x T8	68.00	20	L3 x T1	2.30
13	8	L1 x T8	5.95	23	L3 x T4	68.50	37	L5 x T3	2.30
14	51	L8 x T8	5.93	43	L5 x T9	69.00	22	L3 x T3	2.30
15	61	L7 x T8	5.91	26	L3 x T8	69.00	32	L4 x T6	2.32
105	85	L10 x T4	2.73	101	L12 x T1	79.00	3	L1 x T3	2.73
106	59	L7 x T6	2.65	2	L1 x T2	79.00	62	L7 x T9	2.74
107	57	L7 x T4	2.24	102	L12 x T2	80.00	9	L1 x T9	2.77
108	86	L10 x T5	2.13	106	L12 x T6	80.00	86	L10 x T5	2.77
109	62	L7 x T9	0.89	94	L11 x T3	80.00	89	L10 x T8	2.79
1	110		5.93	110		66.00	110		2.30
2	115		5.86	111		68.00	113		2.44
3	112		4.44	114		71.00	112		2.64
4	111		4.41	115		71.50	115		2.67
5	113		4.39	112		73.00	114		2.83
6	114		4.19	113		75.00	111		2.83

GY Grain yield (t ha^{-1}); AD days to 50% anthesis; ASI anthesis silking interval; Entry 110=SC403; Entry 111=SC513; Entry 112=SC627; Entry 113=PAN53; Entry 114=PAN4M-21 and Entry 115=P2859W

Table 5.8 Plant height and ear characteristics of the 15 best and poorest five hybrids under random drought stress, with six checks

Rank	Entry	Testcross	PH	Entry	Testcross	EH	Entry	Testcross	EPO	Entry	Testcross	EPP
1	79	L9 x T8	135.10	61	L7 x T8	96.70	52	L6 x T9	0.66	35	L5 x T10	1.34
2	70	L8 x T9	135.50	67	L8 x T5	97.50	34	L4 x T9	0.66	41	L5 x T7	1.32
3	16	L2 x T6	138.10	79	L9 x T8	98.40	4	L1 x T4	0.65	93	L11 x T2	1.25
4	42	L5 x T8	139.30	62	L7 x T9	100.20	51	L8 x T8	0.65	107	L12 x T7	1.24
5	62	L7 x T9	141.20	42	L5 x T8	101.70	48	L6 x T4	0.64	39	L5 x T5	1.24
6	40	L5 x T6	144.40	40	L5 x T6	102.60	58	L7 x T5	0.64	87	L10 x T6	1.13
7	12	L2 x T2	144.90	85	L10 x T4	104.30	76	L9 x T5	0.64	44	L5 x T10	1.12
8	86	L10 x T5	146.50	87	L10 x T6	104.40	24	L3 x T5	0.64	101	L12 x T1	1.09
9	18	L2 x T8	146.90	16	L2 x T6	104.90	61	L7 x T8	0.64	37	L5 x T3	1.08
10	14	L2 x T4	147.00	70	L8 x T9	105.50	93	L11 x T2	0.64	97	L11 x T7	1.07
11	1	L1 x T1	147.70	14	L2 x T4	105.60	95	L11 x T4	0.63	13	L2 x T3	1.07
12	67	L8 x T5	147.70	9	L1 x T9	106.60	107	L12 x T7	0.63	27	L4 x T1	1.06
13	31	L4 x T5	148.80	86	L10 x T5	107.80	87	L10 x T6	0.63	18	L2 x T8	1.06
14	15	L2 x T5	150.20	34	L4 x T9	108.30	39	L5 x T5	0.62	67	L8 x T5	1.06
15	106	L12 x T6	150.50	69	L8 x T8	108.30	104	L12 x T4	0.59	50	L6 x T7	1.05
105	107	L12 x T7	200.80	25	L3 x T6	140.20	15	L2 x T5	0.79	85	L10 x T4	0.58
106	10	L1 x T10	203.80	36	L5 x T2	143.80	12	L2 x T2	0.79	86	L10 x T5	0.58
107	103	L12 x T3	205.10	10	L1 x T10	144.20	70	L8 x T9	0.78	80	L9 x T9	0.54
108	93	L11 x T2	207.60	103	L12 x T3	148.90	108	L12 x T8	0.78	57	L7 x T4	0.52
109	101	L12 x T1	217.00	101	L12 x T1	153.60	17	L2 x T7	0.77	62	L7 x T9	0.24
1	114		129.70	114		98.40	110		0.59	111		0.98
2	111		149.00	115		105.20	112		0.66	110		0.96
3	113		154.00	111		112.30	115		0.67	113		0.93
4	115		160.10	110		112.80	114		0.75	114		0.91
5	110		190.50	113		124.00	111		0.76	112		0.86
6	112		200.60	112		132.00	113		0.80	115		0.79

PH plant height (cm); EH ear height (cm); EPO ear position; EPP number of ears per plant; Entry 110= SC403; Entry 111= SC513; Entry 112= SC627; Entry 113= PAN53; Entry 114= PAN4M-21 and Entry 115= P2859W

5.3.2.5 Grain yield and agronomic testcross performance across optimum environments

The highest yielding genotype across optimum environments was testcross hybrid 46 with 8.72 (t ha^{-1}) followed by entry testcross hybrid 83 with 8.50 t ha^{-1} (Table 5.9 and Table 5.10). The highest 91 testcross hybrids yielded significantly higher (between 12.13% and 42.95%) than the highest check P2859W, which yielded 6.10 t ha^{-1}. Seventy-three testcross hybrids recorded higher mean yields than the trial mean (7.30 t ha^{-1}). The lowest yielding hybrid was testcross 77 with 5.16 t ha^{-1}, but was better than checks SC513 and PAN4M-21 which had average means of 4.69 t ha^{-1} and 5.11 t ha^{-1} respectively. All the commercial checks were among the 11 lowest yielding hybrids across optimum environments. Inbred lines selected for crossing were from a pool of early maturing types, but testcross hybrids (progeny) took a bit longer to reach 50% anthesis, with testcross hybrid 58 and commercial check, SC403, with 68.86 days, the earliest. Commercial check PAN53 took the longest time to reach 50% anthesis, recording 76.79 days, followed by testcross hybrids 74 (76.57 days) and 66 (76.50 days). Line 7 and tester 8 appeared frequently among the top hybrids for early maturity, indicating their importance in earliness in the hybrid combinations they were involved in. Testcross hybrids with line 7 as a parent had reduced plant stature and reduced susceptibility to root lodging. Hybrid combinations involving line 5 were highly prolific, with more ears per plant.

Table 5.9 Grain yield and agronomic testcross performance of the 15 best and poorest five hybrids across optimum environments, with six checks

Rank	Entry	Testcross	GY	Entry	Testcross	AD	Entry	Testcross	ASI	Entry	Testcross	PH	Entry	Testcross	EH
1	46	L6 x T2	8.72	58	L7 x T5	68.86	82	L10 x T1	2.25	58	L7 x T5	227.07	58	L7 x T5	112.86
2	83	L10 x T2	8.50	61	L7 x T8	69.07	92	L11 x T1	2.27	59	L7 x T6	228.21	15	L2 x T5	114.43
3	21	L3 x T2	8.31	62	L7 x T9	69.93	1	L1 x T2	2.27	61	L7 x T8	229.43	61	L7 x T8	117.21
4	45	L6 x T1	8.31	60	L7 x T7	70.64	17	L2 x T7	2.28	77	L9 x T6	230.50	42	L5 x T8	123.21
5	94	L11 x T3	8.27	8	L1 x T8	70.86	88	L10 x T7	2.28	15	L2 x T5	233.79	77	L9 x T6	123.36
6	37	L5 x T3	8.27	33	L4 x T8	70.86	91	L10 x T10	2.29	60	L7 x T7	235.71	57	L7 x T4	123.71
7	82	L10 x T1	8.19	26	L3 x T8	70.93	30	L4 x T4	2.30	62	L7 x T9	236.14	14	L2 x T4	124.36
8	100	L11 x T10	8.14	34	L4 x T9	71.07	97	L11 x T7	2.30	70	L8 x T9	236.71	66	L8 x T4	125.07
9	24	L3 x T5	8.13	89	L10 x T8	71.21	36	L5 x T2	2.31	80	L9 x T9	237.71	69	L8 x T8	125.57
10	52	L6 x T9	8.09	63	L7 x T10	71.21	4	L1 x T4	2.31	69	L8 x T8	238.07	86	L10 x T5	125.64
11	7	L1 x T7	8.07	42	L5 x T8	71.29	18	L2 x T8	2.32	79	L9 x T8	238.29	59	L7 x T6	126.07
12	47	L6 x T3	8.07	23	L3 x T4	71.29	74	L9 x T3	2.32	57	L7 x T4	238.29	31	L4 x T5	127.43
13	32	L4 x T6	8.06	55	L7 x T2	71.43	66	L8 x T4	2.33	76	L9 x T5	238.36	62	L7 x T9	128.14
14	2	L1 x T2	8.04	59	L7 x T6	71.50	70	L8 x T9	2.33	23	L3 x T4	239.86	8	L1 x T8	128.57
15	54	L7 x T1	8.01	80	L9 x T9	71.64	6	L1 x T6	2.33	66	L8 x T4	240.21	60	L7 x T7	128.93
105	58	L7 x T5	6.01	64	L8 x T2	75.79	105	L12 x T5	2.44	10	L1 x T10	265.00	102	L12 x T2	148.71
106	40	L5 x T6	5.84	107	L12 x T7	75.93	10	L1 x T10	2.45	44	L5 x T10	265.07	10	L1 x T10	148.79
107	66	L8 x T4	5.51	83	L10 x T2	76.29	76	L9 x T5	2.45	2	L1 x T2	266.50	101	L12 x T1	149.14
108	59	L7 x T6	5.34	66	L8 x T4	76.50	50	L6 x T7	2.45	91	L10 x T10	266.86	2	L1 x T2	153.57
109	77	L9 x T6	5.16	74	L9 x T3	76.57	79	L9 x T8	2.47	102	L12 x T2	267.50	44	L5 x T10	153.93
1	115		6.10	110		68.86	110		2.33	114		181.47	115		114.97
2	110		5.73	111		71.07	113		2.38	111		188.21	114		119.44
3	112		5.60	114		72.86	112		2.54	115		196.34	110		120.74
4	113		5.38	115		73.29	115		2.57	113		197.14	111		122.74
5	114		5.11	112		74.14	114		2.63	110		213.86	113		133.43
6	111		4.69	113		76.79	111		2.68	112		220.77	112		142.64

GY grain yield (t ha^{-1}); AD days to 50% anthesis; ASI anthesis silking interval; PH plant height (cm); EH ear height (cm); Entry 110= SC403; Entry 111= SC513; Entry 112= SC627; Entry 113= PAN53; Entry 114= PAN4M-21 and Entry 115= P2859W

Table 5.10 Agronomic testcross performances of the 15 best and poorest five hybrids across optimum environments

Rank	Entry	Testcross	EPO	Entry	Testcross	EPP	Entry	Testcross	RL	Entry	Testcross	SL
1	58	L7 x T5	0.49	35	L5 x T1	1.32	57	L7 x T4	2.51	22	L3 x T3	2.53
2	15	L2 x T5	0.49	41	L5 x T7	1.28	56	L7 x T3	2.51	54	L6 x T10	2.58
3	86	L10 x T5	0.50	92	L11 x T1	1.26	59	L7 x T6	2.54	96	L11 x T6	2.64
4	85	L10 x T4	0.50	37	L5 x T3	1.25	20	L3 x T1	2.54	101	L12 x T1	2.65
5	14	L2 x T4	0.50	97	L11 x T7	1.22	106	L12 x T6	2.55	95	L11 x T4	2.65
6	49	L6 x T4	0.51	88	L10 x T7	1.21	60	L7 x T7	2.55	35	L5 x T1	2.66
7	105	L12 x T5	0.51	22	L3 x T3	1.20	61	L7 x T8	2.56	23	L3 x T4	2.66
8	51	L8 x T8	0.51	39	L5 x T5	1.19	70	L8 x T9	2.56	82	L10 x T1	2.67
9	61	L7 x T8	0.51	48	L6 x T4	1.19	75	L9 x T4	2.57	78	L9 x T7	2.68
10	42	L5 x T8	0.51	36	L5 x T2	1.18	79	L9 x T8	2.57	86	L10 x T5	2.69
11	39	L5 x T5	0.52	94	L11 x T3	1.18	31	L4 x T5	2.58	106	L12 x T6	2.69
12	31	L4 x T5	0.52	49	L6 x T5	1.18	53	L6 x T10	2.58	39	L5 x T5	2.70
13	89	L10 x T8	0.52	43	L5 x T9	1.18	83	L10 x T2	2.59	5	L1 x T5	2.71
14	57	L7 x T4	0.52	82	L10 x T1	1.17	86	L10 x T5	2.59	81	L9 x T10	2.71
15	95	L11 x T4	0.52	105	L12 x T5	1.16	55	L7 x T2	2.59	84	L10 x T3	2.73
105	68	L8 x T7	0.58	79	L9 x T8	0.97	72	L9 x T1	2.81	19	L2 x T9	3.22
106	73	L9 x T2	0.58	16	L2 x T6	0.96	77	L9 x T6	2.81	51	L8 x T8	3.23
107	101	L12 x T1	0.58	10	L1 x T10	0.95	109	L12 x T9	2.84	12	L2 x T2	3.24
108	72	L9 x T1	0.59	59	L7 x T6	0.95	90	L10 x T9	2.85	61	L7 x T8	3.25
109	20	L3 x T1	0.59	77	L9 x T6	0.95	40	L5 x T6	2.58	62	L7 x T9	3.26
1	110		0.57	114		0.95	110		2.88	110		2.56
2	112		0.59	110		0.95	111		2.44	115		2.58
3	115		0.59	113		0.93	114		2.45	112		2.83
4	111		0.6	111		0.92	115		2.48	111		2.89
5	114		0.65	112		0.90	112		2.49	113		3.13
6	113		0.67	115		0.87	113		2.54	114		3.14

EPO ear position; EPP number of ears per plant; RL root lodging; SL stalk lodging; Entry 110= SC403; Entry 111= SC513; Entry 112= SC627; Entry 113= PAN53; Entry 114= PAN4M-21 and Entry 115= P2859

5.3.3 Estimation of broad sense heritability and variance components

Broad-sense heritability estimates were highest for grain yield across combined and optimum test environments while low for low N environments (Table 5.11). Heritability estimates for all characteristics were higher than 0.5 across combined and optimum test environments. Root lodging had very low heritability estimates across all test environments studied. Days to anthesis; plant and ear height, and ear position had heritability estimates above 0.5 while some reported traits had very low estimates. Generally, variance due to location was higher than other variance components across all test environments. Genotypic variances were higher than variances due to G x E for several traits across the reported test environments.

Table 5.11 Variance components and broad sense heritability estimates for grain yield and agronomic traits across test environments

Combined test environments (12)									
Variance component	GY	AD	ASI	PH	EH	EPO	EPP	RL	SL
Error Var	0.88	3.93	3.03	173.26	131.80	0.00	0.02	47.26	50.47
Genotypic Var	0.19	3.36	0.15	56.28	41.22	0.00	0.00	0.20	9.01
G x E Var	0.23	0.53	0.06	3.82	6.21	0.00	0.00	5.91	39.50
Location Var	5.56	58.20	1.01	1232.10	635.77	0.01	0.01	15.50	119.88
Heritability	0.77	0.94	0.53	0.88	0.87	0.79	0.77	0.07	0.63
Grand Mean	5.83	72.04	1.53	224.73	122.09	0.54	1.01	3.43	7.78
LSD	1.84	3.88	3.41	25.80	22.50	0.08	0.25	13.47	13.92
CV	16.08	2.75	113.99	5.86	9.40	7.94	12.78	200.40	91.26
Optimum environments									
Error Var	1.04	4.03	1.94	177.18	155.86	0.00	0.02	32.35	80.93
Genotypic Var	0.33	2.30	0.06	56.77	49.47	0.00	0.00	0.00	26.62
G x E Var	0.21	0.21	0.00	0.32	4.69	0.00	0.00	3.65	61.28
Location Var	1.98	87.81	0.18	248.53	322.10	0.00	0.01	7.34	175.65
Heritability	0.76	0.88	0.31	0.82	0.81	0.71	0.73	0.00	0.65
Grand Mean	7.40	73.22	0.92	250.11	136.46	0.54	1.07	3.59	12.69
LSD	1.99	3.93	2.73	26.09	24.47	0.08	0.26	11.15	17.63
CV	13.76	2.74	152.08	5.32	9.15	7.77	12.16	158.51	70.87
low N environments									
Error Var	GY	AD	ASI	PH	EH	EPO	EPP	RL	SL
Genotypic Var	0.47	3.08	3.94	140.07	99.15	0.00	0.01	76.12	13.36
G x E Var	0.09	4.29	0.18	58.84	27.49	0.00	0.00	0.28	0.00
Location Var	0.15	0.68	0.37	11.13	10.57	0.00	0.00	11.16	1.05
Error Var	2.17	26.09	1.27	268.89	405.94	0.01	0.00	34.23	0.90
Heritability	0.48	0.89	0.24	0.74	0.65	0.51	0.47	0.02	0.00
Grand Mean	3.36	69.62	2.42	194.12	97.59	0.50	0.92	3.95	1.67
LSD	1.34	3.44	3.89	23.20	19.52	0.08	0.24	17.10	7.17
CV	20.36	2.52	82.06	6.10	10.20	8.23	13.21	221.13	219.27

Var Variance; G x E genotype x environment interaction; LSD least significance difference; CV coefficient of variation; GY grain yield; AD days to 50% anthesis; ASI anthesis silking interval; PH plant height; EH ear height; EPO ear position; EPP number of ears per plant; RL root lodging; SL stalk lodging

5.3.3 Correlations of grain yield and secondary characteristics

5.3.3.1 Correlations across combined environments

Correlations between measured characteristics ranged between -0.83 to 0.77 (Table 5.12). Grain yield was positive and significantly correlated with ear height, number of ears per plant, ear position, ET and plant height. It was, however, negative and significantly correlated with days to 50% anthesis, ASI, ear aspect, ear rot, root lodging and senescence. Root lodging was negatively correlated with most characteristics. Days to 50% anthesis was negatively and significantly correlated with ear height, ear position, grain texture, while positive and significantly correlated with ASI, ear aspect, ear rots, root lodging and senescence.

There were very low correlations among grain yield of the 12 individual test environments, ranging between -0.18 and 0.39 (Table 5.13). The correlations were mostly less than 0.30. Potchefstroom random drought stress site yield had the lowest correlations with all other sites' yield, ranging between -0.18 and 0.18. This site had only significant correlations for grain yield with low N sites Harare low N1 (which was negative) and Potchefstroom. Ivordale was significantly correlated with several other trials sites, though it was negatively correlated with the random drought stress site (Potchefstroom). Gwebi low N stress environment had some significant correlations with optimum environments (Ivordale and Lusaka) and with other low N sites (Harare low N1 and 2). Most optimum sites had positive and significant correlations among themselves, while most low N sites were also correlated along their corresponding management levels. Potchefstroom (low N) site was, however, not significantly correlated with other low N stress environments.

5.3.3.2 Correlations across specific management levels

Results observed across low N stress environments generally indicate low correlations among characteristics (below 40%), though most of the characteristics had significant correlations (Table 5.14). Higher positive and negative correlations were observed between days to 50% anthesis with ASI and grain yield, ASI and ear aspect and ear position, grain yield and ear aspect, ear and plant height, ear position and ear height, and between grain yield and ear rot. Grey leaf spot was negatively correlated with ear and plant height, root lodging and grain texture, respectively. Apart from being negatively correlated with grain yield, ear rots were significantly correlated with ear and plant height and root lodging. *Puccinia sorghi* was negatively and significantly correlated with root and stalk lodging and grain texture, respectively.

Across random drought stress environments (Table 5.15), grain yield was positively correlated with ear height, number of ears per plant and plant height. ASI was negatively correlated with the number of ears per plant. The number of ears per plant and plant height were negatively correlated with ear position. Stalk lodging was negatively correlated with senescence ($P<0.05$).

Under optimum conditions, many characteristics had correlations coefficients below 40%, although they were mostly significant (Table 5.16). High correlation coefficients of above 50% were observed between ear height and days to 50% anthesis, days to 50% anthesis and ear rots, grain yield and ear aspect, ear position and ear height, grain yield and number of ears per plant, GLS and stalk lodging, GLS and *Puccinia sorghi,* grain yield and plant height, root lodging and husk cover, plant height and husk cover and between *Puccinia sorghi* and stalk lodging. Grain yield was positively correlated with ASI, ear and plant height, number of ears per plant and ear rot, while negatively correlated with ear aspect, ear position and grain texture.

Table 5.12 Associations among characteristics across all combined environments

	AD	ASI	EA	EH	EPO	EPP	ER	ET	GLS	GY	HC	MSV	PH	PS	RL	SEN	SL
ASI	0.75***																
EA	0.34***	0.60***															
EH	-0.53***	-0.44***	-0.52***														
EPO	-0.50***	-0.60***	-0.43***	0.77***													
EPP	0.09	-0.15	-0.31***	-0.25**	-0.32***												
ER	0.34***	0.42***	0.76***	-0.52***	-0.32***	-0.12											
ET	-0.06	-0.29**	-0.09	-0.05	0.03	0.44***	0.34***										
GLS	0.08	-0.08	-0.07***	-0.34***	-0.18*	0.28**	0.18	0.44***									
GY	-0.53***	-0.64***	-0.83***	0.48***	0.35***	0.43***	-0.60***	0.25**	0								
HC	-0.11	-0.28**	-0.25**	-0.04	0.02	0.24**	0.16	0.34***	0.42***	0.21*							
MSV	-0.16	-0.22*	-0.20*	0.23*	0.20*	-0.05	-0.22*	-0.23*	-0.23*	0.23*	0.12						
PH	-0.15	0.01	-0.29**	0.63***	0.09	-0.07	-0.37***	-0.02	-0.28**	0.25**	0.03	0.22*					
PS	0.09	-0.12	0.02	-0.04	0.08	0.31***	0.19*	0.49***	0.08	-0.05	0.13	-0.21*	-0.16				
RL	0.32***	0.41***	0.13	-0.04	-0.08	-0.45***	-0.17	-0.43***	-0.18	-0.24**	-0.37***	-0.15	0.09	-0.33***			
Sen	0.35***	0.28**	0.50***	-0.42***	-0.43***	0.12	0.55***	0.36***	0.13	-0.39***	0.03	-0.23*	-0.18	0.13	-0.25**		
SL	0.18	0.22*	0.09	-0.25**	-0.40***	-0.03	0.18	0.14	0.12	-0.06	-0.09	-0.10	0.12	-0.31***	0.00	0.34***	
Tex	-0.34***	-0.05	0.06	0.31***	0.04	-0.49***	-0.16	-0.34***	-0.35***	-0.02	-0.27**	0.21*	0.49***	-0.44***	0.13	-0.03	0.38***

***P < 0.001, **P < 0.01 and *P < 0.05; AD days to 50% anthesis, ASI anthesis silking interval, EA ear aspect; EH ear height; EPO ear position; EPP number of ears per plant; ER ear rots; ET *Exserohilum turcicum*; GLS grey leaf spot; GY grain yield; HC husk cover; MSV Maize streak virus disease; PH plant height; PS *Puccinia sorghi*; RL root lodging; SEN senescence; SL stalk lodging; TEX grain texture

Table 5.13 Correlations for grain yield across individual test environments

Environment	Code	2	3	4	5	6	7	8	9	10	11	12
Cedara Opt 1	2	0.18										
Cedara Opt 2	3	0.37***	0.20*									
Gwebi Opt	4	0.37***	0.20*	0.31***								
Gwebi low N	5	0.12	0.16	-0.04	0.10							
Harare low N 1	6	0.00	0.14	0.02	0.21*	0.23*						
Harare low N 2	7	0.20*	0.05	0.12	0.22*	0.28**	0.19*					
Ivordale Opt	8	0.24**	0.19*	0.26**	0.23*	0.24*	0.24*	0.36***				
Lusaka Opt	9	0.16	0.34***	0.18*	0.12	0.19*	0.15	0.07	0.14			
Mpongwe Opt	10	0.18	0.31***	0.39***	0.34***	0.03	0.02	0.06	0.20*	0.24**		
Potchefstroom Low N	11	0.11	0.13	0.17	-0.02	0.12	0.03	-0.07	0.06	0.23*	0.10	
Potchefstroom Random	12	0.09	0.12	0.16	0.13	0.09	-0.18*	0.05	-0.01	0.14	0.15	0.18*

***P < 0.001, **P < 0.01 and *P < 0.05; opt optimum; random random drought stress

Table 5.14 Correlations among characteristics across low N environments

	AD	ASI	EA	EH	EPO	EPP	ER	ET	GLS	GY	HC	PH	PS	RL	SEN	SL
ASI	0.76***															
EA	0.32***	0.55***														
EH	-0.43***	-0.36***	-0.45***													
EPO	-0.42***	-0.51***	-0.38***	0.78***												
EPP	0.04	-0.16***	-0.32***	-0.26**	-0.34***											
ER	0.31***	0.40***	0.74***	-0.41***	-0.27**	-0.12										
ET	-0.12	-0.33***	-0.14	0.03	0.07	0.41***	0.28**									
GLS	0.04	-0.14	-0.12	-0.25**	-0.12	0.27**	0.11	0.39***								
GY	-0.52***	-0.61***	-0.81***	0.41***	0.28**	0.45***	-0.57***	0.31***	0.06							
HC	-0.07	-0.25**	-0.21*	-0.07	-0.03	0.24*	0.19*	0.32***	0.44***	0.16						
PH	-0.12	0.04	-0.25**	0.67***	0.13	-0.10	-0.30***	0.00	-0.23*	0.20*	-0.01					
PS	0.06	-0.13	-0.01	0.03	0.13	0.24*	0.17	0.41***	0.06	-0.01	0.21*	-0.08				
RL	0.28**	0.35***	0.09	0.01	0.00	-0.42***	-0.19*	-0.47***	-0.20*	-0.18	-0.36***	0.11	-0.36***			
SEN	0.29**	0.24**	0.43***	-0.30***	-0.34***	0.11	0.47***	0.30***	0.10	-0.32***	0.02	-0.12	0.04	-0.28		
SL	0.15	0.21*	0.05	-0.21*	-0.37***	-0.01	0.14	0.07	0.08	-0.03	-0.11	0.08	-0.37***	0.00	0.27**	
TEX	-0.29**	-0.02	0.11	0.29**	0.05	-0.48***	-0.11	-0.28**	-0.30***	-0.05	-0.29***	0.46***	-0.35***	0.16	0.01	0.33***

***P < 0.001, **P < 0.01 and *P < 0.05; AD days to 50% anthesis, ASI anthesis silking interval, EA ear aspect; EH ear height; EPO ear position; EPP number of ears per plant; ER ear rots; ET *Exserohilum turcicum*; GLS grey leaf spot; GY grain yield; HC husk cover; MSV Maize streak virus disease; PH plant height; PS *Puccinia sorghi*; RL root lodging; SEN senescence; SL stalk lodging; TEX grain texture

Table 5.15 Correlation of characteristics across random drought stress environments

	AD	ASI	EH	EPO	EPP	GY	PH	RL	SEN
ASI	-0.08								
EH	0.11	-0.17							
EPO	0.05	0.11	0.22						
EPP	0.06	-0.35***	0.16	-0.25**					
GY	-0.19	-0.09	0.38***	-0.05	0.44***				
PH	0.07	-0.23	0.71***	-0.47***	0.32***	0.37***			
RL	-0.14	0.22	0.04	0.12	-0.15	0.02	-0.10		
SEN	0.11	0.10	-0.09	-0.08	-0.02	0.06	-0.06	0.13	
SL	-0.07	-0.15	-0.13	-0.09	0.06	0.08	-0.01	-0.20*	-0.21*

***P < 0.001, **P < 0.01 and *P < 0.05; AD days to 50% anthesis, ASI anthesis silking interval, EH ear height; EPO ear position; EPP number of ears per plant; GY grain yield; PH plant height; RL root lodging; SEN senescence; SL stalk lodging

Table 5.16 Correlations across optimum environments

	AD	ASI	EA	EH	EPO	EPP	ER	ET	GLS	GY	HC	MSV	PH	PS	RL	SL
ASI	-0.15															
EA	0.07	-0.27**														
EH	0.54***	0.15	-0.32***													
EPO	0.44***	0.02	-0.17	0.64***												
EPP	-0.01	0.23*	-0.41***	0.29**	-0.09											
ER	-0.74***	0.24**	-0.24*	-0.44***	-0.40***	0.15										
ET	-0.22*	0.09	0.03	0.28**	0.05	-0.07	0.24*									
GLS	0.35***	0.35***	0.11	0.37	0.41***	0.17	-0.39***	-0.05								
GY	-0.16	0.19*	-0.52***	0.20*	-0.24*	0.86***	0.36***	0.11	-0.12							
HC	0.24*	0.13	-0.05	0.28**	-0.11	0.40***	-0.15	-0.18	0.23*	0.35						
MSV	0.18	0.00	0.21*	0.25**	0.25	0.10	-0.04	0.32	0.05	0.08	0.18*					
PH	0.25**	0.00	-0.22*	0.56***	-0.17	0.44***	-0.12	0.27***	-0.09	0.52***	0.53***	0.20*				
PS	-0.24*	-0.37	0.32***	-0.29**	-0.41***	-0.05	0.26**	0.41**	-0.58***	0.08	-0.24*	0.26**	0.18			
RL	0.11	0.05	0.35***	-0.06	-0.18	0.25**	-0.27**	-0.49***	0.35***	0.07	0.51***	-0.03	0.12	-0.20		
SL	-0.29**	-0.31	0.36***	-0.58***	-0.47***	-0.22*	0.36***	0.10***	-0.50***	-0.02	-0.42***	0.01	-0.15	0.58***	-0.11	
TEX	-0.11	-0.35	0.34***	-0.33***	-0.14	-0.45***	-0.21	-0.22	-0.27**	-0.41***	0.07	0.10	-0.06	0.19*	0.23*	0.10

***P < 0.001, **P < 0.01 and *P < 0.05; AD days to 50% anthesis, ASI anthesis silking interval, EA ear aspect; EH ear height; EPO ear position; EPP number of ears per plant; ER ear rots; ET *Exserohilum turcicum*; GLS grey leaf spot; GY grain yield; HC husk cover; MSV Maize streak virus disease; PH plant height; PS *Puccinia sorghi*; RL root lodging; SEN senescence; SL stalk lodging; TEX grain texture

5.3.4 Principal component analysis

In the principal component analysis (Figure 5.3), PC1 (45.75%) and PC2 (18.95%) explained a cumulative 64.7% of the total variation presented in the maize genotypes evaluated. PC1 accounted for the largest amount of the variation, indicating that most of the characteristics were correlated to PC1. PC2 explained the variation not accounted for by PC1. Characteristics showing an acute angle (less than 45^{o}) between them, showing strong positive correlations, while those that are obtuse showed negative correlations (as the angle approaches 180^{o}) among those characteristics. Grain yield was highly correlated with number of ears per plant and GLS. It was, however, negatively correlated with ear aspect and ear rots. Ear position was negatively correlated with ASI. Grain texture correlated well with stalk lodging. *Puccinia sorghi*, days to 50% anthesis, plant height, ET, ear height, root lodging were highly correlated with each other as these characteristics were clustered together.

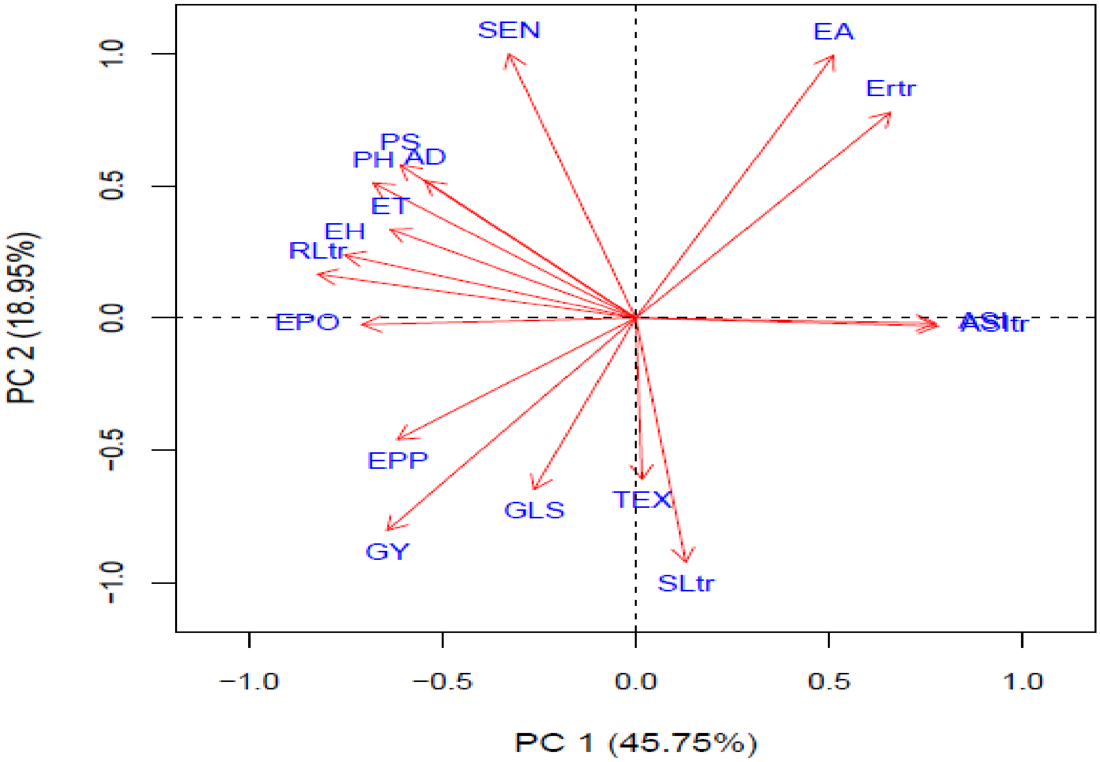


Figure 5.3 Principle component analysis for measured characteristics across all environments

5.4 Discussion

Testcross performance evaluation of maize hybrids helps in identification and selection of high yielding, stable and well adapted genotypes across test environments. Selection under several stress environments is essential to combine stress tolerance in both drought and low N environments, and also to prevent yield penalties under optimum environments (Bruce et al., 2002; Weber et al., 2012; Cairns et al., 2013a;b). Genotypes are then selected based on their combined tolerance to different stresses and selected for either adaptability or stability (Bruce et al., 2002).

The test environments used in this study provided a representation of commercial and smallholder communal environments. According to Bruce et al. (2002), diverse environments are ideal for conducting in-depth measurements related to plant physiological responses. The inbred lines used in this study have been selected for several pedigree generations and screened for their relative tolerance to both drought and low N stress environments. Genotypes that are ideal for release as hybrids are supposed to perform well across several environments, which indicate their suitability across wide growing environments. According to Yan and Kang (2003) and Meseka et al. (2008), the use of several test environments (drought, low N and optimum environments) greatly improves the efficiency of identifying suitable testcross hybrids that are adaptable, and stable (reduced or no G x E interaction) across environments. Across environments ANOVA in this study showed significant G x E interactions ($P < 0.05$) for grain yield, days to 50% anthesis, plant and ear height, number of ears per plant, root lodging and stalk lodging among the drought and low N tolerant testcross hybrids evaluated. G x E interactions were also observed under both low N stress and optimum environments. The occurrence of significant G x E interactions indicates genotype rank changes and different potentials of the test environments. Maize shows wide fluctuations in terms of yielding ability when grown over wide and varied environments (Fan et al., 2007).

There were significant differences observed among testcross hybrids and test environments. The occurrence of significant differences for grain yield between genotypes indicates the existence of variability that can be exploited for hybrid improvement under stress and non-stress environments. Similar results were reported in other studies (Bolaños and Edmeades, 1993; Lafitte and Edmeades, 1994; Vasal et al., 1999; Edmeades et al., 1999; Bänziger et al., 1999; 2000; Diallo et al., 2004; Derera et al., 2008; Kumar et al., 2008). Genotypes performing well (high yielding) across these stressful environments, and showing less G x E interactions, can be classified as stable and widely adapted. Season variability, which is enhanced by the ENSO effect and its interaction with the ITCZ, causes seasonal droughts, and unpredictable, low rainfall across the southern parts of Africa (Dilley and Heyman, 1995; Jury, 2000; Nicholson et al., 2003; Singh, 2006; Shiferaw et al., 2014).

Grain yields under different management levels were significantly different from each other. According to Vivek et al. (2005), low N fertilization trials targets between 20-35% grain yield decrease from the optimal sites. The results indicated over 50% for low N stresses, and 34% decrease under random drought stress sites. The levels of low N stress were more indicative of the conditions of most farmers' fields in SSA. Significant G x E interactions indicate the occurrence of cross-over interactions (Fehr, 1987; Bänziger and Cooper, 2001). Several authors have documented the occurrence of G x E interactions in maize when exposed to stress conditions, especially drought and/or low N stress (Bänziger and Cooper, 2001; Bänziger et al., 2004; Mohammadi and Haghparast, 2010; Tiawari et al., 2011, Cooper et al., 2014). G x E has been cited to cause challenges in identifying high performing genotypes but the use of several test environments can reduce G x E interactions and identify suitable genotypes performing well under all tested environments.

The results indicated that there were significant yield differences among genotypes across the management levels. Yields were lowest across low N environments (mean of 3.37 t ha^{-1}), followed by the random drought stress environment (4.72 t ha^{-1}), and highest under optimum environments (7.31 t ha^{-1}). Across location mean for grain yield was 5.78 t ha^{-1}. Yield reductions compared to the optimum environments mean were 53.89% (low N) and 35.43% (random drought stress). Varying grain yield reduction under drought, ranging from 1-76% depending on the severity, timing, intensity and stage of occurrence was reported. Compared to optimum sites, low N stress reduced the number of ears and plant stature by 14% and 22.34% respectively, while it increased ASI by 5%. The research indicated that maize loses its prolificacy and vigour when exposed to stressful conditions. Similar findings have been reported on maize across stress and non-stress environments (Bänziger et al., 1997; 1999; Gissa et al., 2007; Derera et al., 2008; Umar et al., 2015). Weber et al. (2012) reported over 70% yield reductions under low N and drought stress. Other researchers have obtained even higher yield reductions of maize under stress conditions, in excess of 80% (Betrán et al., 1997; Bänziger et al., 1997; 2006). Byrne et al. (1995) indicated increased ASI when maize is exposed to stress conditions. Though the results indicate the importance of drought and low N stress in reducing the value of grain yields, results from this study indicated the availability of potential cultivars that yielded better than average yields obtained in most farmers' fields in southern Africa, which ranges well below 2 t ha^{-1}. Breeding for drought and low N stress tolerance is an indispensable tool for maize improvement in tropical and sub-tropical regions where the relative importance of drought in the coming years will most likely increase (Williams and Funk, 2010). The best approach towards reducing the deleterious effects of droughts and low N stress is the use of hybrids with high levels of tolerance to drought and low N environments (Kamara et al., 2004). These hybrids can efficiently use limited resources from the soil, and utilize them efficiently.

The higher broad sense heritability estimates for most traits across combined and under optimum test environments was expected. High broad sense heritability estimates indicates that some traits had lower environmental interactions than others, and thus can be used for selection. However, breeders prefer high heritability estimates under low potential test environments that will aid in selection under those conditions. Hence traits which showed higher heritability estimates like days to anthesis, plant and ear height as well as ear position can be used for selection under low N test environments. Reports by Akbar et al. (2008) and Ogunniyan and Olakojo (2014) have also demonstrated high heritability estimates of several traits controlling grain yield in maize.

There were significant differences among the testcross hybrids for grain yield and agronomic characteristics across and at individual management levels. The differences in mean performance among the selected drought and low N stress tolerance genotypes indicated the large variability among the line and testers used in the study. High yielding cultivars under both optimum and random drought stress conditions are useful hybrids that can be adopted or advanced or recommended for further evaluation to confirm the results or for release if their performance is consistent. Random drought stress is usually unpredictable and many farmers suffer yield losses due to these droughts. When the hybrids perform consistently for several seasons and environments, they can be released. The use of these high performing hybrids will increase the chances of boosting maize productivity under stress.

The results also indicated significant differences for days to 50% anthesis, plant and ear height, ear position and the number of ears per plant. Drought, random or managed, usually enhances barrenness in maize hybrids due to increased anthesis silking interval, and poor seed set (Westgate and Boyer, 1986). The testcross hybrids showed positive and significant correlations between prolificacy and grain yield, indicating positive results towards increased vigour under stress conditions. Under optimum conditions, the number of ears per plant were significantly correlated with grain yield (r = 0.86***) while under random drought (r = 0.44***), low N (r = 0.45***) stress conditions and under combined environments (r = 0.43***), it was highly correlated with grain yield. Secondary characteristics like number of ears per plant can be useful under stress conditions. Similar findings have been reported by Bolaños and Edmeades (1993; 1996); Bruce et al. (2002); Monneveux et al. (2005; 2008); Campos et al. (2006); Badu-Apraku et al. (2013); Edmeades (2013) and Masuka (2014).

Anthesis silking interval and grain yield have been reported to be negatively correlated in stress environments (Magorokosho et al., 2003). The current study indicated that grain yield was negatively correlated with ASI at r = -0.61*** (low N); r = -0.09 (random drought stress), and r = -0.64*** (across environments) while they were positively correlated under optimum conditions (r = 0.19*). Similar results were reported by Badu-Apraku et al. (2013) and Masuka (2014).

There were notable differences in plant and ear height among the genotypes across and within individual management levels. Testcross hybrids had a trial mean plant height of 223.18 cm and decreased values under random drought (169.57 cm), low N stress (194.22 cm) and increased values under optimum environments (247.39 cm). Plant stature was highly reduced under stress. Plant height was low but significantly correlated with grain yield under random drought stress, low N stress and under combined environments. However, grain yield was strongly correlated with plant height under optimal conditions. Selection for reduced plant height under drought stress conditions is vital since the genotype matures earlier and helps to escape mid-season drought, though increased plant height has been linked to higher yields. Moser et al. (2006) and Masuka (2014; Masuka et al., 2017) observed no change in plant height under random drought stressed environments.

5.5 Conclusions

The growing occurrence of drought and poor soil fertility challenges in southern Africa is already negatively affecting maize productivity. Maize is an important staple crop for the majority of the smallholder farmers in this region. The potential risk of these farmers is further increased by lack of hybrids that can withstand drought and low N fertility, which has drastically impeded the planned Green Revolution in the region. This study was conducted to evaluate the testcross performance of hybrids that were constituted from drought and low N tolerant lines and single crosses. One hundred and twenty hybrids constituted from the selected 12 drought and low N tolerant lines were crossed to 10 single cross testers, all from the CIMMYT ESA programme, and evaluated for their testcross performance across 12 environments representing the major maize growing environments in southern Africa. Several hybrids were identified which performed better than the local commercial checks evaluated. These testcross hybrids included entry 46 (7.2 t ha^{-1}), 83 (6.7 t ha^{-1}), 15 (6.61 t ha^{-1}), 52 and (6.5 t ha^{-1}), 43 and 21 (6.4 t ha^{-1}), 97 and 30 (6.38 t ha^{-1}), 100 and 84 (6.36 t ha^{-1}). Entries that performed well across all environments have compounded enough tolerance that enables them to be cultivated across stress and non-stress conditions. The line x tester model used under this investigation; and the multi-locations selected for testcross evaluations were successful in identifying potential testcross hybrids for cultivation.

5.6 References

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CHAPTER 6

Determining testcross performance of late maturity maize hybrids using best linear unbiased predictors under optimal, drought and low N stress

Abstract

Late maturity maize hybrids often produce higher yields per unit area compared to early maturity hybrids. This is due to the longer grain filling period, which permits the extended accumulation of biomass with respect to yield. However, droughts and low N fertility often hinder the yield outcome of these hybrids, as the challenges occur randomly over the cropping season. A study was conducted during the 2015/2016 season in Zimbabwe, South Africa and Zambia, to evaluate the performance of 155 testcrosses along with four local commercial checks under drought and low N stress environments. The testcrosses were produced following a line x tester mating design involving 26 inbred lines and six testers and were analysed by the best linear unbiased predictors (BLUPs) using META-R software. Trials were arranged in an alpha lattice design with two replicates. Random drought stress reduced maize yield by 79% while low N stress reduced it by 61%, indicating that random drought stress effects were more severe in terms of yield reduction of late maturity hybrids. Late maturity maize hybrids face a larger risk of exposure to drought conditions that eventually reduce yields drastically. Large variability was observed among the evaluated hybrids, with high yields observed for entries 109 (6.08 t ha^{-1}), 115 (6.05 t ha^{-1}), 22 (5.99 t ha^{-1}), 5 (5.92 t ha^{-1}), 63 (5.91 t ha^{-1}), 10 (5.9 t ha^{-1}) and 24, 21, 20 and 2 (5.87 t ha^{-1}) across all the test environments. These testcrosses performed better than the local commercial checks used and could be recommended as potential hybrids for production in drought prone and low N stress environments.

6.1 Introduction

Maize is the ideal crop to help address food security issues within the resource poor communities of the world. The demand for maize is expected to double by 2050 in the developing world (Rosegrant et al., 2008; Ray et al., 2013) and is currently estimated to cover 100 million hectares in these areas, with the majority being smallholder farmers (FAOSTAT, 2010; Graeub et al., 2016). It is a principal crop in Africa, accounting for an average of 32% of consumed calories in eastern and southern Africa, and rising to 51% of calorie consumption in some countries. The adoption of maize globally far exceeds all other cereals, with white maize dominating the market, compared to yellow maize. The high adoption rate is due to its potential heterotic effects, which often results in higher productivity per unit area. Maize is the most productive crop, ahead of rice and wheat and the three together are the most important cereals of the world (FAOSTAT, 2005; 2008). The recent pressure exerted by the increasing global population and effects of global warming, especially in the tropical regions, pose significant challenges to maize production. Previous research (IPCC, 2007) suggests that SSA will be affected much by the increasing temperatures, frequent droughts and changes in climate due to global warming. Maize as a C_4 crop will have its photosynthetic efficiency reduced by these increasing challenges. Despite the increased importance of maize, drought and low soil infertility, especially low N, have consistently been highlighted as the major yield reducing constraints in SSA limiting maize productivity, food security and economic growth (Bänziger et al., 2006). These stresses have complex interrelationships, for example drought stress reduces nutrient uptake (Weber et al., 2012) justifying the development of stress tolerant genotypes.

Drought alone has been cited to cause over 90% yield losses when it occurs between a few days before anthesis and early grain filling stages (NeSmith and Ritchie, 1992). Badu-Apraku et al. (2004) reported 53% yield losses due to drought with its effects varying according to the stages of maize development. On the other hand, N is a vital nutrient required for vegetative growth of a crop, and its unavailability or low amounts in the soil will cause significant yield losses. Losses due to low N in SSA have been reported at 44%, and those due to weeds, including Striga, at 19% (Gibbon et al., 2007). Heavy nutrient mining, poor soil nutrient recapitalization, top soil erosion has been severe causes of nutrient depletion in SSA. The region also loses nutrients through improper agricultural practices like monocultures, inappropriate cultivation practices (cropping on sloppy areas) resulting in poor soil retention, poor nutrient uses and cycling and increased rates of soil acidity on areas where there is too much rainfall. Thus nutrient availability to plants is highly reduced each season. The SSA region is also estimated to lose more than 4 Mt of fertilisers every year (30-60 kg NPK $ha^{-1} yr^{-1}$) on 45% of cropped land area, and more than 60 kg NPK ha^{-1} yr^{-1} on a further 40% (Henao and Baanante, 2006; Craswell and Vlek, 2013). There is evidence of the benefits of the utilization of genetics (tolerance) in the production of stress-tolerant genotypes, as determined by multi-environment trials. Managed drought and low N input tolerant varieties have proved to be beneficial, as they out-yielded the commercial varieties by approximately 40% at trial yield levels of 1 t ha^{-1} and 2.5% at 10 t ha^{-1} (Bänziger et al., 2006). However, due to the continued efforts by private and public organizations to address these challenges, results may be even better than those reported for 2006.

The use of drought and low N tolerant genotypes will reduce crop losses. The success of maize breeding has been linked to the wide genetic diversity within the maize genome. Plant breeders utilize this variability as a tool for improvement under diverse conditions. The presence of satisfactory genetic diversity and good genetic factors derived from parents, define progress from selection for improved adaptation and desirable agronomic characteristics (Dreisigacker et al., 2004).

Testcross performance evaluation offers the opportunity to identify better performing parents and parental combinations that are needed in maize production and improvement. CIMMYT develops hundreds of new lines with the view of identifying better performing varieties, for specific objectives. Plant breeders have extensively adopted testcross performance as a tool for the evaluation of the relative *per se* performance of inbred lines to aid in line advancement in pedigree breeding.

Several methods have been proposed and tested for their efficiency to predict hybrid performance. BLUPs have shown great potential in maize breeding and improvement (Bernardo, 2002). The use of mixed model methodology has been proved to be useful in the calculation of BLUPs of the random effects (testcross performance or genetic gains) by maximising the combined density function, considering both fixed and random effects of the mixed model. The accuracy of the predictions are based on estimates of the variance components that can be estimated either by the restricted maximum likelihood (REML) and BLUPs, especially in experiments that show some degree of imbalance (Borges et al., 2010).

Maize germplasm is usually grouped according to their divergent heterotic patterns. This includes the line per se performance and heterosis (Smith, 1986; Hallauer, 1990), general combining ability (Cockerham, 1967; Melchinger et al., 1987), BLUPs (Bernardo, 1994; 1996; 1999), molecular genetic distances, marker-based prediction of SCA and heterotic performance (Vuylsteke et al., 2000), among others. Prediction of hybrid performance based on the per se performance of inbred lines has limitations due to the masking dominance effects (Smith, 1986; Hallauer, 1990). BLUPs are promising for predicting hybrid performance using trait-based BLUPs and/or trait and molecular data BLUPs (Bernardo, 1994; 1996; 1999). These estimations include the use of genetic relationships among parental lines, based on co-ancestry coefficients estimated from pedigree records or molecular marker data. The concept of BLUPs was developed by Henderson (1975), initially for estimation of breeding values in animal breeding. It was then adopted by others (Bernardo, 1994; Charcosset et al., 1998; Piepho et al., 2008; Schrag et al., 2009) for the prediction of untested single crosses based on the phenotypic data of related hybrids, and later on using molecular data (Bernardo, 2008). Xu et al. (2000) have successfully proved the effectiveness of BLUPs in rice breeding.

In order to select better performing hybrids, this study was conducted to determine the test cross performance of late maturity hybrids, developed from 26 late maturity inbred lines testcrossed to six testers, across low N, random drought stress and optimum test environments in SSA.

6.2 Materials and methods

6.2.1 Plant materials

A total of 216 three-way hybrids were generated from a 26 x 6 line x tester procedure and evaluated together with four local commercial checks (SC719, PAN7M-81, PAN53 and PHB30G19) were evaluated across 15 test environments in southern Africa as described in Chapter 4 (Section 4.2.1).

6.2.2 Trial management and data collection

Trials were managed as described in Chapter 4 (Section 4.2.3). Data was collected as described in Chapter 3 (Section 3.2.4).

6.2.3 Experimental design and statistical analysis

The experimental design was an incomplete block design (alpha lattice) according to Patterson and Williams (1976) with two replications. The plots consisted of four rows of 4 m length, with an in-row spacing of 0.25 m and inter-row spacing of 0.75 m. The data from individual sites were subjected to ANOVA using Genstat 18th Edition (VSN-International, 2015). ANOVA for genotypes (G), environments (E) and G x E interaction were also done per site. Multi-environment trial analysis (META-R, Schwarzer et al., 2016) was used to estimate BLUPs (Bernardo, 1994; Charcosset et al., 1998; Piepho et al., 2008; Schrag et al., 2009) of the testcross hybrid performance across the 15 test environments. Principal component analysis was done and correlations were determined with Genstat 17th Edition statistical software (VSN-International, 2015). Loadings of 0.3 and more on each PC were considered to be significant.

6.3 Results

6.3.1 Analysis of variance

ANOVA across all test environments indicated highly significant ($P < 0.001$) genotype, environment and G x E interaction effects for all the investigated characteristics (Figure 6.1; Table 6.1). There was highly significant G x E interactions ($P < 0.001$) for grain yield across low N test environments. Genotype and environment effects under low N management were highly significant ($P < 0.001$) for all characteristics except ASI. Genotype by environment interactions across optimum test environments were highly significant ($P < 0.001$) for grain yield, ears per plant, days to 50% anthesis and ASI. There were highly significant ($P < 0.001$) genotype and environment effects for all the evaluated characteristics under optimum test environments. Across random drought stress sites, G x E interactions were only significant (at least $P < 0.01$) for days to 50% anthesis, ASI, ear height and plant height. Genotypes exhibited significant differences for days to 50% anthesis, ASI, ear height, plant height and ear position. Environments also had highly significant ($P < 0.001$) effects on all the characteristics except ears per plant across random drought stress environments.

6.3.2 Grain yield and agronomic testcross performances across test environments

Grain yield ranged between 0.83 and 14.4 t ha^{-1}, with a mean of 7.59 4 t ha^{-1} across optimum test environments; 0.13 to 13.12 t ha^{-1}, with a mean of 2.98 t ha^{-1} under low N test environments; and 0.02 to 9.8 t ha^{-1} with a mean of 1.54 t ha^{-1} across random drought stress environments (Figure 6.1). There were highly significant correlations among the management levels used, based on grain yield (Table 6.2). High correlations were observed for combined vs low N ($r = 0.85^{***}$) and optimum conditions ($r = 0.95^{***}$), while low for random drought stress ($r = 0.42^{***}$). There was also low but significant correlations between random drought and low N stress management levels ($r = 0.36^{***}$) and optimum conditions ($r = 0.28^{***}$). Compared to optimum environments, low N and random drought stress reduced grain yields by 60.74% and 79.71%, respectively. Low N and random drought stress increased days to 50% anthesis by 3.37 and 5.61%, respectively (Table 6.3).

Table 6.1 Mean squares for grain yield and agronomic characteristics for the testcross hybrids evaluated across combined, low N, optimum and random drought stress environments

Source	df	GY	EPP	AD	ASI	EH	PH	EPO
Combined across all 15 test environments								
Rep	1	54.37***	0.14	1.45	0.25	3275.50***	6059.80***	0.00
Entry	154	16.41***	0.13	104.37***	8.25***	1035.10***	2027.40***	0.01***
E	14	2600.12***	8.31	18027.78***	1017.02***	197118.10***	446057.10***	1.26***
G x E	2156	1.70***	0.03	6.94***	3.06***	225.50***	503.50***	0.00***
MSE		1.12	0.02	5.58	2.44	193.50	366.80	0.00
Mean		4.94	0.97	75.49	1.71	117.30	221.90	0.53
SE		1.06	0.15	2.36	0.13	13.91	19.15	0.04
CV		21.44	15.12	3.13	5.50	11.86	8.63	8.44
Low N, five environments								
Rep	1	7.10**	0.00	7.87	3.62	6191.30***	10161.20***	0.01***
Entry	154	5.25***	0.05	57.87***	7.03	507.40***	1049.30***	0.01***
E	4	361.43***	1.56	11352.04***	691.77	87070.30***	285559.70***	1.64***
G x E	770	1.21***	0.02	5.53	3.21	173.30	273.80	0.00
MSE		0.91	0.02	4.84	2.88	195.80	320.70	0.00
Mean		2.89	0.92	76.43	1.61	103.80	200.50	0.52
SE		0.95	0.13	2.20	1.70	13.99	17.91	0.05
CV		32.03	14.27	2.88	6.16	13.48	8.93	9.09
Optimum, eight environments								
Rep	1	25.10***	0.35***	2.95	0.50	952.90**	1066.10*	0.00
Entry	154	15.57***	0.08***	44.12***	2.67***	705.80***	1161.00***	0.01***
E	7	805.62***	3.02***	27240.33***	95.11***	56097.40***	59311.80***	0.60***
G x E	1078	1.86***	0.02***	5.74**	1.43***	130.00	192.00	0.00
MSE		1.30	0.01	4.86	1.19	133.00	182.80	0.00
Mean		7.59	1.07	73.94	0.87	135.70	252.50	0.54
SE		1.14	0.12	2.21	1.09	11.53	13.52	0.04
CV		15.03	11.34	2.98	4.71	8.50	5.36	6.72
Random drought stress, two environments								
Rep	1	38.52***	0.00	22.84	10.58	1391.40	506.00	0.05***
Entry	154	1.12	0.11	22.07***	8.43***	689.10***	2090.00***	0.01***
E	1	269.51***	36.98	21147.81***	1990.84***	549869.80***	459675.00***	5.33***
G x E	154	1.03	0.08	15.34**	8.29***	644.10***	2255.00***	0.00
MSE		1.07	0.06	10.24	5.51	382.90	1134.00	0.00
Mean		1.54	0.76	78.08	4.99	93.10	179.30	0.51
SE		1.03	0.24	3.20	2.35	19.57	33.68	0.06
CV		67.13	31.40	4.10	47.06	21.02	18.78	11.40

***P < 0.001; **P < 0.01 and *P < 0.05; Rep replication; E environment; G x E genotype x environment; MSE mean square error; LSD least significant difference; SE standard error; GY grain yield; EPP number of ears per palnt; AD days to 50% anthesis; ASI anthesis silking interval; EH ear height; PH plant height; EPO ear position

ASI was increased by 84.57% and 473.71% under low N and random drought stress management levels, respectively. Low N stress reduced both plant and ear height by 20.59% and 23.51%, respectively, while random drought stress reduced the same by 28.99% and 31.39%, respectively. Prolificacy was also reduced by low N and random drought stress by 14.14 and 28.77%, respectively.

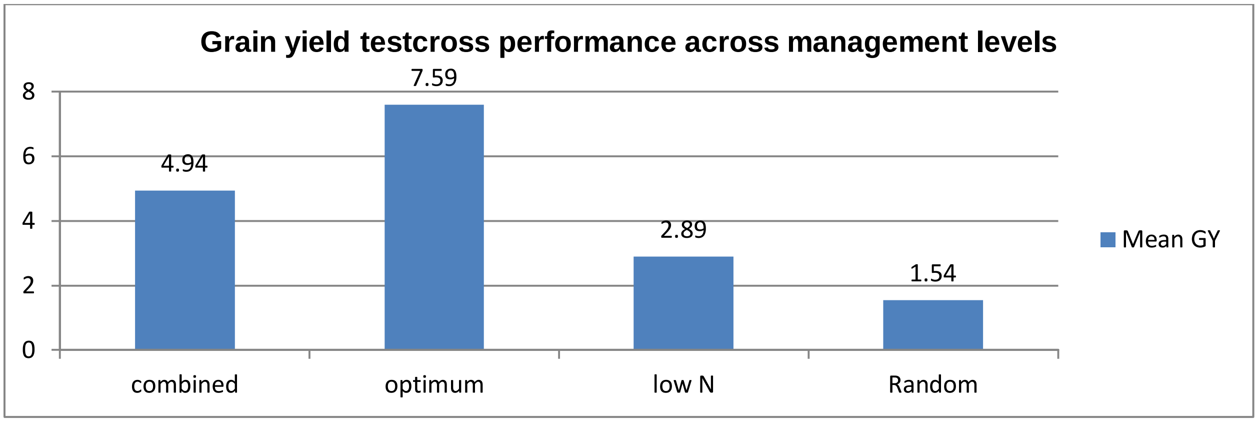

Figure 6.1 Mean grain yield performance across management test environments (LSD =1.6)

Table 6.2 Correlations for grain yield among the management levels

	Combined	Low N	Optimum
Low N	0.85***		
Optimum	0.95***	0.69***	
Random drought	0.42***	0.36***	0.28***

***P < 0.001; **P < 0.01; *P < 0.05

Table 6.3 Mean agronomic performance of testcross hybrids across three management levels

Trait	Optimum	Low N	% change	Random drought	% change
GY	7.59	2.98	60.74	1.54	79.71
AD	73.94	76.43	-3.37	78.09	-5.61
ASI	0.87	1.61	-85.06	4.99	-473.56
PH	252.50	200.50	20.59	179.30	28.99
EH	135.70	103.80	23.51	93.10	31.39
EPO	0.54	0.52	3.70	0.51	5.56
EPP	1.07	0.92	14.02	0.76	28.97

GY grain yield; AD days to 50% anthesis; ASI anthesis silking interval; PH plant height; EH ear height; EPO ear position; EPP number of ears per plant

6.3.3 Best linear unbiased predictors for grain yield and agronomic characteristics across test environments

Testcross hybrid entry 109 recorded the highest mean yield across the combined test environments (Table 6.4), followed by entries 115, 22 and 5. The highest ranking testcross hybrid did not yield significantly higher than the local commercial checks across the test environments. The lowest yielding entries 67 (L12 x T2) and 76 (L13 x T5) were, however, significantly lower yielding than the three local commercial checks; SC719, PAN7M-81 and PAN53. Entry 67 took the most number of days to reach 50% anthesis (80.7 days), followed by entries 37 (79.7 days); 107 (78.9 days) and 61 (78.8 days). These testcross hybrids were significantly lower yielding than the highest yielders and the local commercial checks across all test environments. Entry 76 was among the first to reach anthesis (72.6 days), but recorded the lowest grain yield across the test environments. Plant height and prolificacy did not differ significantly ($P < 0.05$) for the highest yielders and the local commercial checks across the test environments (Table 6.4).

Table 6.4 BLUPs for the highest 10 and poorest five yielding (t ha^{-1}) hybrids and four local commercial checks across 15 combined test environments

Hybrid	Cross	GY	AD	ASI	PH	EH	EPO	EPP
109	L19 x T4	6.08	75.98	1.33	233.88	125.42	0.54	1.04
115	L20 x T4	6.05	77.55	1.13	231.06	119.03	0.52	0.99
22	L4 x T4	5.99	74.53	2.17	228.80	119.69	0.52	0.97
5	L1 x T5	5.92	74.44	1.34	218.67	115.62	0.53	1.08
63	L11 x T4	5.91	76.68	1.60	228.70	124.67	0.54	1.01
1	L1 x T1	5.90	74.70	1.04	220.85	121.85	0.56	1.08
24	L4 x T6	5.87	73.42	1.84	228.58	123.31	0.54	0.98
21	L4 x T3	5.87	74.75	2.13	231.74	124.62	0.53	0.95
20	L4 x T2	5.87	76.32	2.05	232.30	124.79	0.54	0.93
2	L1 x T2	5.87	76.71	1.17	225.98	122.66	0.54	1.05
106	L19 x T1	3.27	77.82	0.84	213.28	116.99	0.55	0.96
112	L20 x T1	3.19	77.46	1.08	207.39	110.27	0.53	0.91
37	L7 x T2	3.04	79.67	1.72	220.08	116.63	0.53	0.80
67	L12 x T2	3.04	80.74	1.50	217.06	118.93	0.55	0.79
76	L13 x T5	2.92	72.60	2.26	205.75	105.80	0.51	0.98
SC719		5.56	76.69	1.60	232.89	128.15	0.55	0.90
PAN7M-81		5.67	75.62	1.64	223.22	120.76	0.54	1.01
PAN53		5.49	73.53	2.03	218.73	115.59	0.53	0.98
PHB30G19		4.77	73.79	2.41	226.41	116.43	0.52	0.90
LSD		1.60	5.68	4.20	62.84	35.71	0.10	0.37

GY grain yield; AD anthesis date, ASI anthesis silking interval; PH plant height; EH ear height; EPO ear position; EPP number of ears per plant; LSD least significant difference

Entries 20 (9.19 t ha^{-1}), 109 (9.11 t ha^{-1}), 22 (9 t ha^{-1}) and 63 (8.95 t ha^{-1}) were the highest yielding testcross hybrids across optimum test environments (Table 6.5). Under the low N test environments, the highest yielding hybrids included entries 115 (4.03 t ha^{-1}), 13 (3.89 t ha^{-1}) and 119 (3.88 t ha^{-1}) (Table 6.6). The highest yielding testcross hybrid recorded 15.88% higher yields than the highest check, PAN7M-81, under low N stress environments, though this was not significant. The lowest yielding hybrids, entries 67 and 37, took a longer time to reach 50% anthesis and had reduced plant height. Low N stress reduced prolificacy for all the testcross hybrids, which may be the main reason for reduced yields at this management level.

Table 6.5 BLUPs for the highest 10 and poorest five yielding (t ha^{-1}) hybrids and four local commercial checks across eight combined optimum test environments

Hybrid	GY	AD	ASI	PH	EH	EPO	EPP
20	9.19	74.49	1.08	271.52	147.13	0.54	1.02
109	9.11	73.48	0.94	264.61	140.51	0.53	1.18
22	9	73.2	1.26	258.23	136.75	0.53	1.04
63	8.95	74.45	0.87	258.63	145.77	0.57	1.14
21	8.83	72.68	1.03	261.89	142.32	0.54	1.01
97	8.83	73.81	0.93	263.99	137.8	0.52	1.09
68	8.79	75.85	0.34	257.52	139.63	0.54	1.09
2	8.77	74.34	0.83	263.39	146.16	0.56	1.22
115	8.76	75.16	0.64	259.94	136.73	0.53	1.13
108	8.76	73.92	0.76	263.67	142.58	0.54	1.16
67	5.45	78.35	0.64	251.65	138.12	0.55	0.98
106	5.43	76.27	0.24	236.38	131.74	0.56	1.12
54	5.32	75.48	0.74	242.07	136.18	0.56	1.01
112	5.26	75.41	0.49	235.79	131.63	0.56	0.99
76	4.26	71.91	1.26	231.97	119.8	0.52	1.06
SC719	8.97	74.96	0.86	273.16	152.49	0.56	1.03
PAN7M-81	8.92	74.39	0.73	258.34	141.16	0.55	1.11
PAN53	8.02	72.43	1.06	249.06	131.82	0.53	1.09
PHB30G19	7.28	72.65	1.23	255.44	129.77	0.51	1.03
LSD	1.97	3.697	2.105	23.7684	20.6993	0.0687	0.231

GY grain yield; AD anthesis date, ASI anthesis silking interval; PH plant height; EH ear height; EPO ear position; EPP number of ears per plant; LSD least significant difference

Table 6.6 BLUPs for the highest 10 and poorest five yielding (t ha^{-1}) hybrids and four local commercial checks across six combined low N test environments

Hybrid	GY	AD	ASI	PH	EH	EPO	EPP
115	4.03	79.12	0.96	212.97	105.33	0.51	0.92
13	3.89	72.07	1.40	195.95	103.12	0.53	0.97
119	3.88	77.86	1.44	212.47	110.05	0.53	0.95
19	3.87	74.20	1.89	207.42	107.91	0.53	0.95
5	3.85	74.76	1.29	198.44	102.97	0.52	1.01
10	3.81	76.93	1.91	204.90	101.50	0.50	0.94
24	3.79	74.14	1.74	204.60	107.92	0.53	0.98
137	3.73	76.38	1.23	204.71	99.15	0.49	0.92
22	3.73	75.88	1.75	209.73	108.38	0.53	0.93
6	3.71	75.60	0.76	206.18	109.43	0.54	0.95
79	1.76	79.70	2.83	189.76	101.51	0.53	0.84
60	1.74	78.74	1.14	188.30	102.65	0.55	0.84
36	1.67	77.18	1.57	197.72	103.44	0.53	0.88
67	1.49	81.31	1.76	185.95	101.44	0.55	0.73
37	1.38	80.26	1.84	198.32	102.64	0.52	0.78
SC719	2.93	78.58	1.42	212.09	111.84	0.54	0.86
PAN7M-81	3.19	76.56	1.51	205.49	108.38	0.54	0.95
PAN53	3.39	74.03	2.30	203.41	105.77	0.52	0.92
PHB30G19	2.91	74.54	2.57	213.10	110.62	0.53	0.84
LSD	1.44	3.65	3.15	26.84	22.56	0.09	0.24

GY grain yield; AD anthesis date, ASI anthesis silking interval; PH plant height; EH ear height; EPO ear position; EPP number of ears per plant; LSD least significant difference

Random drought stress induced lower grain yields, increased ASI, reduced plant height and reduced prolificacy for all the testcross hybrids (Table 6.7). The highest yielding testcross hybrids, entry 109 (6.08 t ha^{-1}), 115 (6.05 t ha^{-1}) and 22 (5.99 t ha^{-1}), recorded yields that were significantly different from the local commercial checks. They exhibited at least 75% higher than local checks indicating their suitability under random drought stresses. Among the highest yielding hybrids, they had at least one ear per plant, as compared to local checks which had significantly lower number of ears per plant. Late hybrids exhibited more synchronization than the local checks. Days to anthesis, plant and ear height were not significantly different among the hybrids.

Table 6.7 BLUPs for the highest 10 and poorest five yielding (t ha^{-1}) hybrids and four local commercial checks across two combined random drought stress test environments

Hybrid	GY	AD	ASI	PH	EH	EPO	EPP
109	6.08	76.07	0.97	235.10	125.10	0.53	1.05
115	6.05	77.87	0.77	235.80	119.10	0.51	1.01
22	5.99	68.80	2.27	235.30	122.00	0.52	0.97
63	5.91	76.70	1.53	233.50	127.60	0.54	1.02
1	5.90	74.53	0.63	224.30	124.20	0.55	1.11
21	5.87	74.63	2.40	232.40	124.00	0.53	0.94
24	5.87	73.50	1.73	230.40	123.80	0.54	0.99
20	5.87	76.30	2.27	239.40	127.40	0.53	0.91
2	5.87	76.83	0.87	233.40	127.00	0.54	1.07
19	5.80	74.30	1.67	232.70	121.80	0.52	0.95
60	3.26	77.00	1.43	201.40	111.70	0.55	0.89
112	3.19	75.23	0.53	201.80	108.80	0.54	0.89
67	3.04	74.83	1.17	213.90	116.80	0.55	0.76
37	3.03	79.90	1.53	222.50	116.90	0.52	0.77
76	2.74	69.97	2.57	201.00	101.90	0.50	0.94
SC719	1.50	77.66	4.02	179.33	93.01	0.53	0.74
PAN7M-81	1.53	77.82	4.37	179.33	92.68	0.53	0.80
PAN53	1.53	77.71	4.85	179.33	92.74	0.53	0.78
PHB30G19	1.52	77.59	4.53	179.33	92.59	0.50	0.76
LSD	1.60	5.68	0.42	62.84	35.71	0.10	0.37

GY grain yield; AD anthesis date, ASI anthesis silking interval; PH plant height; EH ear height; EPO ear position; EPP number of ears per plant; LSD least significant difference

6.3.4 Variance components and broad-sense heritability across test environments

Broad-sense heritability estimates were highest for grain yield across combined, optimum and low N test environments, at 77%, 84% and 90% respectively (Table 6.8), and lowest under random drought stress (17%). Heritability estimates for all characteristics were higher than 0.5 across combined, optimum and low N test environments, except for ASI (0.47) under optimum conditions. Heritability was very low for all characteristics across random drought stress environments (1-32%). Variance due to location was higher than variances due to genotypes, G x E and phenotypic variance for grain yield across combined, optimum, low N and random drought stress test environments. Genotypic variances were 0.04 for random drought stress; 0.37 for low N; 1.03 for optimum and highest for combined test environments (16.43). Variances due to G x E interactions were highest across the test environments (1.7), followed by optimum (0.29), low N stress (0.16) and lowest across random drought stress environments.

Table 6.8 Variance components and broad-sense heritability estimates for grain yield and agronomic characteristics from BLUPs across test environments

Trait/Variance	GY	AD	ASI	PH	EH	EPO	EPP
Combined 15 environments							
Error Var	0.88	3.03	3.93	173.26	131.80	0.00	0.02
Genotypic Var	0.19	0.15	3.36	56.28	41.22	0.00	0.00
Phenotypic var	0.24	0.28	3.56	63.81	47.23	0.00	0.00
G x E Var	0.23	0.06	0.53	3.82	6.21	0.00	0.00
Location Var	5.56	1.01	58.20	1232.10	635.77	0.01	0.01
Heritability	0.77	0.53	0.94	0.88	0.87	0.79	0.77
Grand Mean	5.83	1.53	72.04	224.73	122.09	0.54	1.01
LSD	1.84	3.41	3.88	25.80	22.50	0.08	0.25
CV	16.08	2.71	2.75	5.86	9.40	7.94	12.78
Low N, five environments							
Error Var	0.54	3.46	2.58	187.53	132.46	0.00	0.02
Genotypic Var	0.37	4.36	0.32	55.70	23.45	0.00	0.00
Phenotypic Var	0.44	4.74	0.57	71.33	34.49	0.00	0.00
G x E Var	0.16	0.58	0.21	0.00	0.00	0.00	0.00
Location Var	1.12	36.49	2.15	889.55	266.90	0.01	0.00
Heritability	0.84	0.92	0.56	0.78	0.68	0.69	0.61
Grand Mean	2.98	76.43	1.61	200.50	103.79	0.52	0.92
LSD	1.44	3.65	3.15	26.84	22.56	0.09	0.24
CV	24.71	2.43	100.10	6.83	11.09	8.43	13.36
Optimum, seven environments							
Error Var	1.01	3.56	1.15	147.06	111.53	0.00	0.01
Genotypic Var	1.03	2.69	0.09	66.11	39.82	0.00	0.00
Phenotypic Var	1.14	3.02	0.19	77.40	47.82	0.00	0.01
G x E Var	0.29	0.58	0.13	5.53	0.25	0.00	0.00
Location Var	2.56	87.70	0.30	188.49	178.66	0.00	0.01
Heritability	0.90	0.89	0.47	0.85	0.83	0.79	0.75
Grand Mean	7.58	73.94	0.87	252.45	135.71	0.54	1.07
LSD	1.97	3.70	2.11	23.77	20.70	0.07	0.23
CV	13.27	2.55	123.51	4.80	7.78	6.52	11.00
Random drought stress, two environments							
Error Var	0.66	8.39	4.59	1027.87	331.91	0.00	0.04
Genotypic Var	0.04	1.39	0.00	0.00	6.78	0.00	0.01
Phenotypic Var	0.23	4.90	0.00	0.00	158.45	0.00	0.02
G x E Var	0.05	2.83	1.23	485.39	137.01	0.00	0.01
Location Var	0.75	68.15	6.37	1474.29	1767.05	0.02	0.12
Heritability	0.17	0.28	0.01	0.02	0.04	0.32	0.26
Grand Mean	1.54	78.09	4.99	179.33	93.10	0.51	0.76
LSD	1.60	5.68	4.20	62.84	35.71	0.10	0.37
CV	52.85	3.71	42.96	17.88	19.57	10.22	24.81

Var Variance; GY grain yield; EPP number of ears per plant; AD days to 50% anthesis; ASI anthesis silking interval; EPO ear position; EH ear height; PH plant height; LSD least significance difference; G x E genotype x environment interaction

6.3.5 Correlations between grain yield and secondary characteristics

The correlations among measured characteristics across the combined 15 test environments (Table 6.9) showed grain yield to be highly negatively correlated with ear aspect. There was negative correlation of grain yield with days to 50% anthesis, ear rot, ET, grey leaf spot, *Puccinia sorghi*, senescence and stalk lodging. Grain yield was positively correlated with ear height, ears per plant, plant height and grain texture. Days to 50% anthesis were positively correlated with ear height, ear position, ET, senescence and stalk lodging. ASI was negatively correlated with diseases grey leaf spot, ET, PS, and ears per plant and ear position. Ears per plant was negatively correlated with ear rots, ET and senescence, and stalk lodging. Plant height was negatively associated with senescence.

Grain yield across optimum test environments was negatively correlated with days to 50% anthesis, stalk lodging, diseases, grey leaf spot, ER, PS and ET (Table 6.10). Plant height, ear height, number of ears per plant and grain texture had positive correlations with grain yield across optimal environments. Ear position was negatively correlated with ear rots. Number of ears per plant were negatively correlated with stalk lodging and ASI.

Across the six low N test environments, grain yield was negatively correlated with days to 50% anthesis, ear position, stalk lodging, ear rots, GLS and ET (Table 6.11). It was, however, positively correlated with plant height and number of ears per plant. Days to 50% anthesis had negative correlations with ASI and ears per plant. Ears per plant were negatively correlated with ear rots and ET.

Table 6.9 Correlations of BLUPs for grain yield and agronomic characteristics for the late maize testcross hybrids across combined 15 test environments

	GY	AD	ASI	EA	EH	EPO	EPP	ER	ET	GLS	HC	PH	PS	RL	SEN	SL
AD	-0.28***															
ASI	0.03	-0.26***														
EA	-0.73***	0.13	-0.16*													
EH	0.39***	0.45***	-0.14	-0.46***												
EPO	-0.20	0.52***	-0.21**	0.09	0.62***											
EPP	0.54***	-0.33***	-0.22**	-0.22**	0.06	-0.15										
ER	-0.29***	0.18*	0.07	0.40***	-0.13	0.07	-0.21**									
ET	-0.40***	0.25**	-0.31***	0.42***	0.01	0.28***	-0.19*	0.07								
GLS	-0.34***	0.20*	-0.28***	0.27***	-0.03	0.13	-0.13	0.04	0.28***							
HC	0.12	-0.16*	0.10	0.06	-0.23**	-0.21**	0.17*	0.05	-0.07	-0.06						
PH	0.62***	0.14	-0.05	-0.66***	0.64***	-0.13	0.20*	-0.27***	-0.20*	-0.15	-0.10					
PS	-0.21**	0.09	-0.31***	0.25**	-0.11	0.08	-0.10	-0.03	0.16*	0.25**	-0.05	-0.15				
RL	0.00	-0.01	-0.01	0.01	0.12	0.20*	-0.05	0.10	0.04	-0.08	0.09	-0.06	-0.10			
SEN	-0.31***	0.22**	-0.07	0.22**	0.05	0.36***	-0.19*	0.27***	0.12	0.20*	-0.01	-0.27***	-0.03	0.21**		
SL	-0.24**	0.47***	-0.16*	0.17*	0.26**	0.49***	-0.27***	0.27***	0.35***	0.28***	-0.05	-0.14	-0.01	0.26***	0.20*	
TEX	0.43***	-0.10	-0.03	-0.19*	0.18*	0.06	0.07	-0.10	0.01	-0.17*	0.12	0.14	-0.03	0.02	-0.10	0.17*

***$P < 0.001$; **$P < 0.01$ and *$P < 0.05$ respectively; GY grain yield (t ha^{-1}); AD anthesis date; ASI anthesis silking interval; EA ear aspect; EH ear height (cm); EPO ear position; EPP number of ears per plant; ER ear rot; ET *Exserohilum turcicum*; GLS Grey leaf spot; HC husk cover; PH plant height (cm); PS *Puccinia sorghi*, RL root lodging; SEN senescence; SL stalk lodging; TEX grain texture

Table 6.10 Correlations of BLUPs for grain yield and agronomic characteristics across optimum test environments

	GY	AD	ASI	PH	EH	EPO	EPP	RL	SL	HC	ER	GLS	PS	ET
AD	-0.20**													
ASI	0.14	-0.29***												
PH	0.69***	0.18*	0.01											
EH	0.44***	0.45***	-0.10	0.65***										
EPO	-0.07	0.51****	-0.19*	-0.02	0.70***									
EPP	0.47***	-0.18*	-0.23***	0.25***	0.07	-0.14								
RL	-0.08	0.05	0.08	-0.16*	-0.02	0.13	-0.15							
SL	-0.27***	0.41***	-0.24***	-0.05	0.29***	0.45***	-0.30***	0.19*						
HC	0.06	-0.13	0.07	-0.10	-0.21**	-0.19*	0.11	0.04	-0.07					
ER	-0.22**	-0.03*	0.04	-0.24***	-0.33***	-0.24***	-0.07	-0.09	-0.03	0.16*				
GLS	-0.26***	0.21**	-0.31***	-0.08	0.06	0.16*	-0.05	-0.17*	0.27***	-0.01	-0.02			
PS	-0.26***	0.18*	-0.32***	-0.13	-0.05	0.10	-0.10	-0.02	0.12	-0.08	-0.06	0.30***		
ET	-0.24***	0.25***	-0.33***	-0.09	0.12	0.31***	-0.06	0.05	0.44***	-0.11	-0.04	0.29***	0.19*	
TEX	0.45***	-0.15	0.09	0.24***	0.18*	-0.02	0.04	-0.07	0.06	0.13	0.07	-0.15	-0.03	-0.08

***$P < 0.001$; **$P < 0.01$ and *$P < 0.05$ respectively; GY grain yield (t ha^{-1}); AD anthesis date; ASI anthesis silking interval; EA ear aspect; EH ear height (cm); EPO ear position; EPP number of ears per plant; ER ear rot; ET *Exserohilum turcicum*; GLS Grey leaf spot; HC husk cover; PH plant height (cm); PS *Puccinia sorghi*, RL root lodging; SL stalk lodging; TEX grain texture; MSV maize streak virus disease

Table 6.11 Correlations of BLUPs for grain yield and agronomic characteristics across low N stress environments

	GY	AD	ASI	EH	PH	EPO	RL	SL	EPP	HC	ER	GLS	ET
AD	-0.38***												
ASI	-0.09	-0.28***											
EH	0.16*	0.36***	-0.10										
PH	0.46***	0.12	-0.08	0.66***									
EPO	-0.27***	0.42***	-0.12	0.61***	-0.11								
RL	0.00	0.01	-0.02	0.15	0.03	0.21**							
SL	-0.34***	0.48***	-0.11	0.16*	-0.16*	0.40***	0.29***						
EPP	0.54***	-0.49***	0.00	-0.02	0.07	-0.13	0.06	-0.22**					
HC	-0.01	-0.14	0.09	-0.13	0.00	-0.15	-0.06	-0.15	0.07				
ER	-0.42***	0.26***	0.04	0.05	-0.19*	0.27***	0.16*	0.37***	-0.17*	-0.03			
GLS	-0.24***	0.03	-0.14	-0.07	-0.12	0.07	0.02	0.16*	-0.15	-0.14	0.06		
ET	-0.27***	0.19*	-0.13	-0.05	-0.12	0.11	-0.06	0.10	-0.23***	-0.01	0.14	0.23**	
SEN	-0.36	0.22**	-0.13	0.09	-0.26***	0.41***	0.14	0.22**	-0.14	-0.10	0.31***	0.17*	0.08

***P < 0.001; **P < 0.01 and *P < 0.05 respectively; GY grain yield (tha^{-1}); AD anthesis date; ASI anthesis silking interval; EA ear aspect; EH ear height (cm); EPO ear position; EPP number of ears per plant; ER ear rot; ET *Exserohilum turcicum*; GLS Grey leaf spot; HC husk cover; PH plant height (cm); PS *Puccinia sorghi*, RL root lodging; SL stalk lodging; MSV maize streak virus disease

6.3.6 Principal component analysis

The principal component analysis showed the relationship of characteristics and genotypes across the 15 test environments. PC1 and PC2 contributed a total of 95.48% of variation, 82.09% and 13.39%, respectively (Figure 6.2), with 99.4% of the total variation explained by the first four PC's (Table 6.12). Entries and characteristics that are clustered close to each other have most characteristics in common. Generally most hybrids clustered around the origin, and entries like 17; 76; 151 and 152 were furthest from the origin, and hence were less stable. Grain yield was closely associated with MSV and the number of ears per plant, while the three characteristics negatively correlated with PS, GLS, ET and senescence. Ear rot and grain texture were negatively correlated. Stalk and root lodging and ear position were highly correlated. Days to 50% anthesis and husk cover were negatively correlated. Entries 131, 81, 137, 134, 136, 149 and 86 were identified as high yielding with high number of ears per plant. Plant height contributed positively to PC1 variation and negatively to PC2 variation (Table 6.12). Ear height contributed positive and significantly to both PC1 and PC2 variations. Plant height had negative and significant contribution to PC2 variation. Days to 50% anthesis contributed significantly to PC3 variation, while grain yield contributed negatively to PC4 variation.

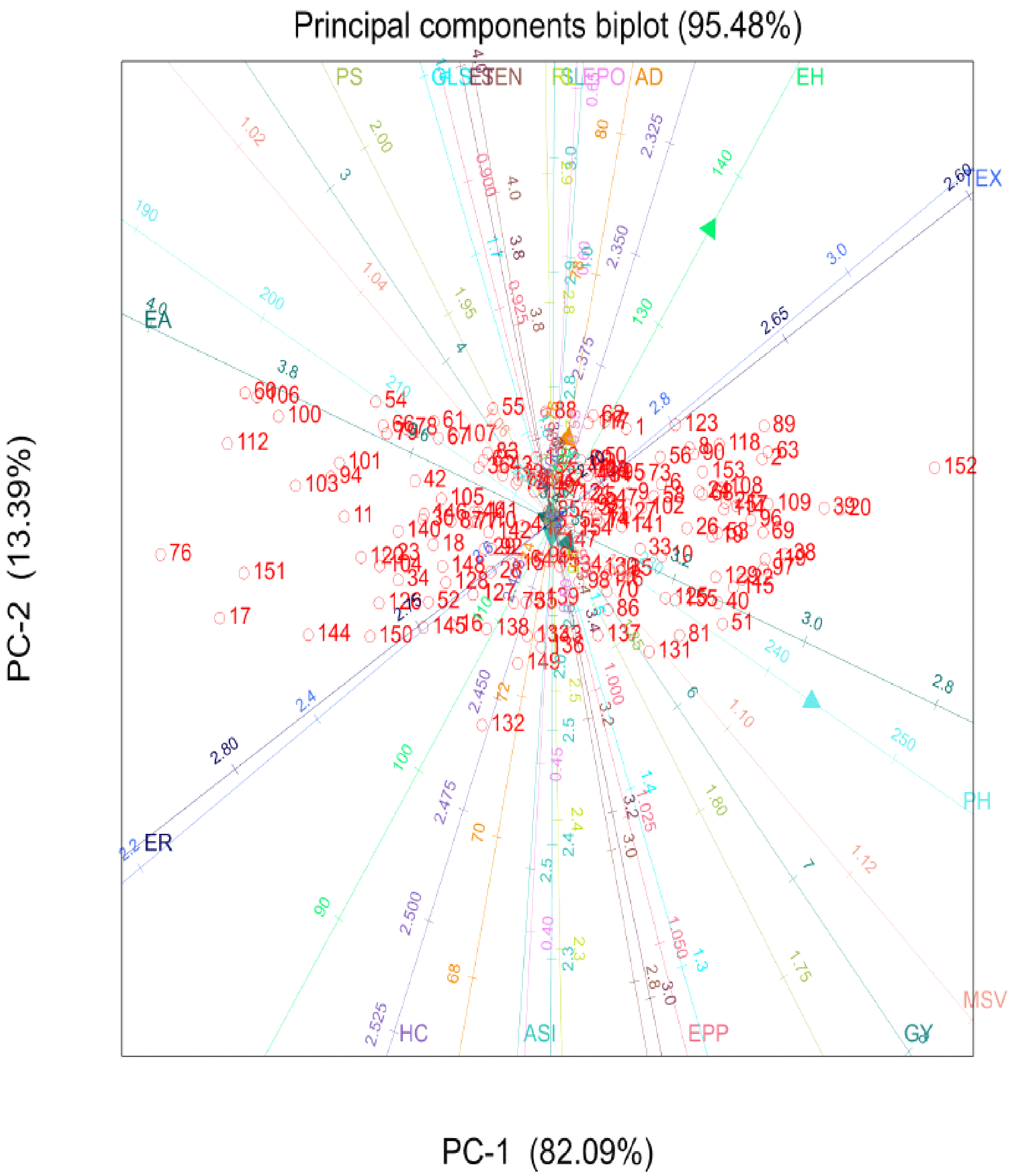

Figure 6.2 Principal component analyses for 115 testcross hybrids across 15 test environments

Table 6.12 Loadings of the first four principal components for 18 characteristics across 15 environments

PC	1	2	3	4
AD	0.05	0.23	**0.96**	-0.11
ASI	0.00	-0.04	-0.02	-0.28
EA	-0.02	0.01	0.02	0.20
EH	**0.52**	**0.82**	-0.23	-0.01
EPO	0.00	0.01	0.00	0.00
EPP	0.00	0.00	0.00	-0.05
ER	0.00	0.00	0.00	0.04
ET	0.00	0.02	0.00	0.18
GLS	0.00	0.01	0.01	0.09
GY	0.05	-0.06	-0.08	**-0.80**
HC	0.00	0.00	0.00	-0.02
MSV	0.00	0.00	0.00	0.01
PH	**0.85**	**-0.51**	0.09	0.07
PS	0.00	0.00	0.01	0.06
RL	0.00	0.01	-0.01	0.09
SEN	-0.01	0.02	0.00	0.06
SL	0.00	0.01	0.00	0.04
TEX	0.01	0.01	-0.06	-0.40
Latent roots	13953.40	2276.50	614.50	53.20
Percentage variation	82.09	13.39	3.61	0.31
Cumulative variation	82.09	95.48	99.09	99.40

AD days to 50% anthesis; ASI anthesis silking interval; EA ear aspect; EH ear height; EPO ear position; EPP number of ears per plant; ER ear rots; ET *Exserohilum turcicum;* GLS grey leaf spot; GY grain yield; HC husk cover; MSV maize streak virus disease; PH plant height; PS *Puccinia sorghi*; RL root lodging' SEN senescence; SL stalk lodging; TEX grain texture

6.4 Discussion

Drought and low N stress in southern Africa are primary yield limiting factors, affecting millions of smallholder communities who depend on maize as their only source of calories. The interactions of El Niño and the ITCZ have brought new challenges to maize production systems in southern Africa, and have increased the frequency of droughts and incidences of disease and pests outbreaks, which hinder maize productivity. Poor access to improved technologies and inaccessibility of mineral fertilisers has impeded maize production systems in the region. The improvement of tolerance of maize hybrids to both drought and low N stress has the potential of improving food productivity in the maize-based communities.

Several models have been used to estimate the testcross performance of maize across both optimal and sub-optimal test environments. BLUPs have been successfully used to estimate the means for single cross and three-way hybrid trials across several test environments. CIMMYT has, over the years, developed and released several maize hybrids tolerant to major stresses that affect maize productivity, especially in the maize-based cropping systems in southern Africa. However, the growing threats of climate variability and change have greatly affected these outputs as the threats increase. This research study was conducted across 15 (random drought, low N stress and optimum) test environments to evaluate the testcross performance of 155 testcross hybrids, produced from the selected elite late maturity maize inbred lines, and single cross testers developed by CIMMYT.

Random drought and low N stresses reduced grain yield and other agronomic characteristics investigated in these evaluations. Yields were reduced by over 79% (random drought) and 60.74% (low N stress) as compared to yields under optimum conditions. These results are in line with the results obtained by other researchers in stress and non-stress test environments. Over 70% yield losses were observed by Gissa (2008), Derera et al. (2008), Weber et al. (2012) and Umar et al. (2015) in maize under drought and low N stress. Betrán et al. (1997) and Bänziger et al. (1997; 2006) reported grain yield losses of over 80% under stress conditions. Wolfe et al. (1988) recorded losses ranging from 10-50% for low N stress alone in western Africa, where the major causes were inadequate mineral fertilization by smallholder farmers, and the rapid mineralization of organic matter from the soil (McCown et al., 1992; Bänziger and Lafitte, 1997). Though the stresses had large negative effects on maize yield, potential hybrids with good yield across these stress-prone environments have been identified. In the current investigation, the effect of random drought stress was more severe than that of low N drought stress. This indicates that random drought stress is a bigger challenge in late maturity hybrids, whereas low N stress is a bigger challenge in early maturity hybrids.

ANOVA indicated high variability among the testcross hybrids evaluated across the three management levels. The occurrence of significant G x E interactions indicated the differential responses of these hybrids across the stress levels. There were also large differential effects of the test environments within each management level, as significant G x E interactions occurred within the management levels. This indicated the occurrence of cross-over interactions within the genotypes evaluated, that calls for further analysis using AMMI and GGE models to partition the G x E interactions, and maybe identify which-won-where hybrids. The occurrence of G x E interactions in maize has been documented in other studies (Bänziger and Cooper, 2001; Bänziger et al., 2004; Mohammadi and Haghparast, 2010; Tiawari et al., 2011; Cooper et al., 2014; Cuevas et al., 2017; Díaz-Gómez et al., 2017; Muzhingi et al., 2017; Navarro et al., 2017).

Entries 109, 115, 22, 5, 63, 10, 24, 21, 20 and 2 recorded the highest grain yields across all the test environments. Though they were not statistically different from the local commercial checks PAN7M-81, SC719, PAN53 and PHB30G19, they produced economically higher yields than all these local commercial checks. The testcross hybrids yielded at least 0.2 t ha^{-1} (3.41%) higher than the local commercial checks. Cairns et al. (2013a) reported that testcross hybrids evaluated yielded at least 0.65 t ha^{-1} better than the donor (CML444) used in drought tolerance breeding, crossed to a broadly-adapted tester, CML539. These hybrids can be recommended for further analysis across several seasons to validate the findings, as potential sources of both random drought and low N stress tolerance genes in southern Africa.

Genetic improvements in maize yield under drought have greatly contributed to yield gains (Barker et al., 2005; Campos et al., 2006; Cooper et al., 2014). Falconer (1951) reported that breeding progress largely depends on the wide variability of desired characteristics, high selection intensity, high heritability of the trait, and the genetic correlations between grain yield in the selection environment and the target population of environments. Broad-sense heritability was very high for grain yield across 15 environments combined; eight optimum and six low N test environments. It was very low (17%) across low N test environments. Generally, all the evaluated characteristics had very low heritability across the random drought stress localities, ranging between 10-32%. There was large variability among the management levels as indicated by high location variances observed in the experiments. The large differences between test environments in discriminating genotypes is a crucial aspect when identifying testcross hybrids under diverse environments (Bruce et al., 2002; Weber et al., 2012; Cairns et al., 2013b). Genotypes are selected based on their compound stress tolerance across the stress gradients as recommended by Bruce et al. (2002) who concluded that diverse test environments are ideal for the identification of testcross hybrids based on their physiological responses against these stress gradients.

Grain yield was negatively correlated with all the diseases evaluated; GLS, ET, ear rots and PS as well as ear position. This indicates that grain yield was reduced with the occurrences of these diseases. Diseases have always been a challenge in southern Africa, and breeding efforts have to concurrently focus on drought, low N, heat and the occurrence of these diseases. The number of ears per plant was reduced with increased days to 50% anthesis and stalk lodging. Senescence also negatively affected plant height across combined and low N stress test environments. Characteristics that are significantly correlated with grain yield such as ears per plant, grain texture, and ear and plant height can be used for selection against combined drought and low N stress in maize.

Testcross hybrid 22 was the most ideal genotype along the grain yield axis. Several other hybrids clustered around the positive axis of the grain yield line, indicating their usefulness across the test environments where they were evaluated. Ears per plant were negatively correlated with senescence, ET and GLS. Reducing the deleterious effects of these diseases will eventually lead to a higher number of ears per plant and will lead to higher grain yields, as ear per plant is a good indicator of yield. Bolaños and Edmeades (1993; 1996), Bruce et al. (2002), Monneveux et al. (2005; 2008), Campos et al. (2006), Mhike et al. (2012), Badu-Apraku et al. (2013), Edmeades (2013) and Masuka (2014) indicated the use of secondary characteristics that are highly correlated with grain yield as a useful way of improving yield under both stress and non-stress test environments.

6.5 Conclusions

Millions of smallholder farmers in southern Africa depend on maize as their only source of calories, and hence regard maize as “life”. The constraints facing maize based cropping systems in this region are a result of climate variability and change that often increase the frequencies of droughts, low soil fertility (especially low N), and increases the effects of heat and diseases. The use of high yielding compound drought and low N tolerance maize hybrids has the potential to improve maize productivity in the region. This study aimed to identify potential high yielding testcrosses with increased tolerance to droughts and low N using late maturity inbreds developed by CIMMYT. Several hybrids performed better than commercial check varieties, indicating their suitability as viable options for use under stress conditions. The large variability observed among the tested genotypes can be useful in developing future breeding programmes for compound stress tolerance. Hybrids that produced economically better yields, higher than local commercial checks, can be used as potential varieties in the region, if they perform consistently across different seasons. They can also be used as potential sources of compound drought and low N stress tolerance for future breeding programmes. Random drought effects were more severe than low N stress effects in the region among late maturity hybrids. This was due to the prolonged exposure of these testcross hybrids to drought stress, which caused significant yield losses. Characteristics like ears per plant, plant and ear height and grain texture can be useful secondary characteristics for grain yield improvement across stress and non-stress test environments. BLUPs were useful for identifying high potential testcrosses across stress and non-stress test environments. Research on the impact of diseases in the current climate variability and change, together with heat stress studies have to be carried out.

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CHAPTER 7

AMMI and GGE analysis of early maturity testcrosses developed from low N and drought tolerant maize inbred lines

Abstract

This study was conducted to understand the complexity of G x E interactions among testcrosses developed from elite early CIMMYT drought and low N tolerant inbred lines using additive main effects and multiplicative interaction (AMMI) and genotype and genotype-by-environment interaction (GGE) biplots, and to identify better yielding, stable and well-adapted hybrids suitable for low potential regions in southern Africa. One hundred and nine testcrosses (those with sufficient seed for trials) together with six local commercial checks were grown in an alpha lattice design with two replications in 12 test environments across Zambia, Zimbabwe and South Africa. These test environments included three management levels; random drought stress, low N stress and optimum environments. ANOVA indicated that the test environments were the biggest source of variation (63.93%) followed by G x E interactions (16.47%), while genotypes accounted for 9.7% of the total variation. G x E interactions were further partitioned into IPCA components of which IPCA 1, IPCA 2 and IPCA 3 were significant and accounted for 72.60% of the total G x E interaction variation. Both the AMMI and the GGE biplots were able to identify genotypes with promising yield potential. The selected 20 high yielding genotypes used in the AMMI and GGE biplots had above average stability and performed better than the local checks. Eight hybrids; entries 46, 83, 15, 32, 6, 82, 100 and 21 consistently out-performed checks across all test environments and are recommended for release as cultivars. The GGE analysis identified three mega environments; entry 46 as an “ideal genotype”, and Mpongwe as an “ideal test environment.” Though G x E interactions complicate breeding progress, the AMMI and GGE biplots were able to successfully identify, analyse and explain the effects of G x E interactions among the evaluated testcrosses and the stress and non-stress test environments yielding results that could be beneficial for smallholder communities in southern Africa.

7.1 Introduction

The importance of maize is increasing globally. It is estimated to be cultivated on 144 million hectares, with an estimated annual production of 700 million tonnes (FAO, 2011). The United States is by far the largest producer, followed by China and Brazil (FAOSTAT, 2012). Maize is estimated to be produced on 26.12 million hectares in SSA, with an estimated yield of 1771.22 kg ha^{-1}. All this production is mostly done by either smallholder or medium scale farmers, who are characterised by low income and resource-limited status. Usually the lower yields are a direct result of cash shortages limiting the utilization of high cost inputs like fertilisers and chemicals for weed and pests control, which are required in maize production (Dawit et al., 2008). Despite these challenges, the demand for maize, which is the most important African staple, is increasing and as such, production in SSA encroaches into marginal areas, which are not ideal for agricultural productivity. The use of marginal areas for maize production exacerbates the incidence of biotic and abiotic threats leading to minimal productivity. To meet the growing demand for maize in SSA, it is necessary to boost productivity by reducing yield losses due to various stress factors including droughts, low soil fertility, diseases and pests, among others (Dagne et al., 2004; Wegary et al., 2012) by the use of stress tolerance, which improves yield despite the presence of a stress factor.

Crop improvement is negatively influenced by the occurrence of G x E interactions. Research into the individual behaviour of a genotype developed for any breeding objective will be vital for the progress of crop improvement. Research over multi-locations and several seasons will help scientists to identify and analyse various major factors that are responsible for the adaptation of a particular genotype to an environment (DeLacy et al., 1996; Akçura et al., 2006). G x E analysis techniques have been important tools to plant breeders, physiologists and agronomists, as stability analysis is used to characterise genotypes, with those interacting less with the environment as ideal candidates for selection.

There are three main sources of variation in plant breeding; genotype (G), environment (E) and G x E interaction. G x E interactions are often used to refer to fluctuations of yield across the environments, a phenomenon which forces plant breeders to check genotypic adaptation (Ramagosa and Fox, 1993; Basford and Cooper, 1998). According to Ceccarelli (1989), crop improvement is done within mega-environments, or within a wide range of environments. A successful cultivar needs to possess high and stable yield potential over a wide range of environmental conditions (Becker and Léon, 1988). It is often used to refer. Eberhart and Russel (1966) stated that knowledge of G x E interaction could help to reduce the cost of extensive genotype evaluation by eliminating unnecessary testing trials and by fine-tuning breeding programmes. Genotypic responses to an environment are either with respect to rank changes (qualitative/crossover interactions) or scale (quantitative/non-crossover interactions) (Baker, 1988; Ramagosa and Fox, 1993; Nleya et al., 2000). Quantitative G x E interactions results from differential genotypic responses due to non-crossover interactions and usually do not cause challenges during selection, while crossover interaction cause changes in rank across environments complicating selection on breeding experiments (Nleya et al., 2000).

G x E interaction can be expressed as imperfect genotypic or environmental correlation (crossover interaction), or as heterogeneity of variance across environments (non-crossover interaction). According to Bernardo (2002), the genotype performance testing is dependent on the magnitude of the G x E interaction when these genotypes differ in their relative performance across multi-environments. The occurrence of G x E interactions necessitates genotype evaluations in more than one environment to obtain repeatable rankings of genotypes (Hallauer and Miranda, 1988). Of great value, is the occurrence of crossover interactions (Crossa and Cornelius, 1997; Baker, 1988). These occur when the relative ranking of genotypes change across environments during evaluation. Previous results have indicated that stress trials produced rankings that usually differ significantly from one trial to another as a result of G x E interaction, making the choices for best performing genotype difficult (Bänziger et al., 2000).

G x E interaction and yield stability analysis has continued to be important in measuring varietal stability and suitability for cultivation across seasons and ecological zones. The yielding ability of a genotype is the result of its interaction with the environment. Environmental factors such as soil characteristics, moisture, sowing time, fertility, temperatures and day length vary across years and locations. There is also a strong influence of the environmental factors during various stages of crop growth (Bull et al., 1992), thus genotypes differ widely in their response to environments. Some genotypes exhibit highly specific response to a particular environment, others are uniform in performance over a range of environments. Stability analysis provides a method to characterise the response of a hybrid to varying environmental conditions. Stability tests can be done by several biometric analyses, including the AMMI and the GGE among other stability analysis methods.

The AMMI method was introduced by Gauch (1988). AMMI is an important tool for evaluation of the performance of genotypes across environments. AMMI combines ANOVA and PCA into one model with additive and multiplicative parameters. The PCA is a mathematical process that decomposes a covariance matrix into eigenvalues and column eigenvectors. It has been used to analyse the performance of crop cultivars under multiple stress environments, from which ideal cultivars, mega-environments, and core testing sites were identified. The applications of AMMI have led to more insight than ANOVA in the complicated patterns of genotypic responses to changed environmental conditions (Ramagosa et al., 1996; Voltas et al., 1999). The AMMI analysis gives more precise estimates of genotype yields within locations than means across replicates in different trials (Crossa et al., 1991).

The main important feature of AMMI analysis is its graphical (biplot) representation. This displays main effect means of the abscissa and scores for the first axis (IPCA1 values) as ordinate of both genotypes and environments simultaneously (Crossa, 1990; Gauch and Zobel, 1988). Genotypes or environments with large IPCA (positive or negative) scores have large interaction, whereas an IPCA score near zero indicates small interaction effects (Zobel et al., 1988; Crossa et al., 1991). Accordingly, a large genotypic IPCA1 value reflects more specific adaptation to environments with IPCA1 values of the same sign. Genotypes with IPCA1 values closer to zero show wider adaptation to the tested environments. Thus, IPCA scores of a genotype in the AMMI analysis are the key to interpret the pattern of genotype responses across environments (Zobel et al., 1988; Crossa et al., 1991).

GGE biplots produce a graphical display of results that facilitate a better understanding of complex G x E interaction in multi-environment trials of breeding and agronomic experiments. The GGE biplot uses the first two principal axes (PC1 and PC2) to analyse the interrelationships among rows (entries) and columns (testers) based on environment-centred PCA. Though the total variation of a phenotype/trait could be partitioned into the environment factor, genotype effect, and G x E interaction effect, GGE biplot models consider only G and G x E as relevant to cultivar evaluation (Gauch and Zobel, 1996), removing the environment effect. This is so because the concept of crop performance and stability, are centred on G and G X E effects only, irrespective of how large the E effect is. More recently, GGE biplots have been employed in genetic analysis of diallel data to estimate combining ability and identify heterotic groups among inbred parents. Genotype-by-trait biplots have also been utilized in trait profile analysis and in identification of characteristics that are reliable for indirect selection of a target primary trait.

Depending on the type of data and the objective of the analysis, GGE biplots use four different scaling (singular value partitioning) methods, including genotype-focused scaling, environment-focused scaling, symmetric scaling and equal-space scaling. A scaling method describes the type of standardisation used for the mean values before the analysis is carried out (Yan, 2002). In genotype-focused scaling, the genotype scores are in principal coordinates, such that the vector lengths represent the original unit of the genotype data while the environment scores are in standard coordinates (DeLacy et al., 1996). In environment-focused scaling, on the other hand, the environment data assumes the principal coordinates and the vector lengths represent the original unit of the environment scores while the genotype scores are standardised. The first gives the polygon view, which reveals the winning entry (vertex genotype) of different testers (which may be environments, characteristics or strains). The second view gives the average tester coordination (also known as 'mean-versus-stability') view, which ranks entries according to their performance and stability (consistency) across testers.

Entries are ranked along the average-tester axis (ATC abscissa), which has an arrow pointing to a greater value based on their mean performance across all testers. The third view of a GGE biplot is the vector view that displays the discriminating ability (the ability of a tester to differentiate among entries being tested and is displayed by the length of the vector, which approximates the standard deviation of the tester) and representativeness (the ability of the tester to represent other testers of its group) of the tester (Yan and Tinker, 2005).

The study was undertaken to identify stable and well adapted maize testcrosses, developed from elite early maturity CIMMYT inbred lines, across 12 test environments in Zambia, Zimbabwe and South Africa.

7.2 Materials and methods

7.2.1 Plant materials

The 20 highest yielding testcross hybrids were selected from the 120 hybrids used previously for the testcross and combining ability estimate studies, together with six commercial checks. The 120 hybrids were developed from a 12 x 10 line x tester mating design as described in Chapter 3 (Section 3.2.1). The six commercial checks included in the study were SC403, SC513 and SC627 from SeedCo, PAN53, PAN4M-21 from Pannar and P2859W from Pioneer.

7.2.2 Testing environments and trial management

Test environments included 12 test sites in Zambia, Zimbabwe and South Africa as described in Chapter 3. All trials were managed as described in Chapter 3, specific for each environment.

7.2.3 Experimental design and data collection

The trials were arranged in an alpha lattice design with two replicates per environment. Twelve sites were used for the early maturing germplasm as outlined in Chapter 3. Agro-morphological characteristics data collection was done as outlined in Section 3.2.4.

7.2.4 Statistical analysis

Additive main effects and multiplicative analysis

To determine the G x E interaction for yield, an AMMI analysis was performed. Biplots were drawn by placing both the genotype and environment means on the axis (abscissa) and the respective eigenvectors or scores called the PCA on the y-axis (ordinate), according to Gauch and Zobel (1996). The AMMI statistical model in GenStat 18th Edition (VSN-International, 2015) was used to analyse the yield data.

The following AMMI model was used:

$Y_{ger} = \mu + \alpha_g + \beta_e + \Sigma\lambda_n Y_{gn} \delta_{en} + \rho_{ge} + E_{ger}$

Where: Y_{ger} is the yield of genotype *g* in environment *e* for replicate *r,* μ is the grand mean; α_g denotes the genotype mean deviations (genotype means minus grand mean), β_e is the environment mean deviation; n represents the number of PCA axes retained in the model; λ_n denotes the singular value for PCA axis n, Y_{gn} denotes the genotype eigenvector values for PCA axis n, δ_{en} represents the environment eigenvector values for PCA axis n, ρ_{ge} denotes the residuals and E_{ger} is the error term.

GGE biplot analysis

GGE biplot analysis was conducted using GGE biplot software (Yan and Tinker, 2005). The model for a GGE biplot (Yan, 2002) based on singular value decomposition (SVD) of the first two PC's was used: $Y_{ij} – \mu – \beta_j = g_{i1}e_{1j} + g_{i2}e_{2j} + \varepsilon_{ij}$

Where Yij = performance expected of genotype i in environment j, μ is the overall constant mean from the observations, β is the main effect of the environment j, g_{1i} and e_{1j} are the main scores for the i^{th} genotype in the j^{th} environment respectively, g_{i2} and e_{2j} are the secondary scores for the i^{th} genotype in the j^{th} environment, respectively and ε_{ij} is the residual not explained by either of the effects.

7.3 Results

7.3.1 AMMI analysis of early maturing hybrids

ANOVA indicated that treatments, environments, genotypes and G x E interactions were highly significant (P < 0.001) (Table 7.1). Environments contributed the highest amount of total sums of squares (63.96%), followed by G x E (16.46%) and genotypes (9.69%), explaining 90.10% of total variation. G x E interaction effects had higher magnitude than the effects of genotypes. G x E interaction effects were further partitioned into interaction principal component axes (IPCA) using the AMMI model. IPCA1 and IPCA2 were highly significant (P < 0.001). IPCA3 was significant at P < 0.05. The IPCA1, IPCA 2, IPCA 3 and IPCA 4 explained 49.58%, 14.54%, 8.47% and 7.18%, respectively, of variation, all collectively explaining 79.78% of the G x E interactions.

Table 7.1 AMMI analysis of grain yield for 20 hybrids and six local commercial checks, across 12 test environments

Source	df	Sum of squares	Mean squares	Total variation explained (%)	G x E explained	G x E cumulative
Total	623	4285.80	6.88	-		
Treatments	311	3861.40	12.42***	90.10		
Genotypes	25	415.60	16.62***	9.70		
Environments	11	2740.00	249.09***	63.93		
Block	12	32.70	2.72*	0.76		
G x E	275	705.80	2.57***	16.47		
IPCA 1	35	350.00	10.00***	8.17	49.59	49.59
IPCA 2	33	102.60	3.11***	2.39	14.54	64.13
IPCA 3	31	59.80	1.93*	1.40	8.47	72.60
IPCA 4	29	50.70	1.75	1.18	7.18	79.78
IPCA 5	27	44.60	1.65	1.04	6.32	86.11
IPCA 6	25	28.90	1.16	0.67	4.09	90.20
IPCA 7	23	24.50	1.07	0.57	3.47	93.67
IPCA 8	21	19.50	0.93	0.45	2.27	96.43
IPCA 9	19	12.20	0.64	0.28	1.73	98.16
IPCA error	32	13.00	0.41	0.30	1.84	100.00
Pooled Error	300	391.80	1.31	9.14	-	-

***P < 0.001; **P < 0.01; *P < 0.05; IPCA interaction principal component axis; G x E genotype x environment interaction; df degrees of freedom

7.3.2 Genotype means and IPCA scores across environments

The means for the hybrids selected and environments are shown in Tables 7.2 and 7.3. The highest yielding hybrids were entries 46 (7.20 t ha^{-1}), 83 (6.74 t ha^{-1}) and 15 (6.61 t ha^{-1}). IPCAs of genotypes and environments had both positive and negative scores. The lowest yielding cultivars were the commercial checks, with SC513 recording the lowest yield (3.96 t ha^{-1}), followed by PAN4M-21 with 4.34 t ha^{-1}. Genotypes or environments with large negative or positive IPCA values indicate unstable genotypes or environments. All the selected hybrids showed positive IPCA 1, except entry 84, which, though high yielding, showed a negative IPCA 1 score, while all the commercial checks had negative IPCA scores. Entries 84, 88, 35, 15, 43, 6 and 52 were more stable as they recorded lower IPCA 1 values (lower than 0.20) indicating small deviations from zero. All the commercial checks had negative IPCA scores ranging from -0.76 (SC403) to -1.54 (PAN53), indicating their bigger responses to G x E interactions compared to the testecross hybrids evaluated.

Table 7.2 Genotype means and IPCA scores for the top yielding 20 entries, with six local commercial checks

Rank	Genotype	Name	Grain yield (t ha^{-1})	IPCA 1	IPCA 2
1	Entry 46	G9	7.20	0.39	-1.31
2	Entry 83	G14	6.74	0.40	0.49
3	Entry 15	G2	6.61	0.13	-0.13
4	Entry 52	G11	6.50	0.18	-0.84
5	Entry 6	G1	6.50	0.18	-0.45
6	Entry 21	G3	6.40	0.76	0.28
7	Entry 43	G8	6.40	0.14	-0.05
8	Entry 97	G19	6.38	0.29	0.46
9	Entry 30	G5	6.38	0.29	0.90
10	Entry 100	G20	6.37	0.47	0.06
11	Entry 84	G15	6.36	-0.07	-0.21
12	Entry 88	G16	6.35	0.10	-0.01
1	Entry 32	G6	6.33	0.60	-0.13
14	Entry 82	G13	6.33	0.59	-0.27
15	Entry 35	G7	6.33	0.10	-0.40
16	Entry 93	G17	6.32	0.38	0.11
17	Entry 94	G18	6.30	0. 70	0.54
18	Entry 47	G10	6.30	0.52	-0.75
19	Entry 54	G12	6.29	0.67	0.95
20	Entry 24	G4	6.29	0.51	0.55
21	P2859W	G26	5.22	-1.02	-0.23
22	SC403	G21	4.79	-0.76	-0.56
23	PAN53	G24	4.76	-1.54	0.59
24	SC627	G23	4.51	-1.50	-0.07
25	PAN 4M-21	G25	4.34	-1.47	0.19
26	SC513	G22	3.96	-1.05	0.29

IPCA interaction principal component axis

Table 7.3 Environment means for grain yield (t ha^{-1}) and IPCA scores

Test environment	Env	Grain yield (t ha^{-1})	IPCA 1	IPCA 2
Mpongwe, optimum	8	9.15	2.27	-0.90
Gwebi, optimum	5	8.13	1.52	0.14
Lusaka, optimum	9	8.00	-0.83	0.31
Ivordale, optimum	7	7.40	0.94	0.22
ART, optimum	6	7.13	0.81	0.66
Cedara 2 optimum	11	6.54	-0.55	-0.22
Cedara 1optimum	10	5.94	-0.63	0.05
Potchefstroom, low N	4	5.76	-0.93	-1.77
Potchefstroom, random drought	12	5.00	-0.98	-0.76
Harare, low N B	3	4.36	-0.47	1.15
Harare, low N A	2	2.74	-0.32	0.69
Gwebi, low N	1	1.96	-0.82	0.45

IPCA interaction principal component axis; Env environment code

7.3.3 AMMI biplots

The AMMI 1 (IPCA 1 vs genotypic means) biplot is shown in Figure 7.1. IPCA 1 and IPCA 2 contributed 49.65% and 14.47% of the G x E interactions, respectively, together contributing 64.12% of total variation. The remaining interactions were distributed up to IPCA 9. Genotypes with IPCA 1 scores near zero had little interaction across environments, while the genotypes with large IPCA 1 scores, either positive or negative were highly interactive. Similarly, sites with IPCA 1 scores near zero had little interaction across genotypes, and low discriminating ability among genotypes (Tarakanovas and Rugas, 2006). Higher potential environments and genotypes were predominating in the second and third quadrants. Those that were further away are therefore not recommended. The lower potential environments and the lower yielding genotypes were observed to the left of the vertical line, and in contrast, high yielding genotypes are to the right of the vertical lines. All genotypes clustered in the top right quadrant of the AMMI biplot when the means were plotted against IPCA 1, except G15 which was in the lower right quadrant. All the commercial checks were in the left lower quadrant. These hybrids showed high adaptability and high yield potentials under optimum environments 2 and 3. All the commercial checks were low yielding (Figures 7.1 and 7.2) while the selected hybrids were on the right side of the vertical line, and were all high yielding. Overall, commercial checks, though less adaptable, performed well under both random drought and low N stress environments. Commercial checks SC627, PAN53 and PAN4M-21 were furthest from the origin and thus contributed much to IPCA 1 effects. Environments Mpongwe (optimum 4), Gwebi (optimum 1) and Gwebi (low N1) were further away from the origin and interacted with the genotypes evaluated.

Grain yield vs IPCA 2 shows that several genotypes were clustered around the origin, indicating their relative low contribution to the G x E interactions. Genotypes 9, 12 and 5 were furthest from the origin and contributed much to IPCA 2 effects. Environments Cedara 1 (optimum 6) was very close to the origin, indicating its low contribution to IPCA 2 effects. Low N environments were furthest from the origin, indicating their relative importance to the higher IPCA 2 effects. Hybrids further from the biplot origin showed high adaptation to specific environments. Results from IPCA 1 vs IPCA 2 biplot (Figure 7.3) showed that entries 9, 10 and 11 were specifically adapted to Potchefstroom (low N4 and random drought) and Mpongwe (optimum 4) environments. These environments had the longest vectors from the origin and were thus highly interactive. Several hybrids were adapted to specific environments, as observed for commercial checks, which are adapted to low potential environments. SC627 was the most stable commercial check variety.

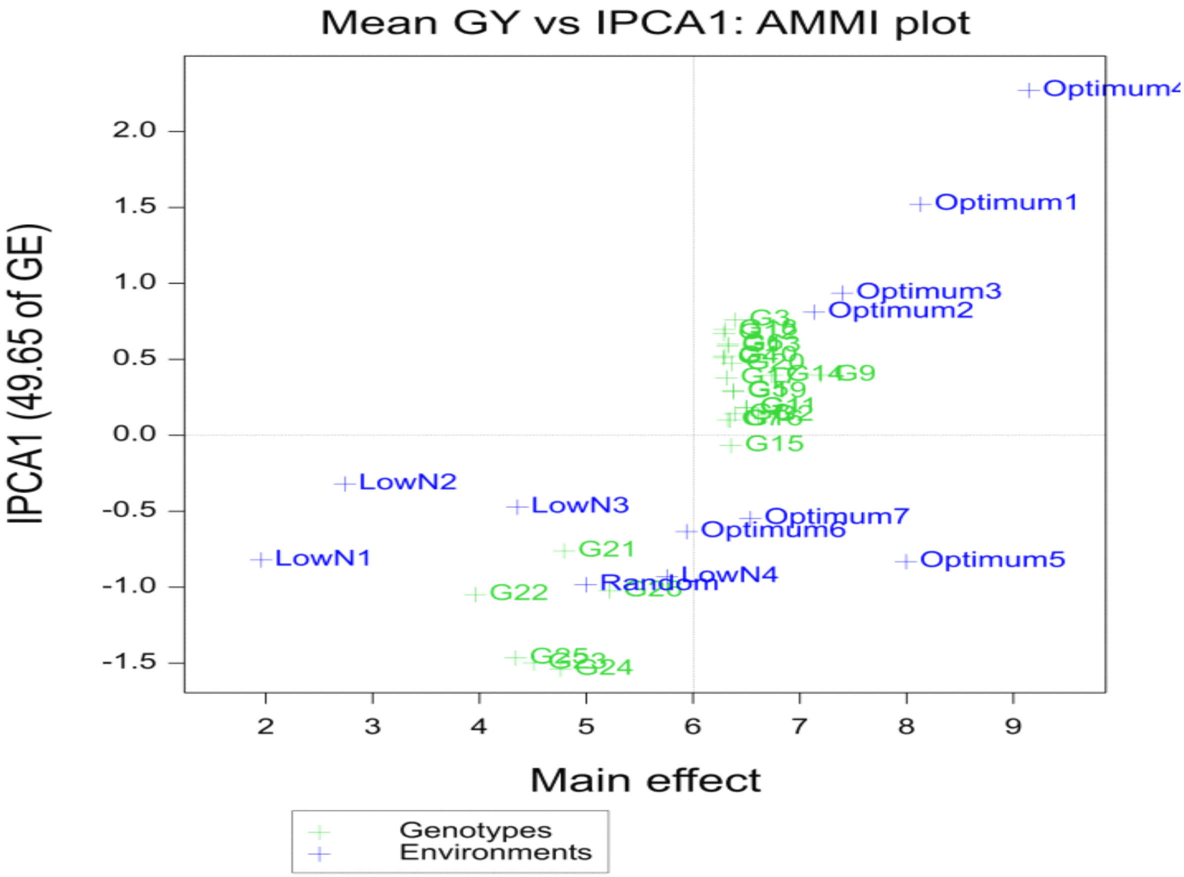

Figure 7.1 AMMI biplot for genotype grain yield means vs. IPCA 1 across 12 environments

G21 = SC403, G22 = SC513; G23 = SC627; G24 = PAN53; G25 = PAN 4M-21; G26 = P2859W

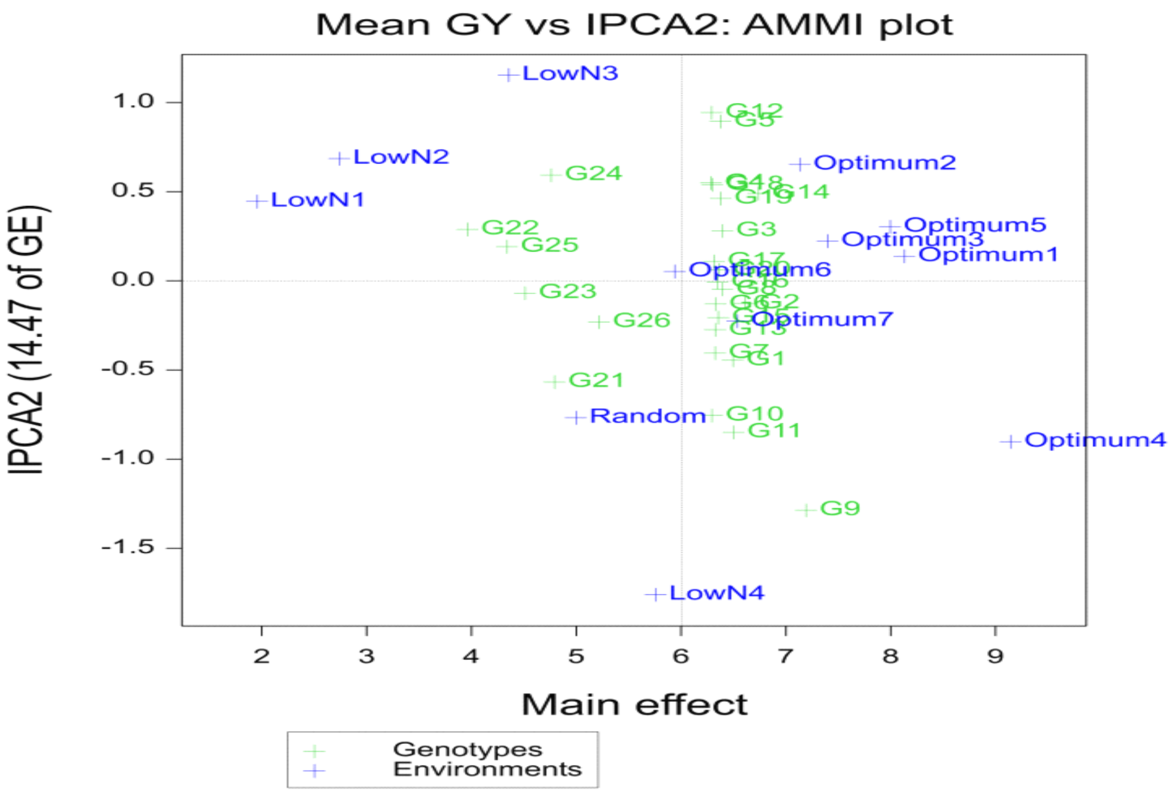

Figure 7.2 AMMI biplot for genotype grain yield means vs. IPCA 2 in 12 environments

7.3.3.1 Analysis of variance across pooled management levels

The three management environments were pooled together to obtain variance among genotypes across management levels. There were significant differences among the treatments, genotypes and management levels (Table 7.4). G x E interaction mean square was significant. Only IPCA 1 was significant and accounted for 62.53% of the G x E interactions. The effect of management contributed much to the total variation, contributing 65.55%. It was followed by genotypes, which contributed 14.73%. The large environmental contribution to the total sum of squares indicated the discriminatory power of the management levels (stress and non-stress test environments) to the variations of the selected genotypes. Ten out of the 26 genotypes evaluated had negative IPCA 1 effects, indicating their adaptability to particular environments (Table 7.5).

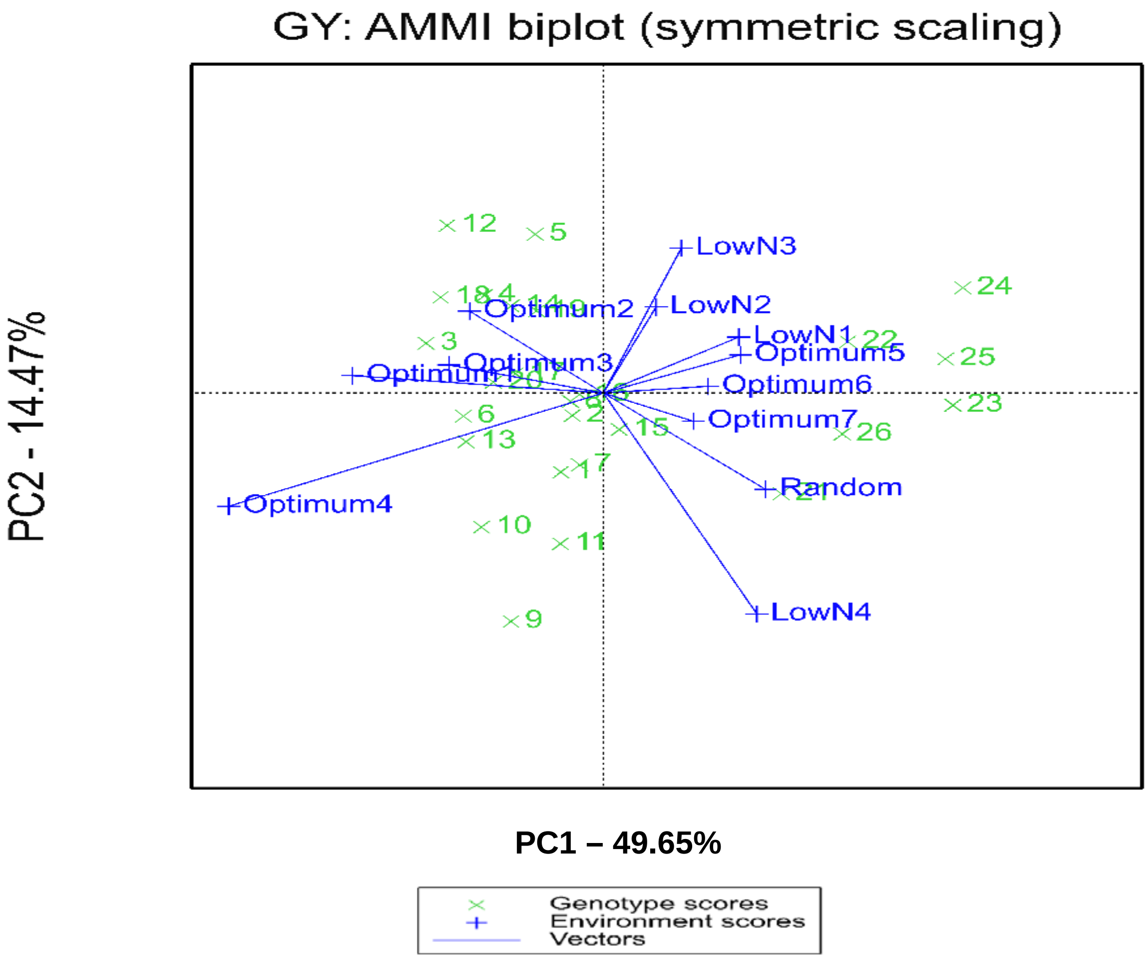

Figure 7.3 AMMI 2 biplot (PC1 vs PC2) for genotype grain yield in 12 environments

Table 7.4 AMMI analysis of variance for pooled management levels

Source of variation	Df	Sum of squares	Mean squares	Total variation explained (%)	G x E explained (%)	G x E cumulative (%)
Total	155	585.8	3.78	-	-	-
Treatments	77	523.4	6.8***	89.35	-	-
Genotypes	25	86.3	3.45***	14.73	-	-
Management	2	384	192***	65.55	-	-
Block	3	3.1	1.02	0.53	-	-
G x E	50	53.1	1.06**	9.07	-	-
IPCA 1	26	33.2	1.28*	5.67	62.53	62.53
IPCA 2	24	19.9	0.83	3.40	37.48	100.00
Error	75	59.4	0.79	10.14		

***P < 0.001; **P < 0.01 and *P < 0.05 respectively; df degrees of freedom, G x E genotype x environment interaction; IPCA interaction principal component axis

The optimum management level recorded the highest yields (7.47 t ha^{-1}), followed by random drought stress, with 5.0 t ha^{-1} (Table 7.5). IPCA 1 effects were positive for both optimum management levels and low N stress environments. The negative IPCA 1 for the random drought management level indicated the highly interactive potential of the environments on the genotypes. IPCA 2 was positive for both optimum and random drought stress, with low N recording the negative IPCA 2 effect.

Table 7.5 Management means for 20 highest yielding hybrids and six commercial checks across 12 environments

Rank	Management level	Environment mean (t ha^{-1})	IPCA 1	IPCA 2
1	Optimum	7.47	1.22	0.97
2	Random drought	5.00	-1.57	0.45
3	Low N	3.69	0.34	-1.42

IPCA interaction principal component axis

7.3.3.2 AMMI biplots for pooled management levels (environments)

AMMI 1 and AMMI 2 biplots for grain yield across the three management levels are presented in Figures 7.4, 7.5 and 7.6. Genotypes, G3, G6, G17, G9, G14 and G11 were closer to the origin, and thus contributed less to the genotype by management interactions (Figure 7.6) and are recommended across the three major environments (management levels). All the commercial checks were on the left side of the vertical axis, indicating their poor performance for the three management levels. IPCA 1 and IPCA 2 contributed 62.48% and 37.52%, respectively. Genotype by management contributed only 9% of the total variation. The commercial hybrids PAN 4M-21(G25), P2859W (G26), PAN53 (G24), SC627 (G23) and SC513 (G21), together with hybrids 21 (G4), 97 (G19) and 94 (G18) were further from the origin, indicating that they were more interactive (Figure 7.4). AMMI 1 indicates that all the management levels were highly interactive with the genotypes, as they were further from the origin. Random drought stress was, however, a lower yielding environment. Genotypes 43 (G8), 100 (G20), 24 (G5), SC627 (G23), SC513 (G21), 35 (G7), and 88 (G16) were stable when the genotype means were regressed on IPCA 2 (Figure 7.5). Entry 24 (G4) was the most desirable genotype with high yields across the three pooled management levels.

The environments were diverse, with each located in its own quadrant, with optimum a high yielding environment (Figure 7.5). Genotype SC513 (G22) was more adapted to the low N environments, while entries 24 (G4) and 97 (G19) were more adapted to the random drought environment. Genotypes 21 (G3), 46 (G9), 47 (G10) and 6 (G1) were more adapted to optimum environments. However, all the commercial checks were more adapted to both random drought and low N environments, indicating their suitability for cultivation under these stress conditions. Hybrids 30 (G5), 35 (G7), 43 (G8), 88 (G16) and 100 (G20) were stable across all environments, and thus can be recommended for both low potential and high potential environments. All management levels were far from the origin, indicating that they were all highly interactive.

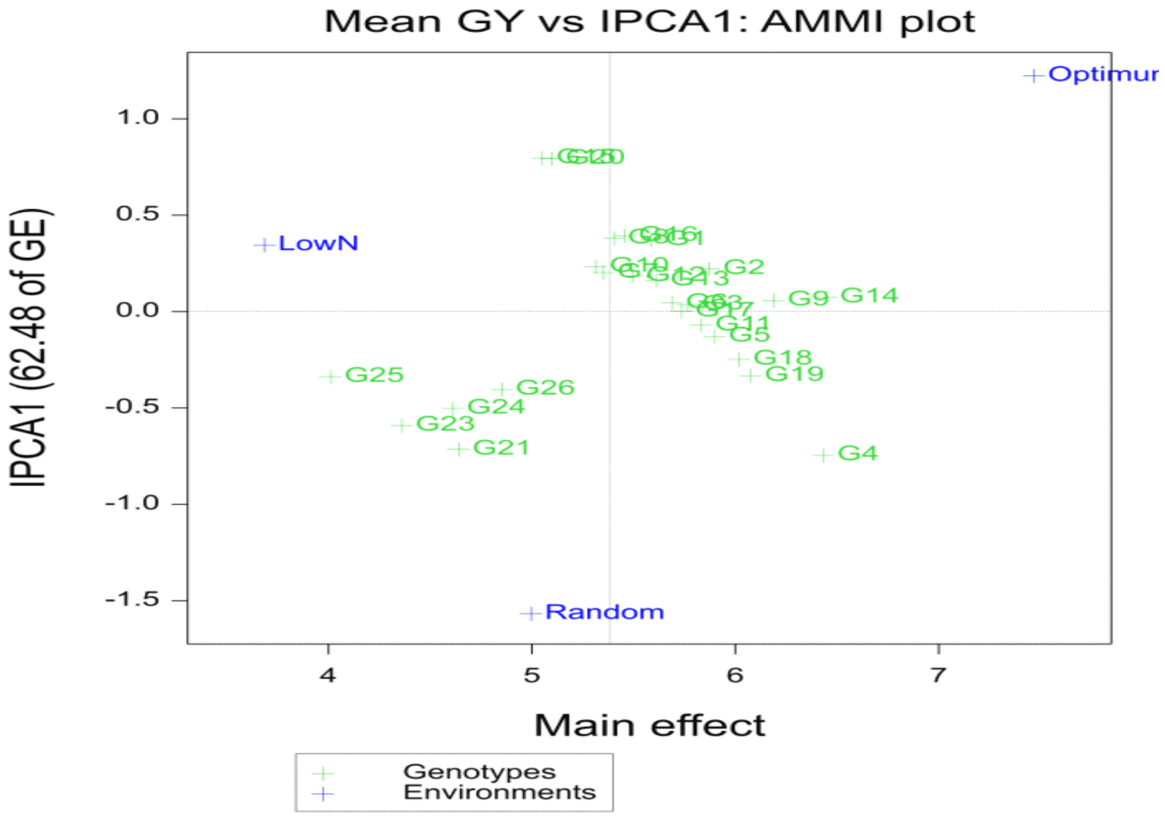

Figure 7.4 AMMI 2 biplot for the 20 highest yielding hybrids and six commercial checks evaluated across random drought, low N stress and optimum test environments

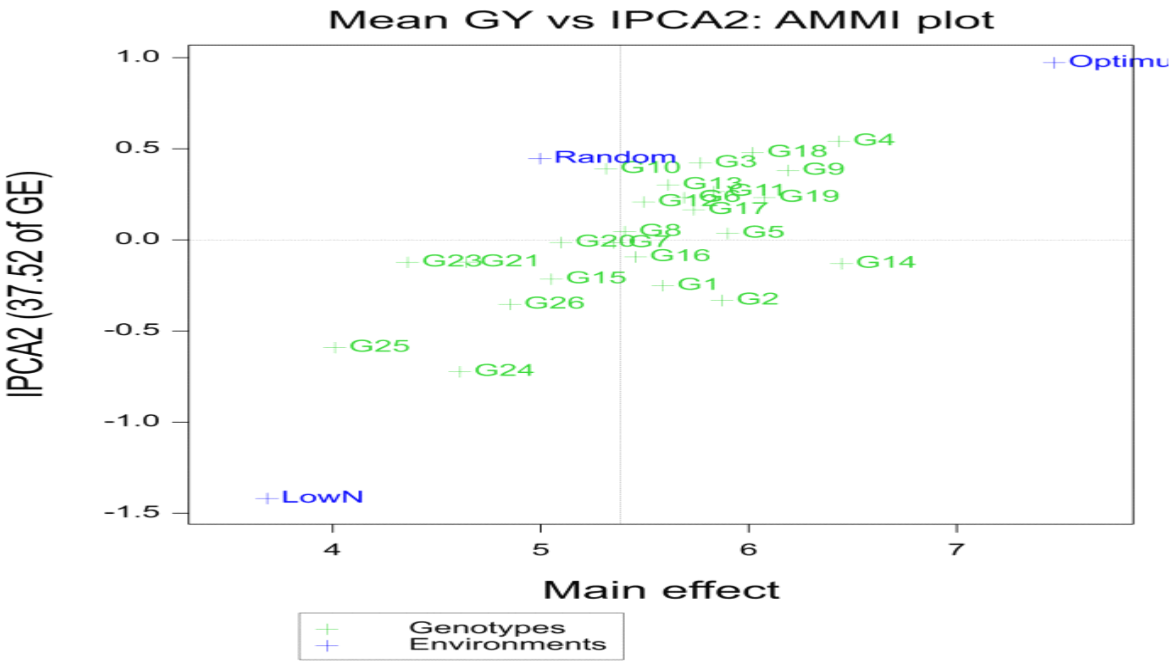

Figure 7.5 Grain vs IPCA 2 AMMI biplot for the 20 highest yielding hybrids and six commercial checks evaluated across random drought, low N stress and optimum test environments

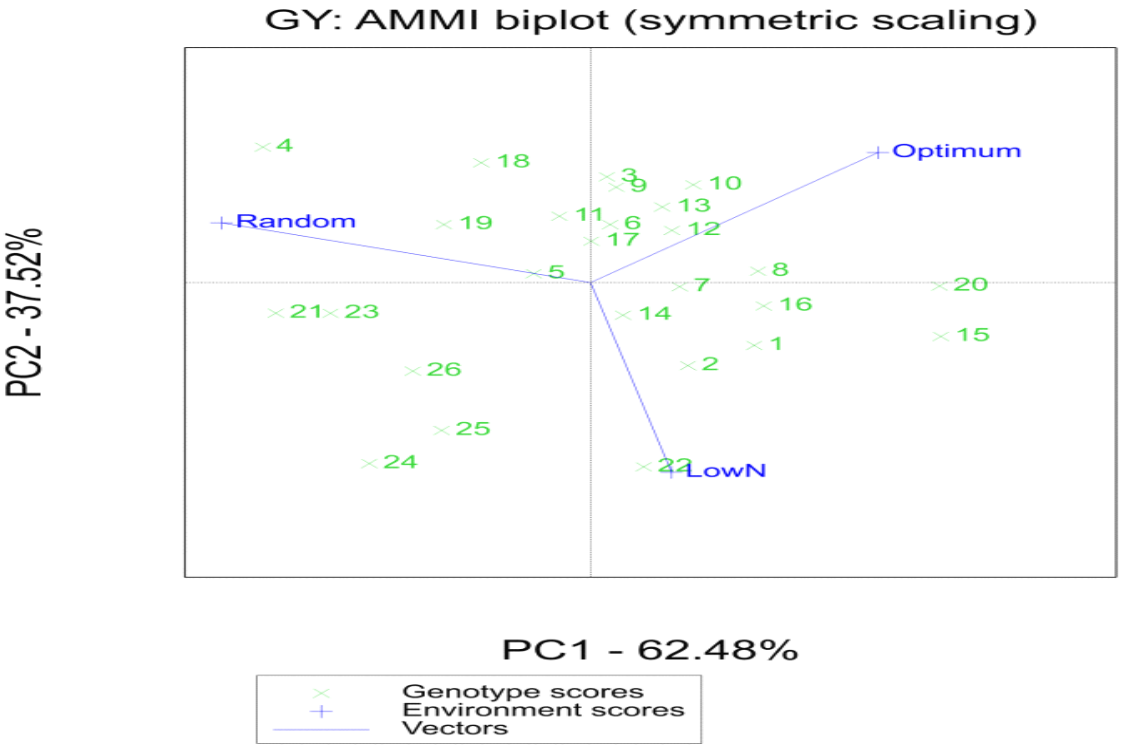

Figure 7.6 IPCA 1 vs IPCA 2 AMMI biplot for the 20 highest yielding hybrids and six commercial checks evaluated across random drought, low N stress and optimum test environments

7.3.4 GGE interactions

The mean yields for the selected 20 genotypes and six checks across the 12 environments were subjected to GGE biplot analysis for visual graphical analysis of the G x E interactions. Ranking of hybrids based on their average grain yield performance and their relative stability across the 12 stress and non-stress test environments are presented in Figure 7.7. PC1 contributed 66.59%, while PC2 contributed 7.91%, together contributing a total of 74.49% of the total G x E interaction variation. Genotypes in the direction of the blue arrow indicate their high yielding ability and stability across the 12 test environments. Genotype TCH46 (entry 46) was the best yielding hybrid across all the test environments. SC513 (G22) and PAN4M-21 (G25) had the lowest average yields and were some of the least stable of the evaluated hybrids.

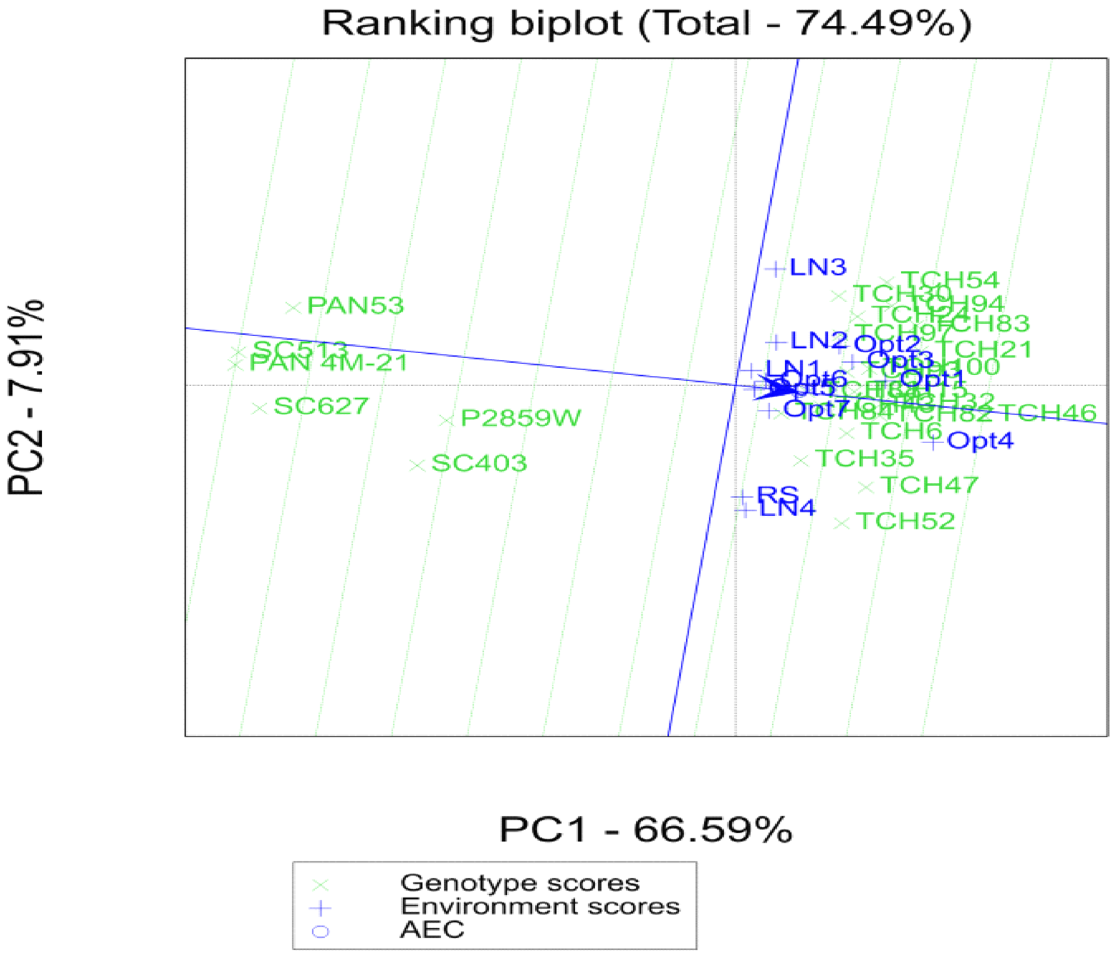

Figure 7.7 Ranking GGE biplot (genotype centred) showing the relationship between genotypes with an ideal genotype across the 12 test environments

The relative discriminativeness and representativeness of test environments are presented in Figure 7.8. Environments, Gwebi low N (LN1), Lusaka (opt 5), Cedara 1 (opt 6) and Cedara 2 (opt 7) were very close to the average environment. Mpongwe (opt 4) was a highly discriminative environment, followed by Gwebi optimum (opt 1). So the ranking for test environments was: Mpongwe (opt 5) > Gwebi optimum (opt 1) > Ivordale (opt 3) > ART (opt 2) > Cedara 2 (opt 7) = Harare B (LN3) = Harare A (LN2) > Cedara 1 (opt 6) > Lusaka (opt 5) > Gwebi low N (LN1) > Potchefstroom low N (LN4) > Potchefstroom random drought (RS).

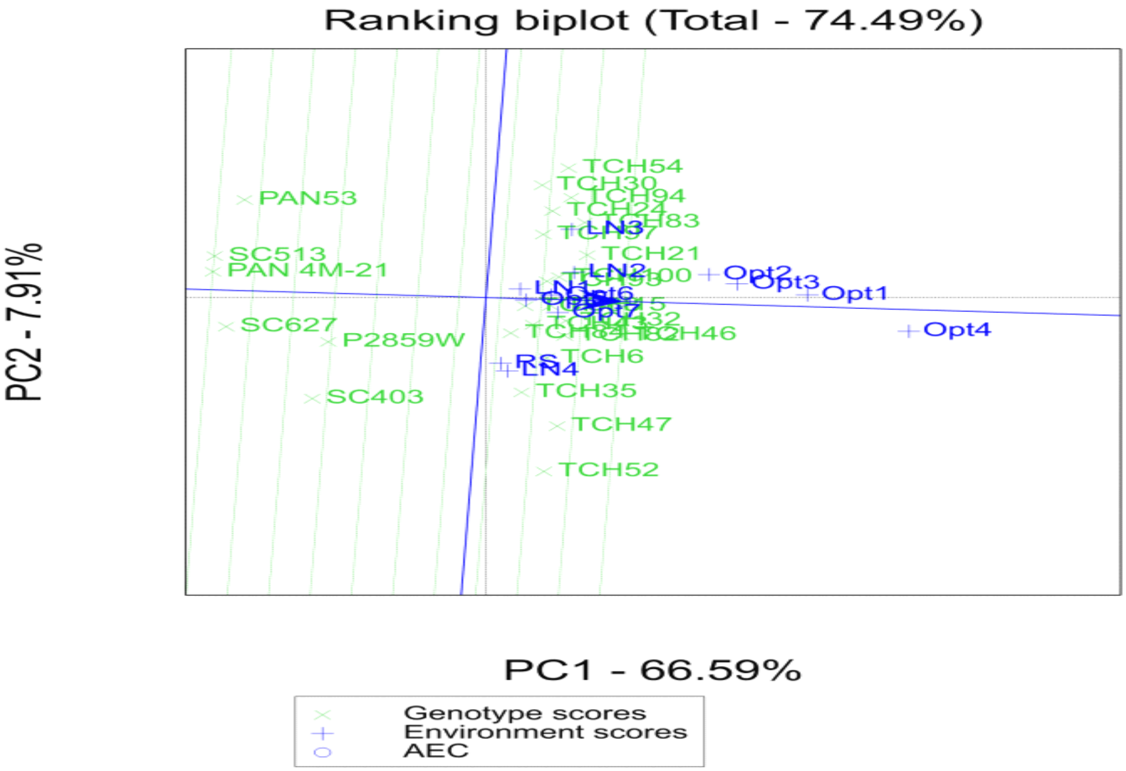

Figure 7.8 Ranking GGE biplot showing the relatedness and discriminative ability of different test environments on the selected 20 high yielding hybrids and six commercial checks

A comparison GGE biplot, showing the ranking of genotypes relative to the ideal genotype are presented in Figure 7.9. Entry 46 (TCH46) was the most ideal hybrid, as it was found in the epicentre of the biplot. Other notable hybrids that were close to the “ideal genotype” included entries 82 (TCH82), 32 (TCH32), 15 (TCH15), 100 (TCH100), 93 (TCH93), 6 (TCH6), 21(TCH21) and 83 (TCH83). All commercial checks were far from both the biplot origin and the “ideal genotype.” P2859W (TCH26) was better than SC403 (TCH21), while SC513 (TCH22) and PAN4M-21(TCH25) were equal and the poorest performing hybrids.

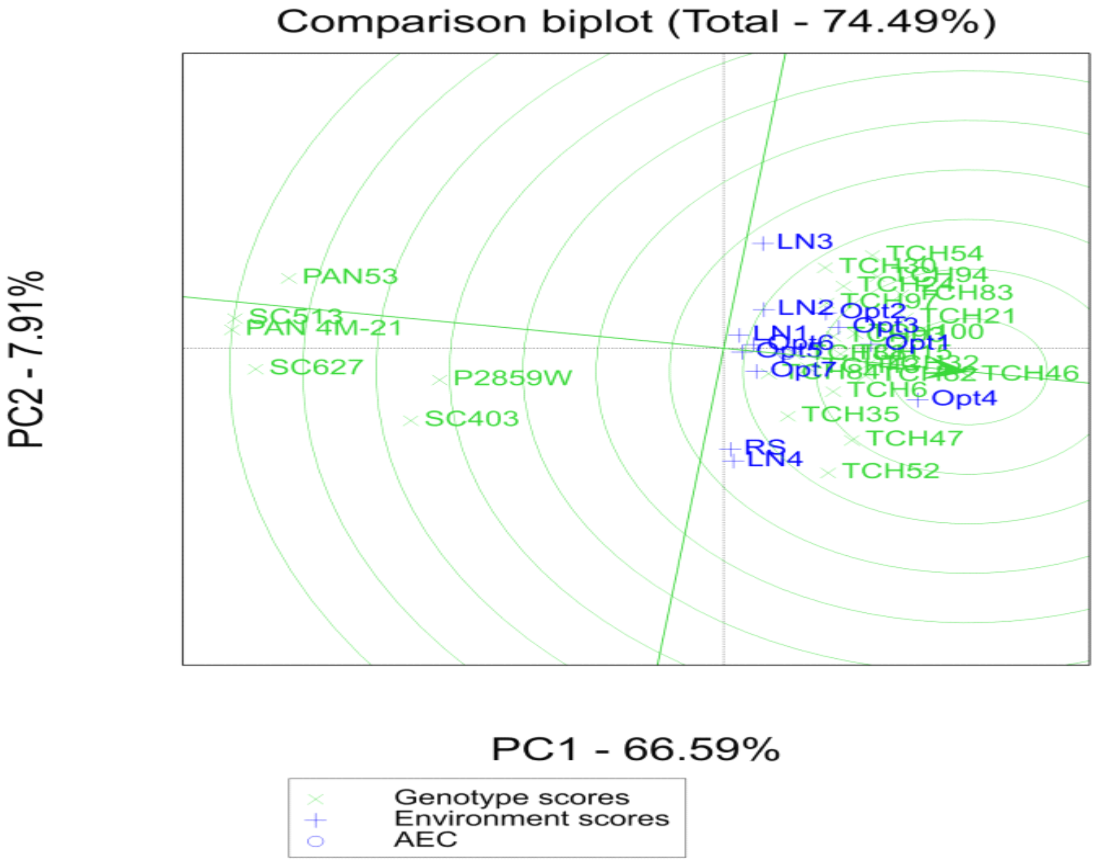

Figure 7.9 A comparison GGE biplot showing the ranking of genotypes relative to the ideal genotype based on grain yield (t ha^{-1}) performance of 20 high yielding genotypes and six commercial checks across 12 stress and non-stress test environments

The differentiating ability of test environments for genotypes and their relationship with an ideal test environment are presented in Figure 7.10. The differentiating ability of a test environment is measured as the absolute distance of the environment from the biplot origin, while the length of its projection onto the ATC Y-axis represents its representativeness. Mpongwe (opt 4) was an "ideal environment" as it was found at the edge of the concentric circle. It was followed by Gwebi (opt 1), Harare B (opt 3) and Harare A (opt 2) showing their better representativeness. All the other environments were further from the ATC, and thus were less representative. The test environments, Mpongwe (opt 4), Gwebi (opt 1), Harare B (opt 3) and Harare A (opt 2) were also far from the origin of the biplot, indicating that they were more discriminating compared to their counterparts.

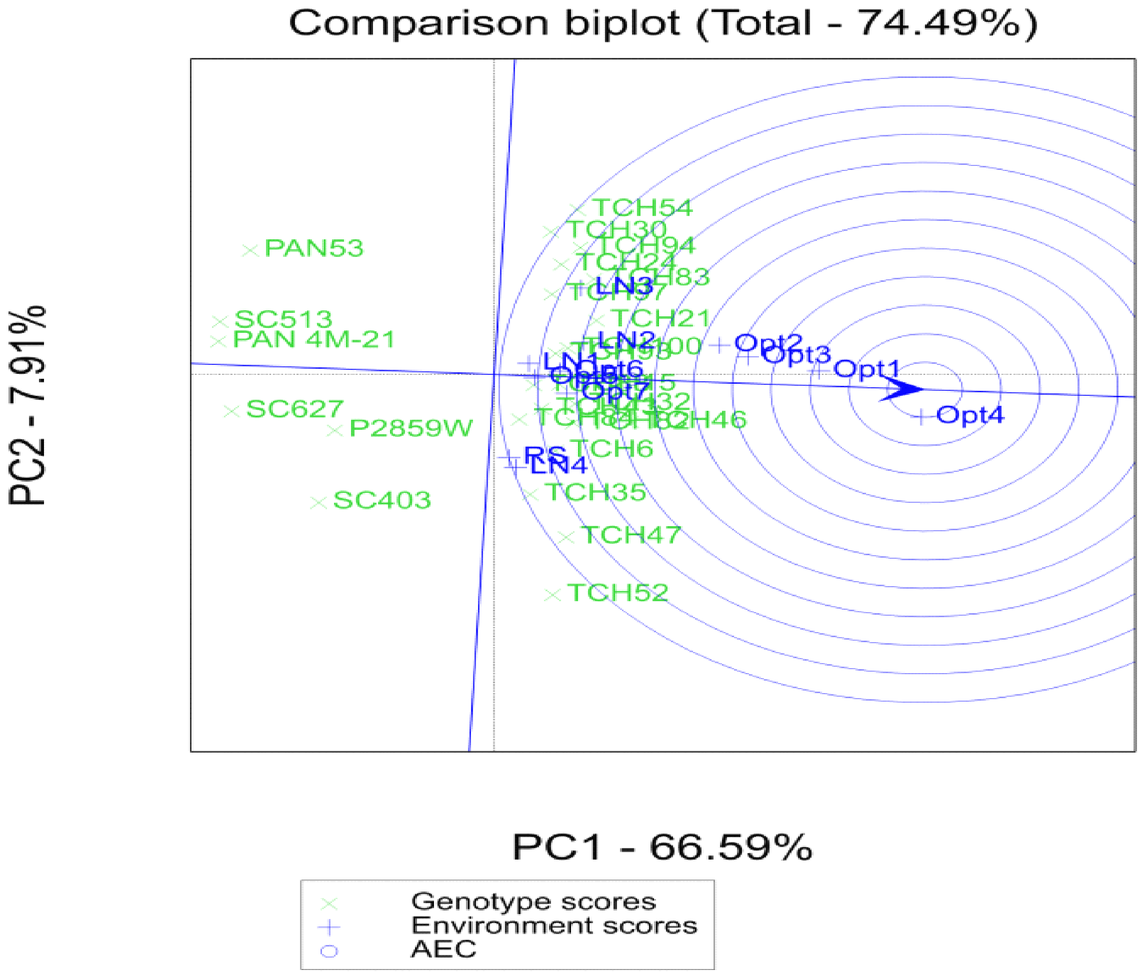

Figure 7.10 A comparison GGE biplot showing the discriminativeness and representativeness of test environments based on the grain yield (t ha^{-1}) performance of 20 highest yielding hybrids and six commercial checks

Figure 7.11 shows the association and relationship among the genotypes and environments. A very important feature of the GGE biplot is its ability to display top performing genotypes at a specific environment, as well as poor performing genotypes across environments, popularly known as the "which-won-where" analysis hence it is a clear summary of the G x E pattern of a multi-environment yield trial (MEYT) data set. The polygon view was formed from PAN53 (TCH24), entry 54 (TCH54), entry 46 (TCH46), entry 52 (TCH52), SC403 (TCH21), SC627 (TCH23), PAN4M-21 (TCH25) and SC513 (TCH22). Eight sectors were drawn from the origin of the biplot, and running perpendicular to the side of the polygon. Five sectors had genotypes inside them. Genotypes were clustered away from the origin, signifying that they made a substantial contribution to both G and GE interactions. However, commercial hybrids were furthest from the origin, indicating their large contribution to the G x E interactions.

Genotypes within the same sector were not significantly different in their mean performance. All optimum test environments were in the same sector, an indication that they were highly correlated in discriminating the selected genotypes. In this same sector, several hybrids performed well, including entries 83 (TCH83), 97 (TCH97), 21 (TCH21), 100 (TCH100), 93 (TCH93), 15 (TCH15), 32 (TCH32), 43 (TCH43), 82 (TCH82), 6 (TCH6), 84 (TCH84) and 46 (TCH46), and thus are recommended for production under optimum test environments. Test environments, Gwebi, Harare A and B (all in Zimbabwe) were in the same sector indicating that they were highly correlated. Hybrids that performed well under these test conditions included entries 54, 30, 94, 24 and 97. These hybrids can also be recommended for these specific low N test environments. Potchefstroom random drought stress and Potchefstroom low N stress environments were also highly correlated, with entries 35, 47 and 52 performing above average in these environments. PAN53 was found in its own sector, indicating its uniqueness from other commercial hybrids. SC403, SC513, SC627, PAN4M-21 and P2859W were in the same segment, which was, however furthest from all the test environments.

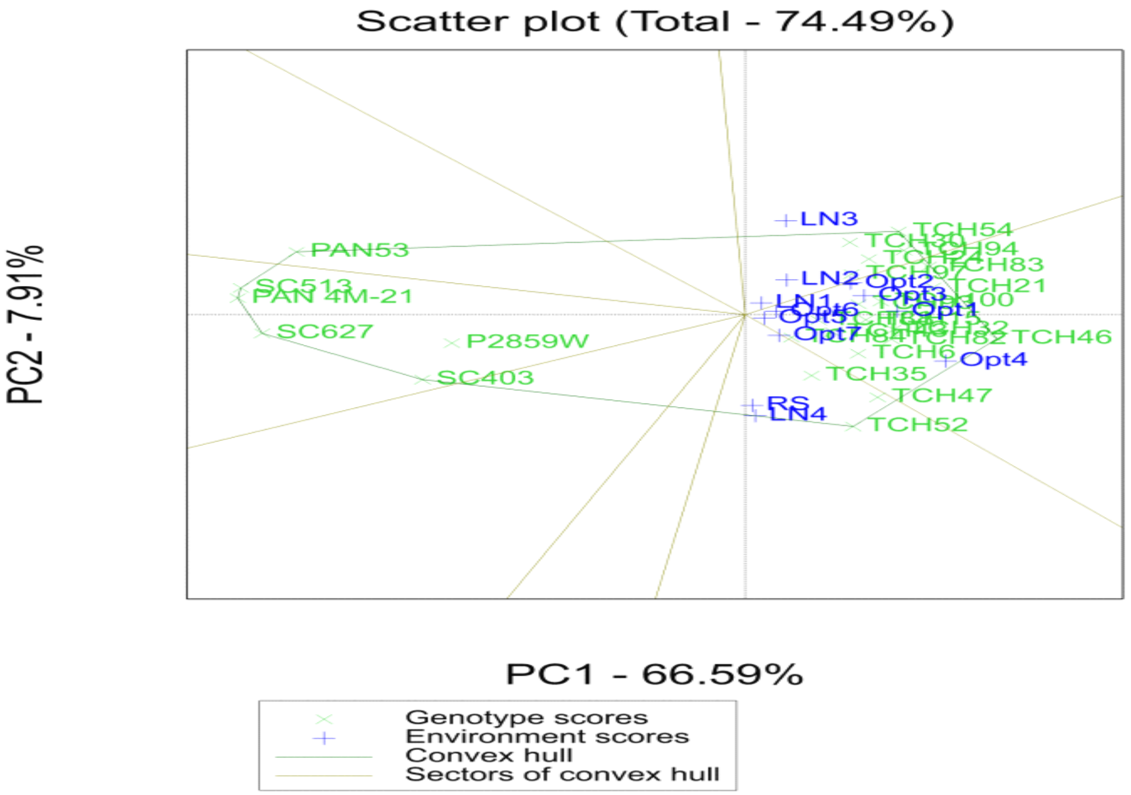

Figure 7.11 A scatter GGE biplot showing "which-won-where" for the selected 20 highest yielding genotypes and six commercial checks based on the grain yield (t ha^{-1}) across the 12 stress and non-stress test environments

The test environments were studied in order to delineate them into mega-environments based on grain yield (t ha^{-1}) for the selected 20 hybrids and six local checks (Figure 7.12). The 12 environments used grouped into three mega-environments that were separate but interlinked. Potchefstroom low N (LN4) and Potchefstroom random drought stress (RS), Lusaka (opt 5), Cedara 1 (opt 6) and Cedara 2 (opt 7) optimum sites were grouped into one mega-environment. Gwebi low N (LN1), Harare A (LN2), Harare B (LN3) low N environments and Lusaka (opt5); Cedara 1 (opt 6) and Cedara 2 (opt 7) optimum environments were grouped into another mega-environment. Gwebi low N (LN1), Harare A (LN2), Harare B (LN3) low N environments and all optimum environments, except Gwebi optimum (opt 1) were in mega-environment 3. The distinct overlap of mega-environments indicates the relatedness of these environments in discriminating the selected genotypes.

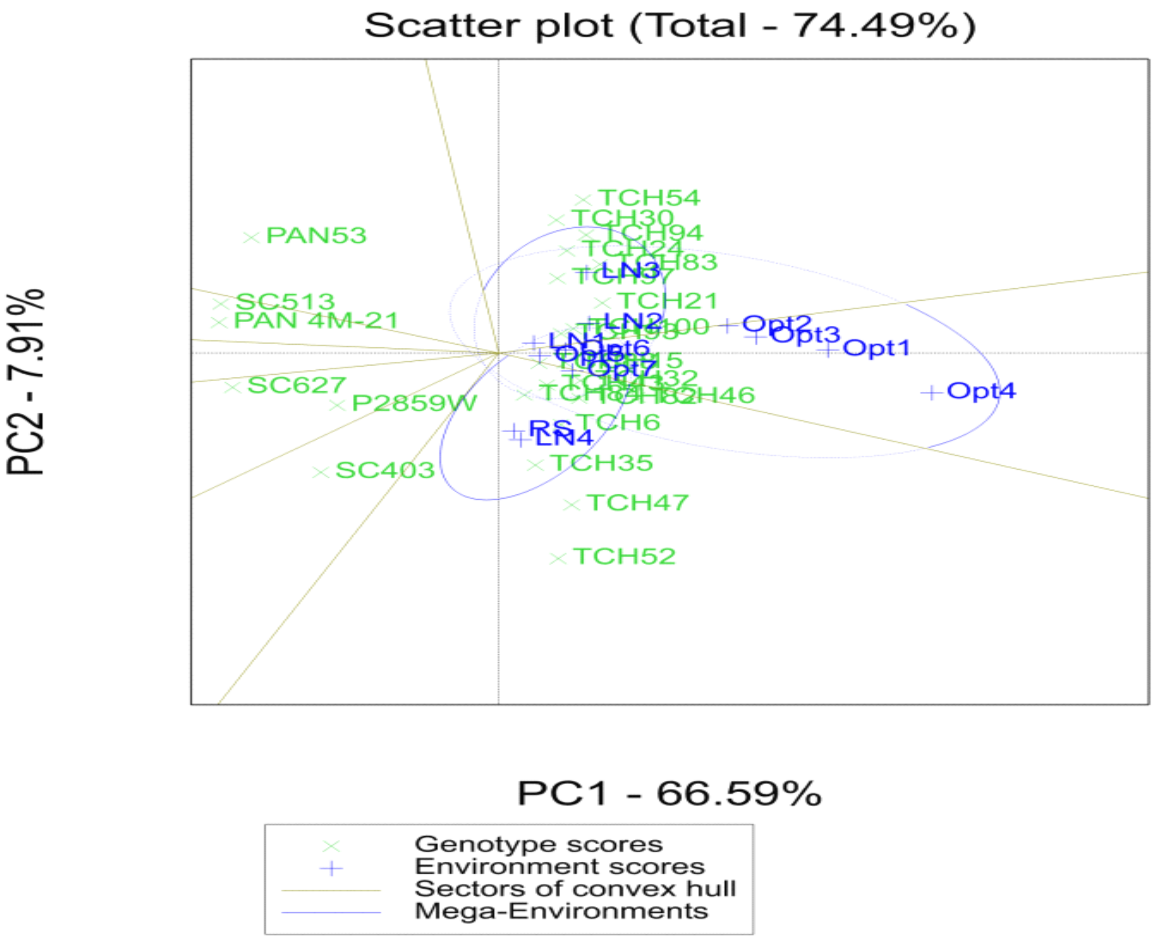

Figure 7.12 A scatter GGE biplot showing the mega-environments formed by the 12 test environments based on the grain yield (t ha^{-1}) performance for the selected 20 high yielding hybrids and six commercial checks

7.4 Discussion

The complexity of G x E interactions limits progress in breeding, as selection of the best suitable cultivars for release are affected and limited by the occurrence of these interactions. Significant G x E interaction for a quantitative trait like yield can reduce the usefulness of subsequent analyses, restrict the significance of inferences and conclusions that would otherwise be valid, and seriously limit the feasibility of selecting superior cultivars. The AMMI model incorporates both the classical additive main effects model for G x E interaction and the multiplicative components into an integrated least square analysis and thus becomes more effective in selection of stable genotypes (Crossa et al., 1991; McLaren and Chaudhary, 1994; Ariyo, 1998;

De Cauwer and Ortiz, 1998; Haji and Hunt, 1999; Ariyo and Ayo-Vaughan, 2000; Taye et al., 2000; Yan and Hunt, 2001).

The results indicated significant effects of genotypes, environments and G x E interactions ($P < 0.001$) on yield. The significant G x E interaction effects demonstrated differential responses of environments as well as genotypes, which indicated the differential potential of the environments and genotypes, respectively. The AMMI ANOVA indicated the presence of highly significant contribution of genotypes, environments and G x E interactions to the variation. These results are in agreement with previous findings (Sabaghnia et al., 2008; Ramburan et al., 2011; Thangavel et al., 2011; Ndhlela et al., 2014).

The variations among the test environments can be attributed to the different treatments (management levels) applied and different climatic and edaphic conditions specific to each environment. Environment contributed largely (90.1%) to the total variation, which indicated the large diversity of the test environments used. Dari (2011) obtained similar high variability explained by the environments, as compared to the genotypes and G x E interactions. Results indicating higher G x E interactions and environmental contributions to yield variation in maize than genotypic effects were observed by Arulselvi and Selvi (2010), Khaldun et al. (2012), Jha et al. (2013), Nzuve et al. (2013), Abuali et al. (2014) and Kumar et al. (2014). The significant differences among hybrids indicate that they can be selected for adaptation to particular environments (Derera et al., 2008). Carson et al. (2002), Makumbi (2005), Menkir and Ayodele (2005) and Nzuve et al. (2013) also reported significant G x E interactions among maize genotypes across stress and non-stress environments.

Significant G x E interaction for quantitative characteristics minimizes the efficiency and the usefulness of selecting genotypes over various environments (Pham and Kang, 1988). The presence of G x E interactions observed in the current study can be utilised for increased selection efficiency of better adapted and stable genotypes. The results indicated the suitability of the AMMI model in dissecting the effects of environments on the performance of genotypes. The AMMI 1 and AMMI 2 models were both important in identifying potential test environments, and genotypes to be utilized for future breeding programmes. The results indicated good potential of the selected high yielding genotypes, as they were placed on the right side of the vertical line, indicating their high yielding potential across stress and non-stress test environments. The highest yielding hybrids among the selected 20 included entries 46 (7.2 t ha^{-}

^{1}), 83 (6.74 t ha^{-1}) and 15 (6.61 t ha^{-1}). The selected hybrids showed sufficient stability and high yielding potential under stress and non-stress environments. The genotypes were relatively tolerant to random drought and low N conditions, but performed better when conditions were optimal. These hybrids could be used as sources of drought and low N tolerance genes. Badu-Apraku et al. (2011; 2013; 2015) obtained similar results and concluded that there is large variability among CIMMYT maize hybrids developed for drought and low N tolerance, which can be utilized in environments that are prone to drought and low N stress. In this study, as differential responses of genotypes were observed and stable and high yielding hybrids were identified, environment-specific adaptation was also identified. These findings validate the use of contrasting multi-environment analysis (random drought stress, low N and optimum environments) as a way of identifying stable, well adapted and high yielding varieties (Sabaghnia et al., 2008; Morghaddam and Pourdad, 2009).

The most recently developed stability analysis method, the GGE biplot model, provides breeders with a more complete and visual evaluation of all aspects of the data by creating a biplot that simultaneously represents mean performance and stability, as well as identifying mega-environments (Yan, 2001; Yan and Kang, 2003; Ding et al., 2007). The GGE biplot can be useful to display the which-won-where pattern of the data that can lead to identification of high-yielding and stable cultivars and discriminating and representative test environments (Yan et al., 2001; Yan et al., 2007).

The AMMI and the GGE biplot models are the most powerful tools for effective analysis and interpretation of multi-environment data structure in breeding programmes. The results from the GGE biplots indicated high variability among genotypes and high yielding potential for the selected genotypes compared to the commercial hybrids. The large grain yield variations among the selected hybrids, that was largely due to the environment, suggested the use of the GGE biplot analysis for the identification of ideal genotypes, test environments and mega-environments (Ghaffari and Depao, 2005; Samonte et al., 2005). According to Yan et al. (2000; 2010) and Yan (2001) the length of the projection of a cultivar from the origin determines the stability of a cultivar - the further away the less stable, while the closer it is the more stable it is. Highly interactive hybrids were identified in this investigation, which were largely commercial hybrids. All the selected genotypes were closer to the origin, as compared to the local commercial cultivars, indicating their potential as high yielding and stable cultivars.

In this study, GGE biplots identified entry 46 as an ideal genotype. The investigation was also useful in identifying other genotypes that were close to the ideal genotype including entries 82, 32, 15, 100, 93, 6, 21 and 83. The study also identified all commercial cultivars as differentially lower yielding than the selected genotypes. Sharma et al. (2009) highlighted that genotypes closer to the ideal genotype can be recommended for further evaluations, and/or for release. The GGE biplot was also effective in establishing and identifying an ideal test environment, in this case, Mpongwe (Opt 4), validating its potential use in maize breeding programmes. An ideal environment has been described by Yan and Kang (2003) as a test environment with the longest vector of the highest yielding genotype with zero G x E interaction.

The GGE biplot was also able to identify the “which-won-where” pattern of genotypes, as suggested by Baker (1988) and Yan and Rajcan (2002), thus essentially exploiting both the genotype and G x E in aiding the selection of highly adapted hybrids to a specific test environment. There were three mega environments identified in the GGE biplot analysis in this investigation. The overlapping environments meant that they can be excluded when resources are limiting. Mega-environments were interlinked, which is similar to findings observed by Mengesha (2013). The occurrence of mega-environments in this study was similar to the findings by Efron (1985), Fajemisin et al. (1985), Menkir et al. (2003) and Setimela et al. (2005).

7.5 Conclusions

The occurrence of G x E interactions reduces progress of breeding programmes in maize. This has led to the use of multi-location and multi-season trials and the development of models to explain the G x E interactions. The AMMI and the GGE models are currently the most important tools for quantifying and explaining these effects in maize breeding. AMMI analysis is preferred for its use of the additive analysis of variance, coupled with the multiplicative explanation of the G x E interactions. The GGE also shares the advantages of the better identification of genotypes well adapted to particular environments, identification of highly discriminative and representative test environments, and mega environments, which will aid in making informed decisions and inferences about the behaviour of genotypes and their interactions with the environments.

Significant differences were observed among genotypes for grain yield in different test environments that indicate the presence of large genetic variability among the hybrids that allows for selection for yield improvement in this material. The effects of the test environments were very large, indicating the differences in the discriminating ability of the test environments. Random drought and low N stress environments recorded lower yields than optimum environments. Several hybrids performed better than the local commercial varieties, indicating their suitability as potential cultivars under stress and non-stress environments. Entries 46, 82, 32, 15, 100, 6, 21 and 83 were consistently identified by the AMMI and GGE biplots as performing above average in terms of yield and stability, and warrants recommendation as hybrids under both stress and non-stress environments in southern Africa.

In southern Africa, the increase in drought conditions and unpredictability of rainfall, and low fertiliser inputs by the small farmer communities justify continued improvements of genotypes for drought and low N tolerance. There is sufficient variability within CIMMYT developed genotypes that can be useful in southern Africa and other similar sub-optimal environments in Africa. Some test environments could be redundant as they fall in the same mega environments, and can be excluded when resources are limiting

The AMMI and the GGE models were efficient in identifying, analyzing and interpreting the effects of genotypes and their interactions with the test environments, which was shown by the large G x E interaction extracted by both models. With the increased importance of maize, and challenges facing farmers in southern Africa, the use of AMMI, together with GGE models will contribute to breeding programmes for drought and low N environments.

7.6 References

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CHAPTER 8

Predicting grain yield performance and stability of late maturity maize hybrids under stress and non-stress environments using AMMI and GGE models

Abstract

The use of both GGE and AMMI models as stability instruments has been increasing in plant breeding programmes. It is aimed at identifying efficient genotypes, test environments and mega-environments. An experiment was performed to assess the magnitude of G x E interactions and stability among the late maturity maize hybrids in southern Africa. One hundred and fifty-five hybrids were valuated across 15 test environments, which involved three stress levels; random drought, low N and optimum conditions. Treatments were arranged in an alpha lattice design, replicated twice. AMMI analysis identified highly significant ($P < 0.001$) effects of test environments, hybrids, and G x E interactions on yield. G x E interactions were partitioned into eight IPCA components which were highly significant up to IPCA 6 and significant at $P < 0.05$ for IPCA 7 and 8, all contributing 82.14% of the total variation. There were complex G x E interactions of the genotypes with test environments. AMMI analysis for pooled management levels also indicated highly significant differences among environments and hybrid performance. IPCA1 and 2 accounted for 99.46% of the total variation and were both highly significant. Entries 109, 115, 22, 63, 1, 24, 21, 20, 2, 19, 5, 6, 10, 14, 25, 9, 108 and 114 performed better than all commercial check cultivars at a range of 5.71 to 6.08 t ha^{-1}. Optimum environments recorded an environmental mean of 7.58 t ha^{-1}, followed by low N (2.98 t ha^{-1}) and random drought (1.53 t ha^{-1}) translating to 60.68 and 79.81% yield reductions, respectively. GGE biplots identified six mega-environments with hybrids well adapted to these specific environments. Entries 24, 25, 97, 20, 109, 114 and 115 dominated in the optimum test environments, and entries 13, 14, 19 and 137 were predominant across low N stress test environments. Under random drought stress, entries 9, 6, 5 and local checks 154 and 155, 10, 2 and 16 were dominant, indicating their adaptation to this particular test environment. The two models were useful for increasing the efficiency of identifying potential test environments, and high yielding and stable genotypes. This is crucial for the success of maize production systems in southern Africa where droughts and low N fertility are a common cause of poor yields and low productivity.

8.1 Introduction

Maize (*Zea mays* L.) is the principal grain crop and globally ranks third after wheat and rice in terms of production and consumption. It remains the food security crop in eastern and southern Africa predominantly grown by resource-constrained and small-scale farmers. Newly developed superior maize cultivars should have good yield potential and average stability over a wide range of environmental conditions, to be released. High G x E interactions lead to differential response and stability among genotypes. In maize breeding, choice of a suitable candidate cultivar is subject to two considerations, (1) high grain yield across a wide range of environments and (2) consistent performance over varied environments. Consistent performance is dependent upon the G x E interactions. Cultivars which show lower G x E interactions are more stable or well buffered. Stability of yield is defined as the ability of a genotype to avoid substantial fluctuations in yield over a range of environments (Kang, 1998).

Maize has been grown in several environments throughout its evolutionary history. This has lead to wide adaptation of this crop, contributing to its success as a staple food crop across many economies. Different crop varieties respond differently to a given environment, which affects their yield either positively or negatively. These responses are due to the genotypes (genetic) or genotypic response to the environment, or an interaction of the genotype and the environment. Plant breeders rely on these measures to identify and select better performing inbred lines and hybrids. Genotypes that are less responsive to environmental changes or those well adapted to particular environments are selected.

There are various methods that are utilized to discriminate genotypes and understand the nature and magnitude of genotypic, environmental and G x E interaction variation. AMMI analysis (Gauch, 1992; Gauch and Zobel, 1996) and the GGE biplot model (Yan et al., 2000) are the most recent techniques to study G x E interactions. These have been extensively utilized in both maize and other important cereals.

The AMMI model extracts the genotype (G) and environment (E) effects to predict the genotypic performance under specific environments, and lastly the G x E interactions (Gauch and Zobel, 1988; 1996). The AMMI model has been extensively used to depict adaptive responses and understand complex G x E interactions (Gauch and Zobel, 1989; 1997; Crossa, 1990). The AMMI model combines classical ANOVA and PCA into a single model with additive and multiplicative parameters (Zobel et al., 1988; Thillainathan and Fernandez, 2001; Pinnschmidt and Hovmoller, 2002). In essence, the AMMI summarizes patterns and relationships of genotypes and environments (Crossa, 1990). Results from the AMMI model can be graphically presented with the main and interaction effects of both the genotype and the environments on the same scatter plot, with the noise rich residual discarded and the data separated into a pattern rich model in order to gain the accuracy of results (Gauch and Zobel, 1996). The graph is used to visualize the average (adaptability) and the consistent (stability) performance across the trial environments. The differences in main effects are indicated along the abscissa while the differences in the interaction are indicated along the ordinates. Genotypes located close to the abscissa are relatively stable, while those further away from the abscissa interacts more with the environment (unstable). This is different from the GGE biplot model which extracts the genotype and the G x E interactions, with the exclusion of environmental effects (Yan et al., 2000; 2007).

The genotype and G x E interaction biplot analysis (GGE) is a graphical representation of the genotype main effects and the G x E interactions of multi-location trials for visual evaluation of genotypes and testing environments and the identification of mega-environments (Yan et al., 2000). The GGE analysis is widely used in G x E interactions studies in plant breeding research (Butran et al., 2004; Samonte et al., 2005). According to Yan et al. (2001), the effects due to genotype and G x E interactions are the integral sources of variation relevant to cultivar evaluation. It is based on the plotting of the first two interaction principal component axes (IPCAs) against each other with IPCA1 on the x-axis and IPCA2 on the y-axis. The GGE biplots are used for cultivar identification, testing environment evaluation and mega-environment analysis as well as the identification of high yielding, stable and ideal genotypes (Yan et al., 2000). An ideal genotype ranks highest for any characteristic in all locations (Yan and Kang, 2003) and if available, can be used as a reference during genotype evaluation. GGE biplots use vectors and angles to visually depict and discriminate individual performances and are therefore able to identify which genotype won in which environment. The GGE analysis exploits both genotype and G x E interactions in a way beyond what ANOVA can do (Muungani et al., 2007).

The polygon view has the ability to characterise existing interactions among genotypes and test environments (Yan and Kang, 2003). It also has advantages of identifying the cross-over interactions which describe the presence of mega-environments (Gauch and Zobel, 1997; Yan and Tinker, 2006). Within the scatterplot, genotypes that lie furthest from the origin are used to construct a polygon with all the other genotypes occurring inside the polygon (Kaya et al., 2006). The hybrids which help to construct the polygon are either high or poor yielding with respect to given test environments (Yan and Rajcan, 2002). Genotypes that are enclosed within the same sector with the test environments are regarded best for that particular environment. Sectors which enclose test environments and genotypes run perpendicular from the origin to the polygon sides. Research findings suggest the complimentary effect of AMMI and GGE models on the evaluation, identification and selection of suitable genotypes, test environments and mega-environments. The rationale is that candidate maize hybrids that are newly developed are tested for their adaptability and comparative yield stability at the target environments to make recommendations based on the interests of the farmers in the target areas.

The objectives of this study were to measure the extent of G x E interactions and assess the stability and adaptability of late maturity maize hybrids under drought and low N environments in southern Africa, and to recommend suitable hybrids based on their attributes.

8.2 Materials and methods

8.2.1 Experimental data

A total of 155 maize hybrids developed from late maturing maize inbred lines were used. Though AMMI and GGE biplot analysis was performed for all the genotypes, the 26 best yielding genotypes were selected and advanced to check their utility as potential hybrids, against four local commercial checks using Genstat statistical software (VSN-International, 2015).

8.2.2 Trial management and statistical analysis

Test environments included 15 test sites in Zambia, Zimbabwe and South Africa as described in Chapter 4 (materials and methods section). To determine the G x E interaction on yield, AMMI and a GGE biplot analyses were performed by the same software as explained in sections 7.2.5 and 7.2.6, respectively. Biplots were drawn by placing both the genotype and environment means on the axis (abscissa) and the respective eigenvectors or scores (IPCA's) on the y-axis (ordinate), according to Gauch and Zobel (1996).

8.3 Results

8.3.1 AMMI analysis of variance for late maturity hybrids

AMMI ANOVA for the 155 three way hybrids and the G x E interactions are presented in Table 8.1. Grain was highly significantly influenced by genotype, environment and G x E interactions across the 15 test environments. The G x E interactions were further partitioned into eight IPCA's, for which the IPCA 1-IPCA 6 were highly significant ($P < 0.001$) and IPCA 7 and 8 were significant at $P < 0.05$. The eight significant IPCA's contributed 82.14% of the total G x E interaction variation. Environments explained 80.70% of the total (G + E + G x E) variation, whilst genotypes and the G x E interactions explained 5.63% and 7.91% of the total variation, respectively.

Table 8.1 AMMI analysis of variance for 155 hybrids across 15 test environments

Source	df	SS	MS	% Contribution to variation	% G x E contribution	Cumulative % G x E Contribution
Total	4649	45225.00	9.70	100.00	-	-
Treatments	2324	42621.00	18.30***	94.24	-	-
Genotypes	154	2546.00	16.50***	5.63	-	-
Environments	14	36496.00	2606.90***	80.70	-	-
Block	15	249.00	16.60***	0.55	-	-
G x E	2156	3579.00	1.70***	7.91	-	-
IPCA 1	167	784.00	4.70***		21.91	21.91
IPCA 2	165	518.00	3.10***		14.47	36.38
IPCA 3	163	388.00	2.40***		10.84	47.22
IPCA 4	161	376.00	2.30***		10.51	57.73
IPCA 5	159	246.00	1.50***		6.87	64.60
IPCA 6	157	233.00	1.50***		6.51	71.11
IPCA 7	155	198.00	1.30*		5.53	76.64
IPCA 8	153	197.00	1.30*		5.50	82.14
Residuals	725	471.00	0.60			
Error	2310	2355.00	1.00			

***$P < 0.001$; **$P < 0.01$; *$P < 0.05$; G x E genotype by environment interaction; IPCA interaction principal components; MS mean squares; SS sum of squares

8.3.1.1 Hybrid grain yield means and IPCA scores across the 15 test environments

Entry 109 (6.08 t ha^{-1}) recorded the highest mean yield across the 15 test environments, followed by entry 115 (6.05 t ha^{-1}) and entry 22 (5.99 t ha^{-1}) (Table 8.2). These highest yielding hybrids had equal or higher yields than the local checks used in the evaluations. All the high yielding genotypes recorded positive IPCA 1 values except entry 5, 7 and local check PHB30G19. Genotypes with a large IPCA (± 0.3) either negative or positive contributed much to G x E interactions, and hence were unstable across environments. Among these genotype entries 24, 5, 10 and 14 which contributed little to G x E interactions on IPCA 1, were stable.

Most hybrids had negative IPCA 2 values. PAN7M-81 and SC719 had high IPCA 1 and 2 values, indicating their instability.

Table 8.2 Mean grain yield and IPCA scores for selected high yielding across 15 test environments

Genotype code	Entry	Entry mean	IPCA 1	IPCA 2
G109	109	6.08	**0.62**	-0.10
G115	115	6.05	**0.59**	0.14
G22	22	5.99	**0.66**	-0.11
G63	63	5.91	**0.69**	0.04
G1	1	5.90	**0.44**	**-0.61**
G24	24	5.87	0.02	0.22
G21	21	5.87	**0.44**	-0.08
G20	20	5.87	**0.41**	0.08
G2	2	5.87	**0.44**	0.05
G19	19	5.80	**0.51**	**-0.37**
G5	5	5.79	-0.03	**-0.53**
G6	6	5.76	0.22	**-0.34**
G10	10	5.76	0.06	**0.48**
G14	14	5.74	0.08	**-0.54**
G25	25	5.73	**0.40**	-0.09
G9	9	5.72	0.19	-0.05
G108	108	5.72	**0.32**	1.10
G114	114	5.71	**0.65**	**0.31**
G7	7	5.67	-0.12	-0.15
G153	PAN 7M-81	5.67	**0.54**	**0.35**
G16	16	5.67	0.15	-0.07
G68	68	5.67	**0.44**	**0.51**
G152	SC719	5.56	**0.82**	**0.65**
G154	PAN53	5.49	0.11	-0.04
G155	PHB30G19	4.77	-0.20	0.21

IPCA interaction principal component analysis, **bolded IPCA** had ± 0.3 greater or less contributed significantly to the respective AMMI

8.3.1.2 Grain yield stability evaluations for hybrids across test environments

Table 8.3 presents the environment and IPCA scores for grain yield for 15 test environments. Mpongwe recorded the highest environment mean grain yields of 10.27 t ha^{-1}, followed by Gwebi (8.34 t ha^{-1}) and Ivordale (7.7 t ha^{-1}). All the highest environment means were from optimum test environments. Of the random drought stress environments, Kaguvi had the lowest mean yield of 0.9 t ha^{-1}. All test environments showed high G x E interactions as shown by high values for both IPCA 1 and 2. Seven environments showed positive IPCA 1 values, including Art Farm, Gwebi, Harare Low N (E7), Ivordale, Lusaka, Mpongwe and Rattrey Arnold (opt). All these, except Harare Low N, contributed negatively to G x E interactions in the stress test environments. Art Farm, Cedara low N, Harare Low N (E7), Lusaka, Mpongwe and Rattrey

Arnold contributed significantly to AMMI 2. Environments with absolute IPCA 1 and 2 values larger than ± 0.30 contributed much to the instability of the evaluated hybrids.

Table 8.3 Environment means and IPCA scores

Environment	Management	NE	Em	IPCAe[1]	IPCAe[2]
Art Farm	Optimum	1	7.13	**1.53**	**-2.60**
Cedara	Low N	2	4.02	-0.28	**-0.79**
Cedara	Optimum	3	4.86	-0.24	0.00
Gwebi	Optimum	4	8.34	**1.09**	0.06
Gwebi	Low N	5	1.96	**-0.95**	-0.11
Harare	Low N	6	3.48	**-0.70**	-0.10
Harare	Low N	7	4.00	**0.41**	**-0.63**
Ivordale	Optimum	8	7.70	**1.50**	-0.15
Kaguvi	Random drought	9	0.90	**-1.50**	0.21
Lusaka	Optimum	10	7.67	**1.13**	**0.78**
Mpongwe	Optimum	11	10.27	**1.19**	**2.69**
Potchefstroom	Low N	12	1.43	**-1.59**	0.12
Potchefstroom	Random drought	13	2.12	**-2.06**	0.00
Rattrey Arnold	Low N	14	2.98	-0.26	-0.07
Rattrey Arnold	Optimum	15	7.13	**0.74**	**0.59**

IPCA interaction principal component analysis; NE number of environment; Em environment mean; **bolded IPCA** of ± 0.3 greater or less than zero contributed significantly to the respective AMMI

8.3.1.3 AMMI analysis across pooled management levels

The results of AMMI ANOVA for pooled management levels are presented in Table 8.4. The effects treatments, genotypes and management levels and G x E on grain yield were highly significant. Only IPCA 1 was significant. Treatments contributed 97.88% of the total variation, with the locations contributing highly (89.76%) while genotypes explained only 4.96%. G x E interactions explained 3.15% of the total variation. Of the G x E interactions, IPCA 1 explained 81.11% and IPCA 2, 19.35%, altogether explaining 99.46% of the G x E interactions.

Table 8.4 AMMI analysis of variance based on the management (stress) levels

Source	df	SS	MS	% contribution to total variation	% contribution of G x E	Cumulative G x E contribution
Total	929	6897.00	7.40			
Treatments	464	6751.00	14.50***	97.88		
Genotypes	154	342.00	2.20***	4.96		
Environments	2	6191.00	3095.70***	89.76		
Block	3	34.00	11.30***	0.49		
G x E	308	217.00	0.70***	3.15		
IPCA 1	155	176.00	1.10***		81.11	81.11
IPCA 2	153	42.00	0.30		18.35	99.46

***P < 0.001; **P < 0.01; *P < 0.05; G x E genotype by environment interaction; IPCA interaction principal component; SS sum of squares; MS mean squares

8.3.1.4 AMMI analysis of pooled management levels

For pooled results, optimum environments recorded an environmental mean of 7.58 t ha^{-1}, followed by low N (2.98 t ha^{-1}) and random drought (1.53 t ha^{-1}) (Table 8.5). Low N stress reduced maize yields by 60.68%, while random drought stress reduced it by 79.81%. Optimum and low N management levels indicated positive IPCA 1 scores, while that for random drought stress was negative. All the test management levels contributed significantly to G x E interactions, except IPCA 1 for low N which was 0.18. High IPCA scores are indicative of instability of the evaluated genotypes. The environments had a negative effect on the stability of the evaluated hybrids. There is need to validate the findings further with the GGE biplots, to identify which were high performing under which particular test environments.

Table 8.5 Management means and IPCA scores

Management	NE	Em	IPCA 1	IPCA 2
E1 (optimum)	1	7.58	**2.07**	**-0.98**
E2 (low N)	2	2.98	0.18	**1.74**
E3 (random drought stress)	3	1.53	**-2.25**	**-0.76**

IPCA interaction principal component; Em management mean yield (t ha^{-1}); **bolded IPCA** had ± **0.3** more or less than zero and contributed significantly to instability

8.3.1.5 IPCA scores and grain yield characteristics of maize hybrids across management levels

The test environments were pooled across the management levels and the best performing hybrids presented in Table 8.6. Entries 20 (4.99 t ha^{-1}), 108 (4.97 t ha^{-1}), 24 (4.96 t ha^{-1}) and 109 (4.94 t ha^{-1}) were among the highest yielders. The 26 highest yielding hybrids yielded between 0.15-1.46 t ha^{-1} higher than the local commercial checks used. In terms of G x E interactions, entries 109, 115, 1, 63, 21, 22 and commercial local checks SC719 and PAN53 all contributed significantly to IPCA 1 scores. Most hybrids had positive IPCA 1 scores, except entries 108, 5, 7, 87, 98 and local check PHB30G19.

Table 8.6 IPCA scores and mean grain yield performance across three management levels

Genotype	NG	Gm	IPCA 1	IPCA 2
G20	20	4.99	0.08	**-0.60**
G108	108	4.97	-0.01	**-0.41**
G24	24	4.96	0.01	0.04
G109	109	4.93	**0.35**	-0.09
G5	5	4.84	-0.13	-0.19
G115	115	4.83	**0.37**	0.24
G14	14	4.80	0.06	-0.06
G7	7	4.80	-0.07	0.19
G87	87	4.80	-0.24	-0.17
G10	10	4.78	0.10	0.03
G98	98	4.76	-0.08	-0.19
G2	2	4.76	0.27	0.02
G1	1	4.76	**0.30**	0.07
G63	63	4.75	**0.37**	-0.11
G21	21	4.74	**0.33**	-0.10
G22	22	4.74	**0.48**	0.02
G6	6	4.74	0.15	0.10
G9	9	4.73	0.15	-0.22
G16	16	4.73	0.07	-0.07
G15	15	4.68	0.03	-0.13
G152	SC719	4.34	**0.47**	-0.19
G153	PAN53	4.52	**0.38**	-0.23
G154	PAN 7M-81	4.53	0.07	0.07
G155	PHB30G19	3.96	-0.14	0.08

IPCA Interaction principal component; genotype number; Gm genotype mean

8.3.1.6 Additive main effects and multiplicative interaction biplots

AMMI 1 vs. grain yield biplot for the top 80 hybrids, inclusive of local commercial checks is presented in Figure 8.1. IPCA 1 contributed only 19.79% of the G x E interaction for grain yield. Optimum environments, Art Farm and Gwebi were high potential environments in terms of stability and yield. Test environments Ivordale, Lusaka, Rattrey Arnold and Mpongwe were high yielding but affected the stability of the hybrids. Rattrey Arnold low N test environment was generally a low potential environment, with low stability and yield. Cedara optimum, Cedara low N, Harare Low N 1 and 2, Gwebi low N, Kaguvi random drought and Potchefstroom low N and random drought were low yielding but highly stable test environments. Art Farm and Mpongwe optimum test environments were furthest away from the origin on the biplot, indicating their high discriminating power for the evaluated hybrids. Genotypes generally clustered around the origin of the AMMI 1 biplot. G75 performed better under Cedara low N, while hybrids G54, G77 and G49 were closer to test environments Ivordale, Rattrey Arnold (optimum), Lusaka and Mpongwe, as they performed better in these environments.

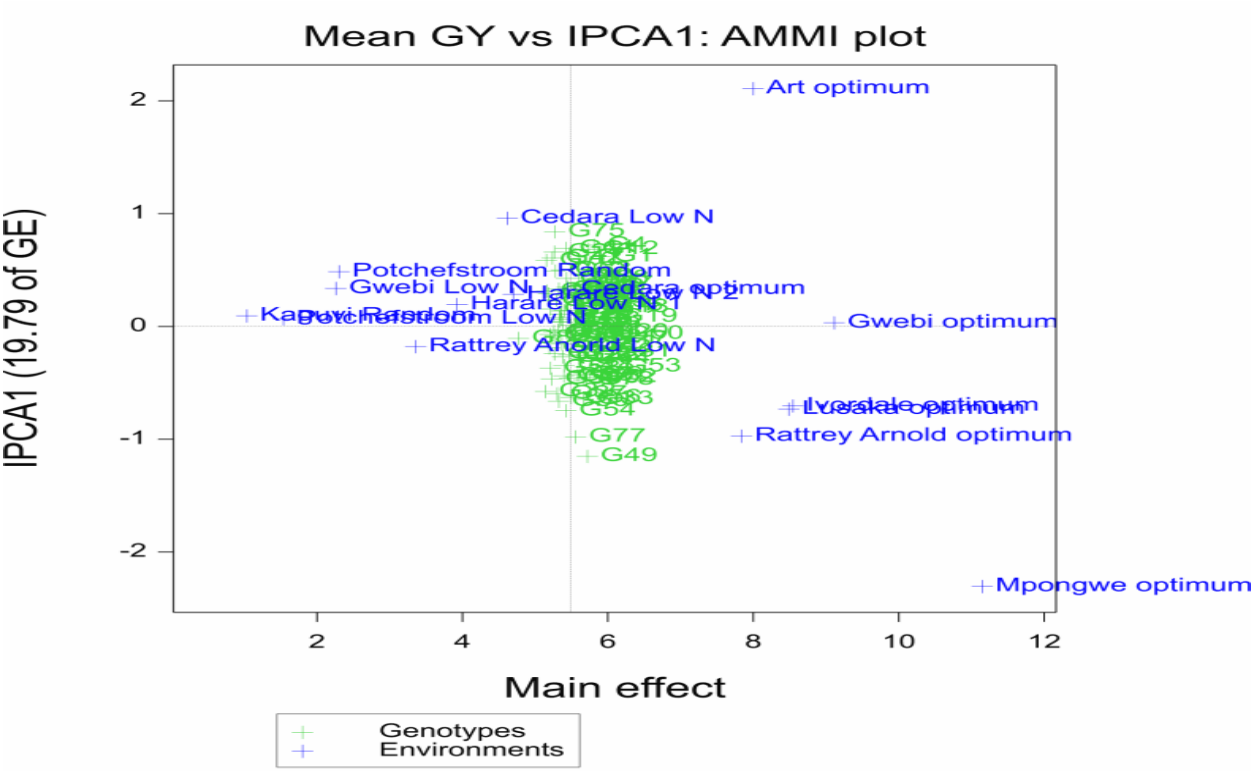

Figure 8.1 Grain yield (main effect) vs. IPCA 1 biplot for the 80 high yielding genotypes, including four local commercial checks across 15 test environments

The AMMI 2 biplot presents the differential performance of 80 high yielding hybrids with relation to the 15 test environments (Figure 8.2). The G x E interaction was partitioned into six IPCA components with the first five being significant. IPCA 1 (19.79%) and 2 (15.49%) accounted for 35.28% of the total G x E interactions. Cedara (low N), Mpongwe (optimum) and Art Farm (optimum) had the longest vectors from the origin, indicating their high discriminating power on the evaluated hybrids, while optimum test environments Lusaka; Gwebi and Rattrey Arnold were very close to the origin, and thus were less discriminating. Cedara (low N and optimum), Kaguvi (random drought), Potchefstroom (random drought and low N), Gwebi (low N) and Harare (low N 1 and 2) were all predominantly in the second quadrant, indicating their high stability. Gwebi (optimum) and Art Farm (optimum) were highly stable test environments. Mpongwe (optimum); Rattrey Arnold (low N and optimum) and Lusaka (optimum) were in the fourth quadrant which indicated that they were low potential environments. Entries 80, 9, 49, 77; 53 and 16 were highly interactive with the environments as they were further away from the origin. Entries 78, 52, 53, 31, 17 and 61 were well adapted to Mpongwe, Rattrey Arnold (low N and optimum), Ivordale and Lusaka. Entries 7 (G6), 45 (G27), 35 (G24), 103 (G47), 147 (G73), 18 (G15), 138 (G69), 13 (G11), 83 (G39), PAN 7M-81 (G79), 135 (G66), 5 (G4), 87 (G41), 14 (G12), 119 (G57), 6 (G5), 16 (G14), 98 (G45), 122 (G59), 84 (G40), 70 (G35) and 19 (G16) were the best hybrids with high yields and better stability across the test environments, and can thus be utilized under environments where random droughts and low N fertility are a challenge.

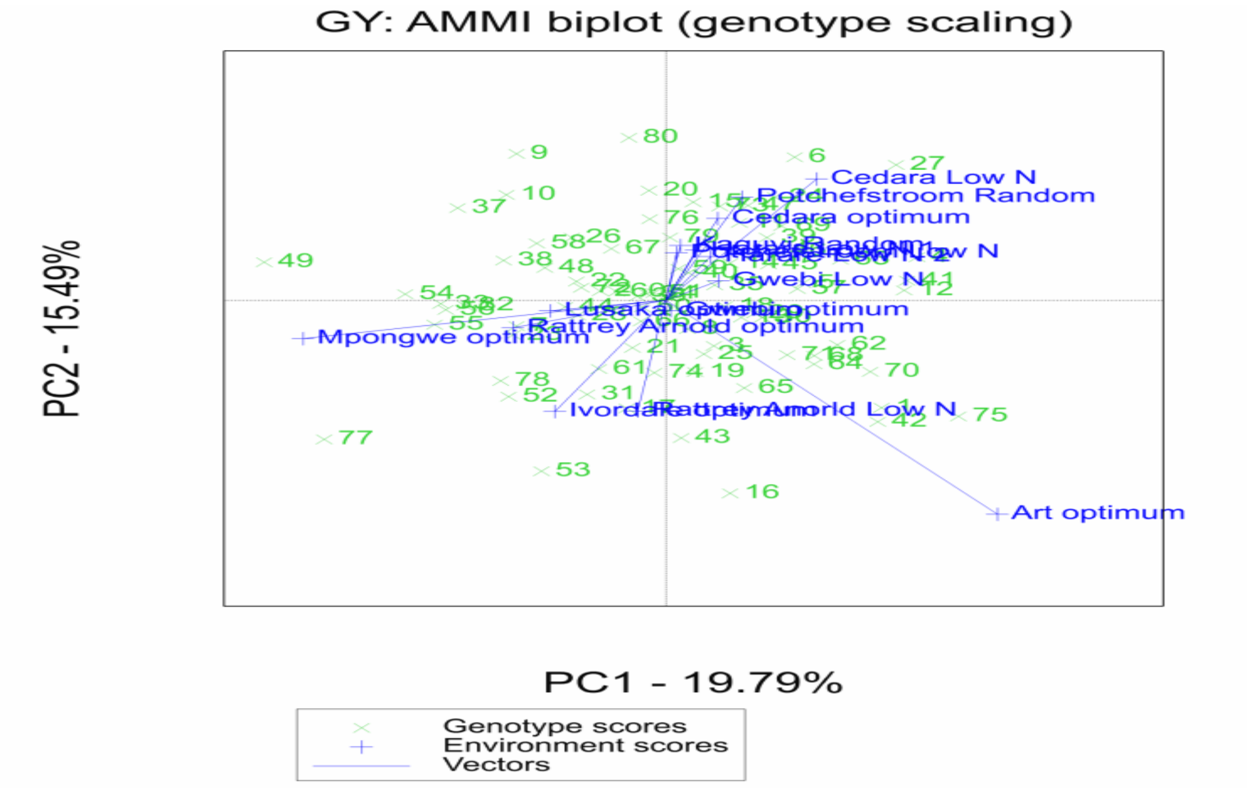

Figure 8.2 AMMI 1 vs. AMMI 2 biplot for the top 30 yielding hybrids across 15 test environments

8.3.1.7 AMMI across management levels

The AMMI for the combined management levels for the top 26 hybrids and four local commercial checks are presented in Figure 8.3. The analysis indicated that IPCA 1 (65.7%) and IPCA 2 (34.3%) explained 100% of the total G x E interactions. Genotypes closer to the origin indicated less interaction with the management levels, while those further away were highly interactive. Optimum environments were generally high potential, predominantly located in the first and second quadrants (Figure 8.3). However, low N management was generally a low potential environment with both low stability and yield. The three management levels had almost the same discriminating ability for the evaluated hybrids, as the vectors are almost the same length. Genotypes G23, 7, 21, 20, 15, 27 and 31 were better yielding and performed the best under optimum conditions. Genotypes 22, 3, 24, 12, 25, 13, 26, 14 and 11 were better yielding under random drought stress. Though low yielding, low N gave high levels of stability for grain yield for the evaluated hybrids.

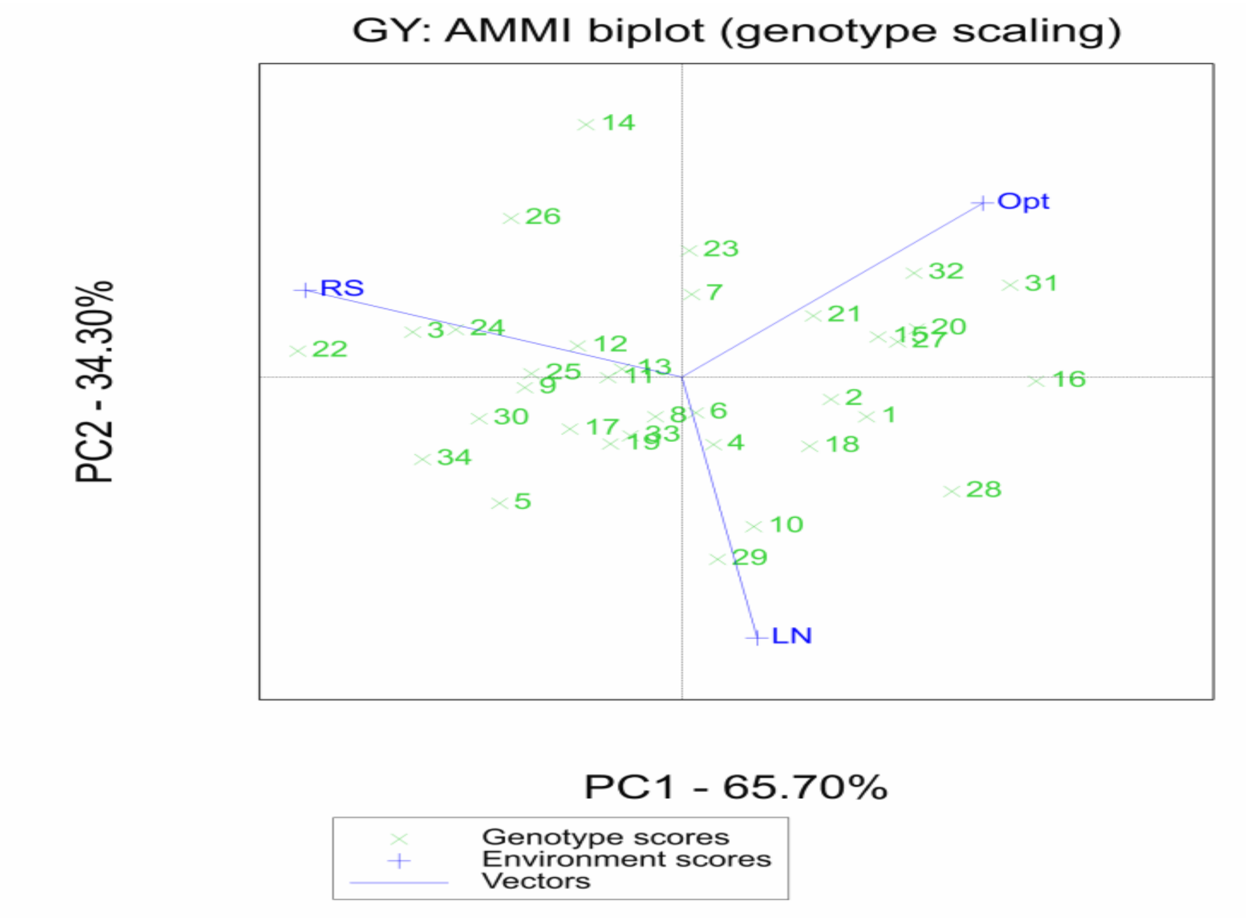

Figure 8.3 AMMI 2 biplot for the top 26 yielding hybrids and four checks across the three management levels; RS random drought stress; LN low N stress; Opt, optimum environments

8.3.2 Genotype, genotype x environment (GGE) biplots

8.3.2.1 Which-won-where and mega-environments

The GGE biplot analysis indicated that PC1 (21.84%) and PC2 (18.20%) explained 40.04% of the total G x E interactions (Figure 8.4). A lower percentage of variability (40.04%) for the two principal components suggests complex G x E interactions in the MET data evaluated.

A graphical presentation of “which-won-where” was used to assess the genotypic performances in particular test environments based on environment scaling. A polygon view (hexagonal) was formed from genotype marker entries 108, 155, 5, 19, 115 and 152. Six perpendicular lines were drawn starting from the origin and extended beyond the polygon such that it was divided into six sectors. Genotypes and test environments that fell in the same sector have high correlations. Lusaka (optimum, 10) in Zambia fell in its own sector, and five genotypes 108, 68, 26, 97 and 109 were highly associated with this environment. The hybrids that are in the same sector with a particular test environment are adapted to that particular environment, and thus can be recommended for production in that environment. Sector 2 included four test environments, Mpongwe, Ivordale, RARS and Gwebi (all optimum environments) and the genotypes that performed well included entries 152, 153, 25 and 63. Test environment 14, alone in sector 3, was associated with genotypes 9, 115, 114 and 20. Sector 4 had no environment in it but enclosed entries 22, 137, 1 and 19. Sector 5 had five test environments which included Cedara (optimum and low N environments), Gwebi (optimum), Harare low N1 and Potchefstroom (low N), with seven genotypes 5, 6, 9, 13, 14, 16, 21 and 119 dominating. Lastly, sector 6 had three test environments 7, 9 and 13 and genotypes that performed well included entries 2, 7, 10, 24 and the local checks 154 and 155.

The graphical presentation also provided information on possible mega-environments (Figure 8.4). The concept of mega-environments facilitates further analysis of winning entries to particular test environments, and helps to identify similar environments that are redundant, based on their similarity in discriminating genotypes. The 15 test environments were partitioned into six mega-environments. Lusaka optimum (10) formed its own distinct mega-environment. Optimum test environments Gwebi (4), Ivordale (8), Rattrey Arnold Research Station (15), all in Zimbabwe and Mpongwe (11) in Zambia were in the same mega-environment. Low N test environments were in one mega-environment; Gwebi (5), Harare 1 (6) in Zimbabwe; Cedara (2) and Potchefstroom (12), but also included one optimum environment (Cedara) in South Africa. Art Farm formed its own mega-environment. Random drought stressed sites Kaguvi (9) and Potchefstroom (13); together with low N stressed site Harare 2, formed a mega-environment. Genotypes that performed well in one of the mega-environments can be tested in the other environments that were similar. These test environments were largely grouped according to the three management levels.

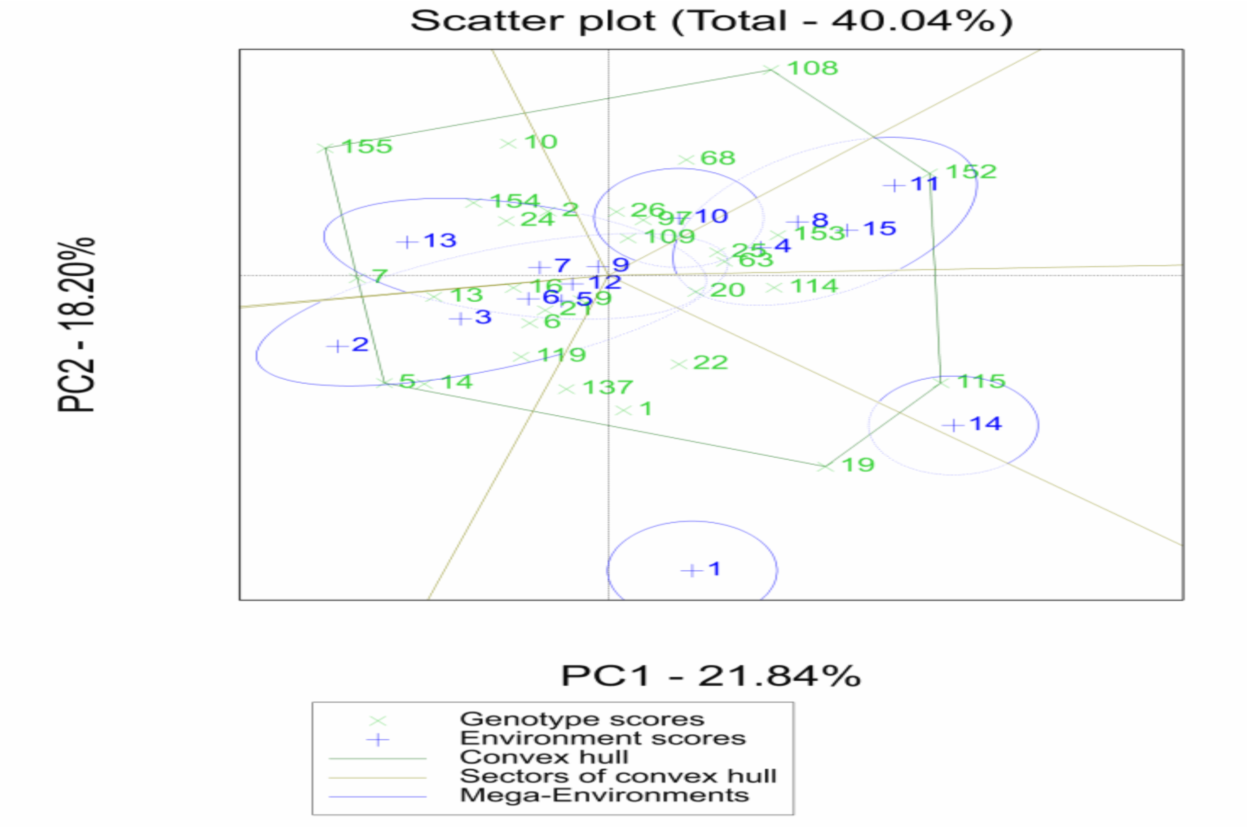

Figure 8.4 A polygon view of "which-won-where" and mega-environment distribution of the test environments and the 26 highest yielding genotypes and four local commercial checks across 15 test environments in Zambia, Zimbabwe and South Africa

Environments are in blue, 1 Art Farm; 2 Cedara (low N); 3 Cedara (optimum); 4 Gwebi (optimum); 5 Gwebi (low N); 6 Harare low N (1); 7 Harare low N 2; 8 Ivordale (optimum); 9 Kaguvi (random drought stress); 10 Lusaka West (optimum); 11 Mpongwe (optimum); 12 Potchefstroom (low N); 13 Potchefstroom random drought stress; 14 Rattray Arnold Research Station (low N); 15 Rattray Arnold Research Station (optimum)

8.3.2.2 Grain yield stability across test environments

The graphical presentation of stability of genotypes using GGE biplot analysis is presented in Figure 8.5. Genotypes that have near zero PC scores are stable, while those that are further away are not stable, and those that lie in the direction of the average environment coordination (AEC) line along PC 2 are high yielding. High yielding genotypes (from highest to lowest) included entries 19, 115, 1, 22, 114, 137, 152, 20, 63, 153, 25, and 119. These hybrids were stable, except local checks 152, 153 and 137 which had the longest perpendicular lines from PC2. Genotype entries 2, 24, 10, 16 and two local commercial checks were low yielding but stable. Entries 108, 5, 7 and 68 were highly interactive with environments.

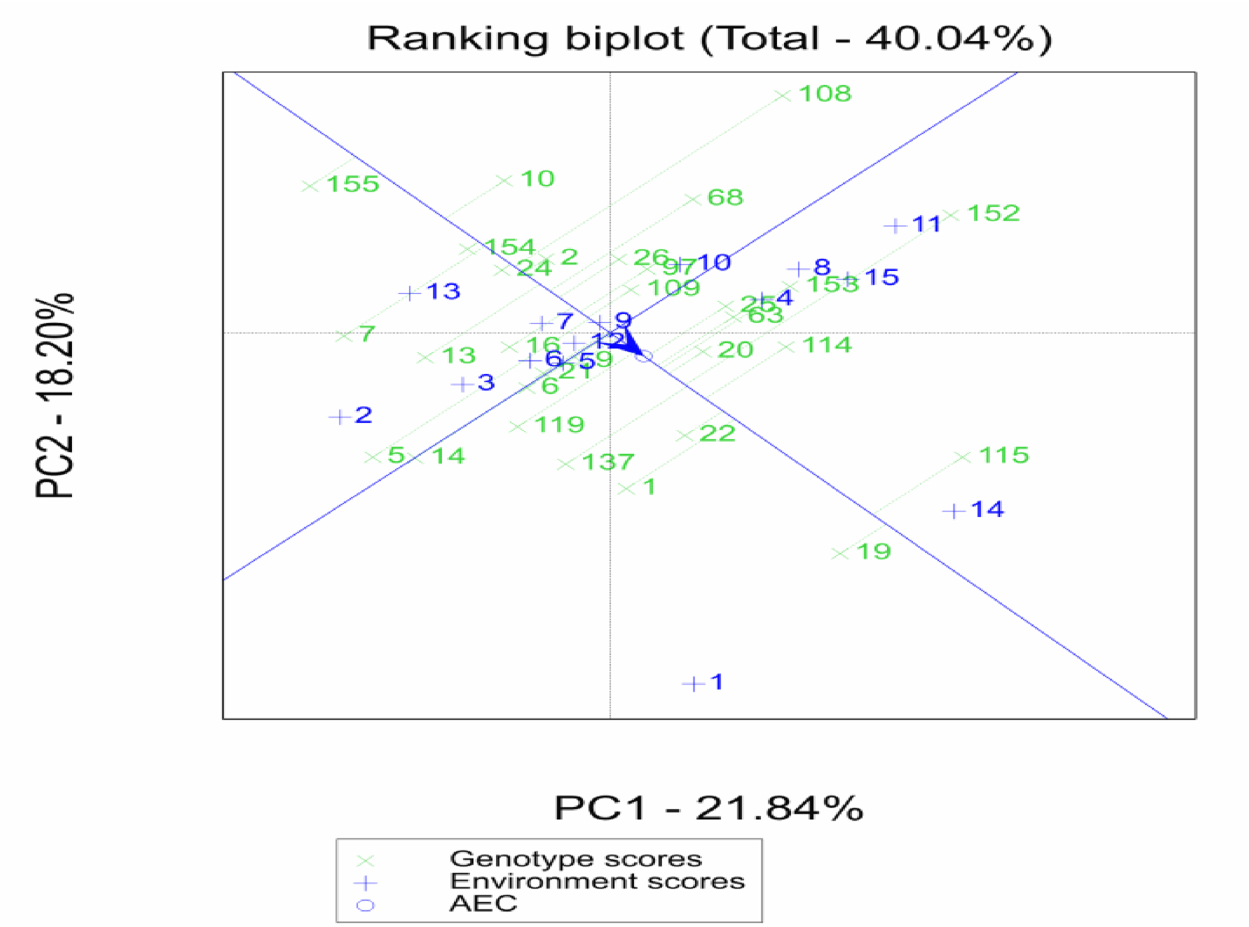

Figure 8.5 The average environment coordination (AEC) views of the GGE biplot based on genotype-focused scaling for the mean grain yield performance and stability of genotypes

Environments in blue, 1 Art Farm; 2 Cedara (low N); 3 Cedara (optimum); 4 Gwebi (optimum); 5 Gwebi (low N); 6 Harare low N (1); 7 Harare low N 2; 8 Ivordale (optimum); 9 Kaguvi (random drought stress); 10 Lusaka West (optimum); 11 Mpongwe (optimum); 12 Potchefstroom (low N); 13 Potchefstroom random drought stress; 14 Rattray Arnold Research Station (low N); 15 Rattray Arnold Research Station (optimum)

The PC 2 zero line indicates that the highest mean grain yields (in descending order) were observed at Art Farm (1), followed by Rattrey Arnold Research Station (low N, 14) and (optimum,15), Gwebi (optimum, 4), Ivordale (optimum, 8) and Mpongwe (optimum, 11). Even under low N stress, Rattrey Arnold Research Station was a high potential test environment. Among these high potential test environments, Art Farm, Mpongwe, Rattrey Arnold Research Station and Ivordale were highly interactive. Test environments Kaguvi (random drought, 9); Harare low N 2 (7) and Potchefstroom (low N, 5) were low yielding but were less interactive on test hybrids.

8.3.2.3 The representativeness and discriminating ability of test environments

The GGE biplot was constructed based on the genotype-focused singular value partitioning to compare the performance of the genotypes to the ideal genotype (Figure 8.6). The circle with an arrow along the PC2 line indicates an ideal genotype, and thus all genotypes that are closest to this inner concentric circle are closer to ideal. According to Yan and Kang (2003), an ideal environment should be both discriminating and representative. Entry 19 was the most ideal genotype, followed by entries 115, 22, 1, 114, 20, 137 in that decreasing order. The local check entry 155 (PHB30G19) was the least ideal genotype evaluated.

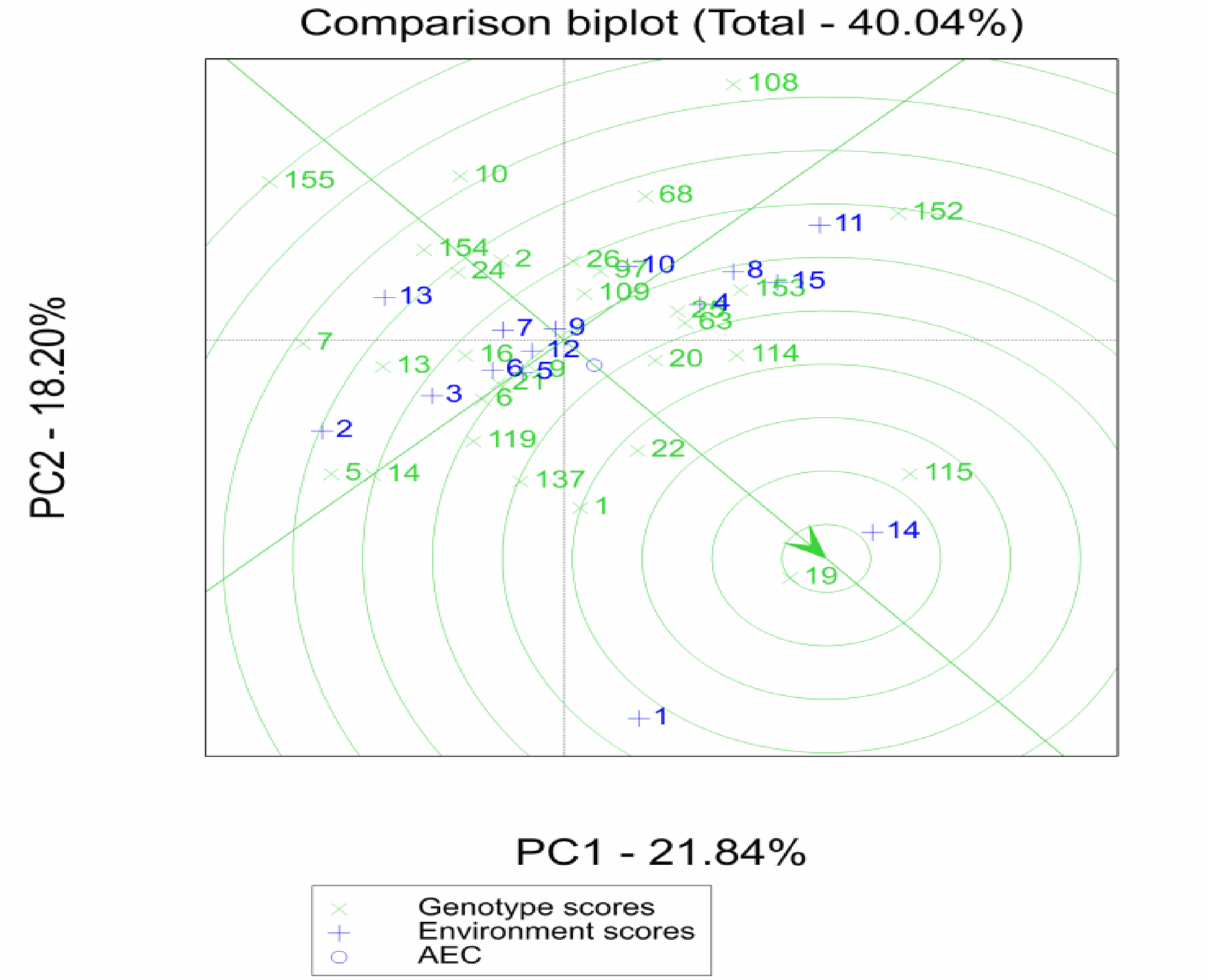

Figure 8.6 GGE biplot based on the genotype-focused scaling for the comparison of genotypes with the ideal genotype; Environments in blue, 1 Art Farm; 2 Cedara (low N); 3 Cedara (optimum); 4 Gwebi (optimum); 5 Gwebi (low N); 6 Harare low N (1); 7 Harare low N 2; 8 Ivordale (optimum); 9 Kaguvi (random drought stress); 10 Lusaka West (optimum); 11 Mpongwe (optimum); 12 Potchefstroom (low N); 13 Potchefstroom random drought stress; 14 Rattray Arnold Research Station (low N); 15 Rattray Arnold Research Station (optimum)

Figure 8.7 illustrates the GGE biplot based on environment-focused scaling for the comparison of test environments to the ideal environment which is encircled along the PC2 line. Rattrey Arnold Research Station (low N, 14) was the most ideal test environment, followed by Art Farm (1), Rattrey Arnold Research station (optimum, 15) and Gwebi (optimum, 4). Potchefstroom (random drought, 13) and Cedara (low N) in South Africa were furthest away from the ideal test environment.

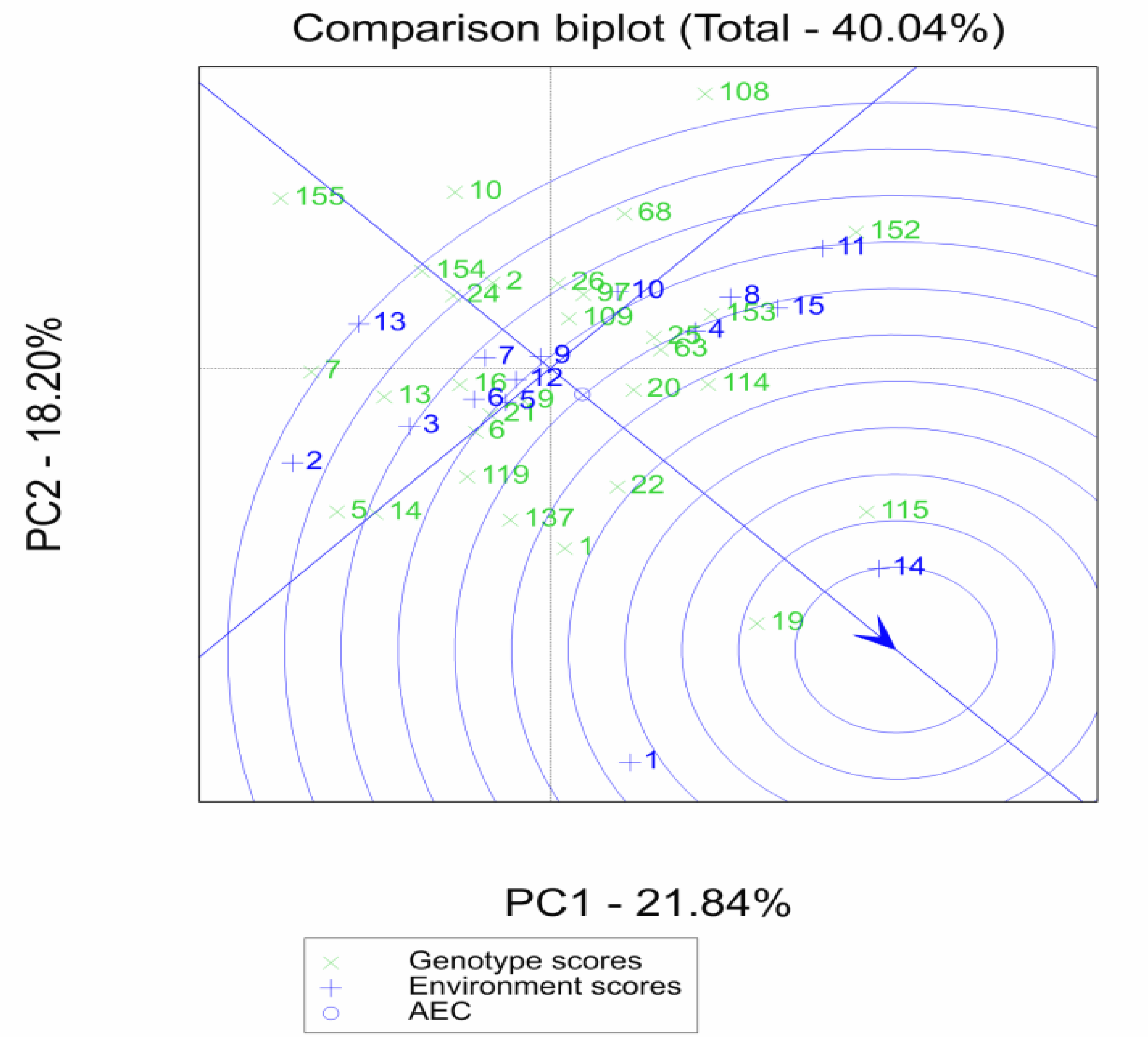

Figure 8.7 GGE biplot based on the genotype-focused scaling for the comparison of genotypes with the ideal environment; Environments in blue, 1 Art Farm; 2 Cedara (low N); 3 Cedara (optimum); 4 Gwebi (optimum); 5 Gwebi (low N); 6 Harare low N (1); 7 Harare low N 2; 8 Ivordale (optimum); 9 Kaguvi (random drought stress); 10 Lusaka West (optimum); 11 Mpongwe (optimum); 12 Potchefstroom (low N); 13 Potchefstroom random drought stress; 14 Rattray Arnold Research Station (low N); 15 Rattray Arnold Research Station (optimum)

8.3.2.4 GGE biplots of pooled management levels for 30 top yielding (including four local commercial checks) genotypes

The principal components 1 (61.71%) and 2 (24.87%) explained a total of 86.58%, and these two were significant ($P < 0.001$). A GGE graphical presentation for the identification of winning genotypes per environment is presented in Figure 8.8. A polygon was drawn with genotypes 108, 114, 152, 1 and 9, with all other hybrids within the drawn polygon. Six sectors delineated by perpendicular lines to the origin, all had genotypes except one sector. Three mega-environments were identified according to the management, with each particular management level constituting a mega-environment. These mega-environments were diverse and distinct as indicated by their occurrence in different sectors of the GGE biplot. Genotypes 24, 25, 97, 20, 109, 114 and 115 dominated the optimum test environments; entries 13, 14, 19 and 137 were predominant across low N stress test environments. Under random drought stress, genotypes 9, 6, 5, local checks 154 and 155, and entries 10, 2 and 16 were dominant, indicating their adaptation to this particular test environment. Two sectors, one with entries 108, 21, 22, 63, 68 and 28 and the other with entries 119 and local checks 152 and 153 had no environments in them.

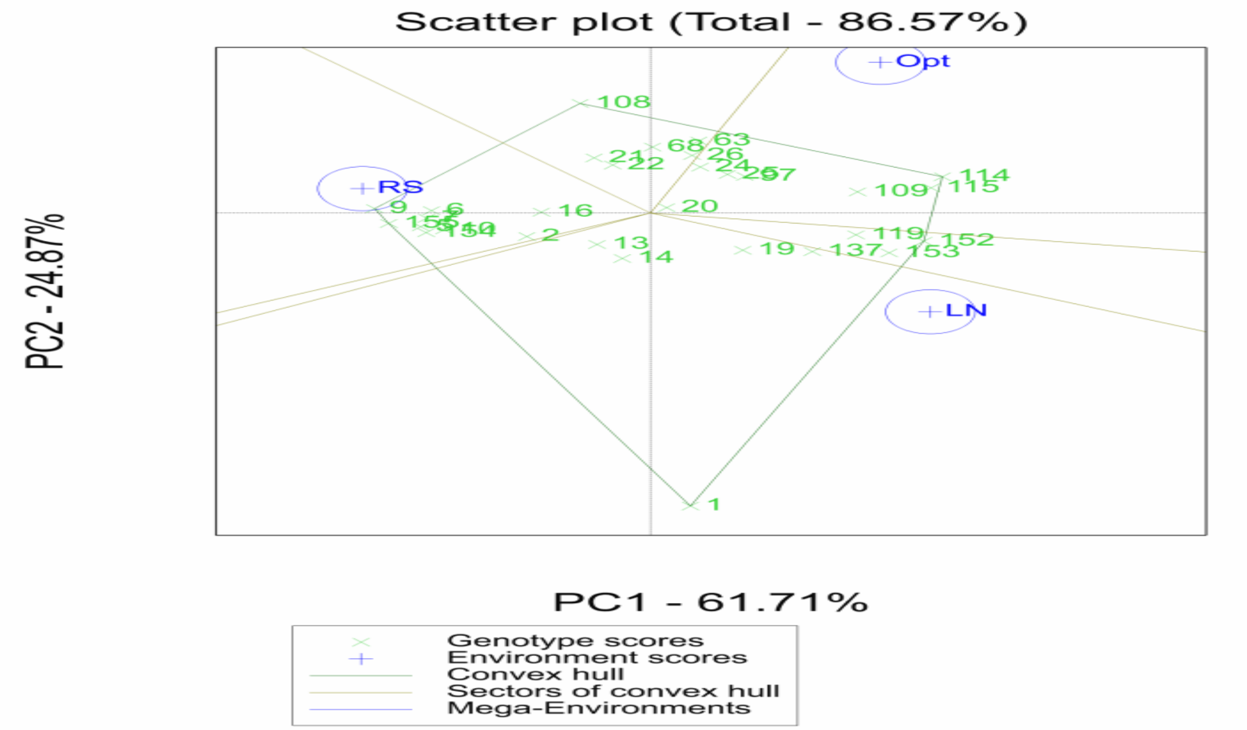

Figure 8.8 GGE biplot showing a polygon view of winning entries per each test management option. RS random drought stress, LN low N, Opt Optimum management/stress levels

GGE biplot graphical presentation of the AEC of the top 26 hybrids, with four local commercial checks under three pooled management levels are presented in Figure 8.9 (symmetrical-focused scaling). Optimum and low N test management options were observed to be high potential environments. Genotypes 114, 115, 109, 119, 63, 26, 25, 24, 137, 68, 22, 21, 19 and local checks 152 and 153 were all high yielding while entries 9, 6, 5, 10, 2, 16 and local checks 154 and 155 were poor yielding hybrids. Among the high yielding genotypes, entries 108, 119, 137 and local checks 152 and 153 were highly interactive with the environments as indicated by the length of the perpendicular lines from the PC 1 zero line. Entry 1 was also highly interactive with the test environments. The high yielding and stable genotypes are potential hybrids for cultivation under varied stress environments.

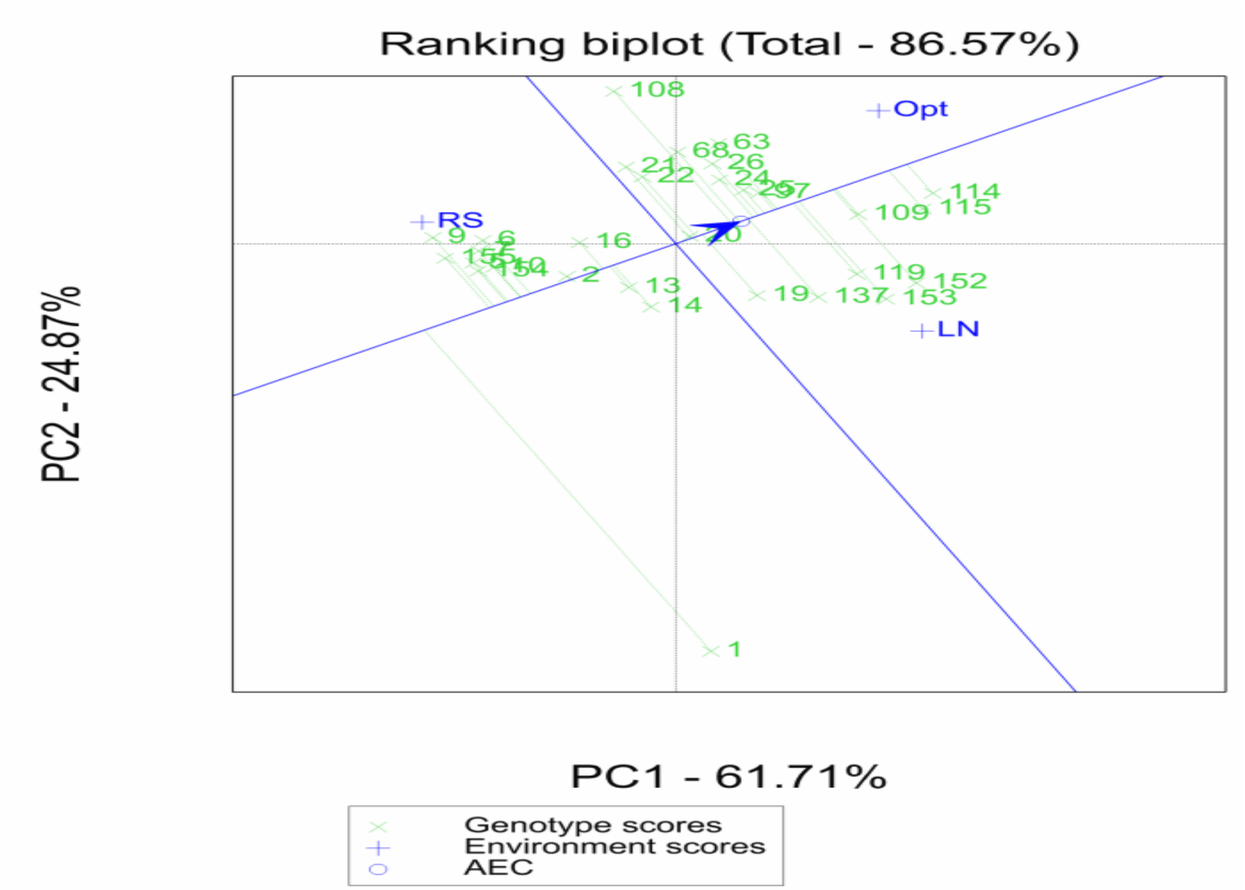

Figure 8.9 GGE biplot showing the AEC views of the GGE biplot based on symmetrical-focused scaling for the mean grain yield performance and stability of genotypes. RS random drought stress; LN low N stress; Opt optimum environments

A comparison GGE biplot (genotype-focused scaling) showing the representativeness and discriminating ability of test environments is presented in Figure 8.10. Entries 114, 115, 109, 63, 25 and 97 were closest to an "ideal genotype", as indicated by their position on the concentric circle; while entries 9, 6, 10, 2, 16 and local check 155 were furthest from the ideal genotype.

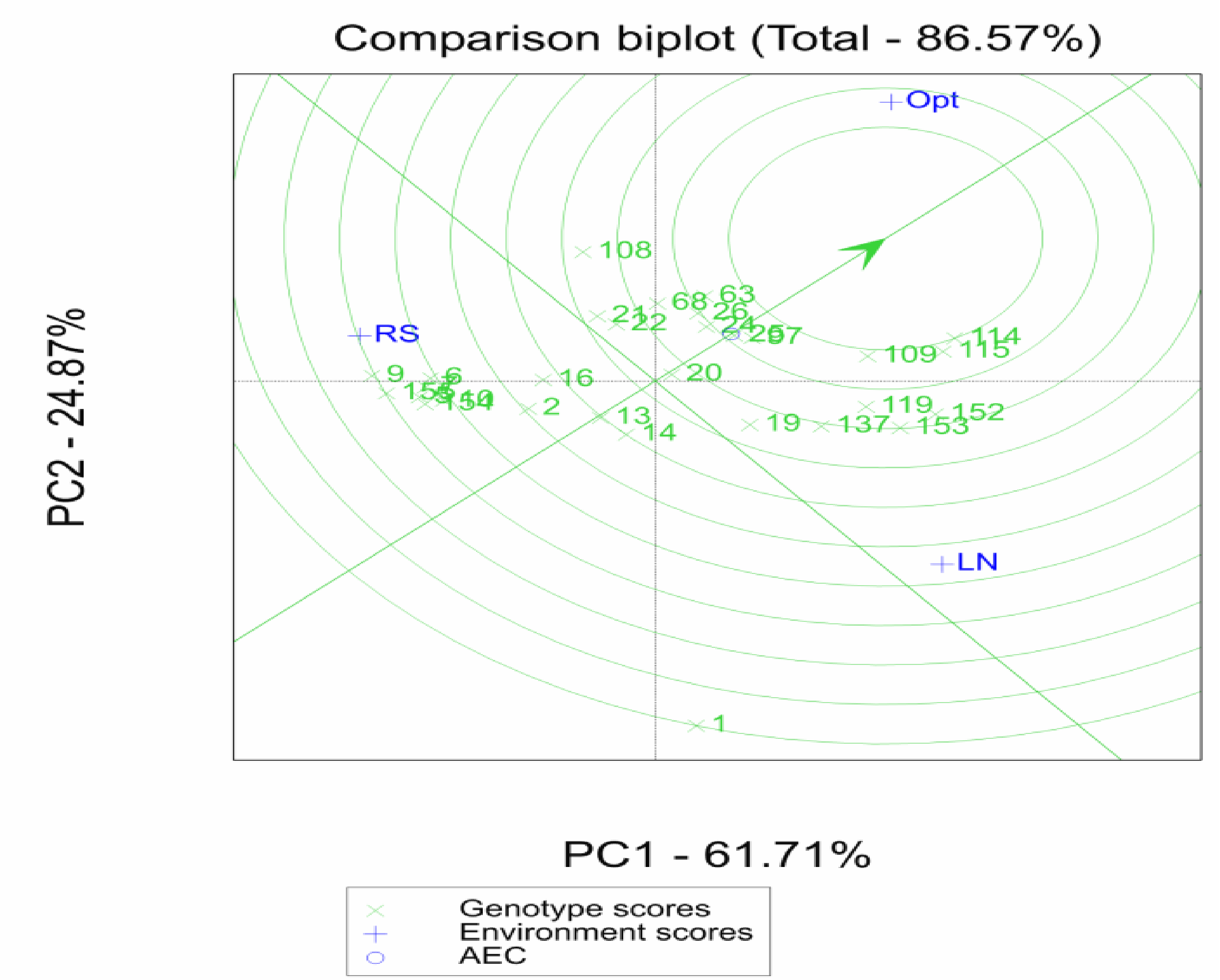

Figure 8.10 GGE biplot based on the genotype-focused scaling for the comparison of genotypes with the ideal environment across three pooled management levels; RS random drought stress; LN low N stress; Opt optimum environments

Ranking for test management levels indicated that optimum was better than low N which was in turn, better than random drought stress (Figure 8.11). The results indicated the potential importance of both drought and low N stress and their effects on reducing maize grain yields.

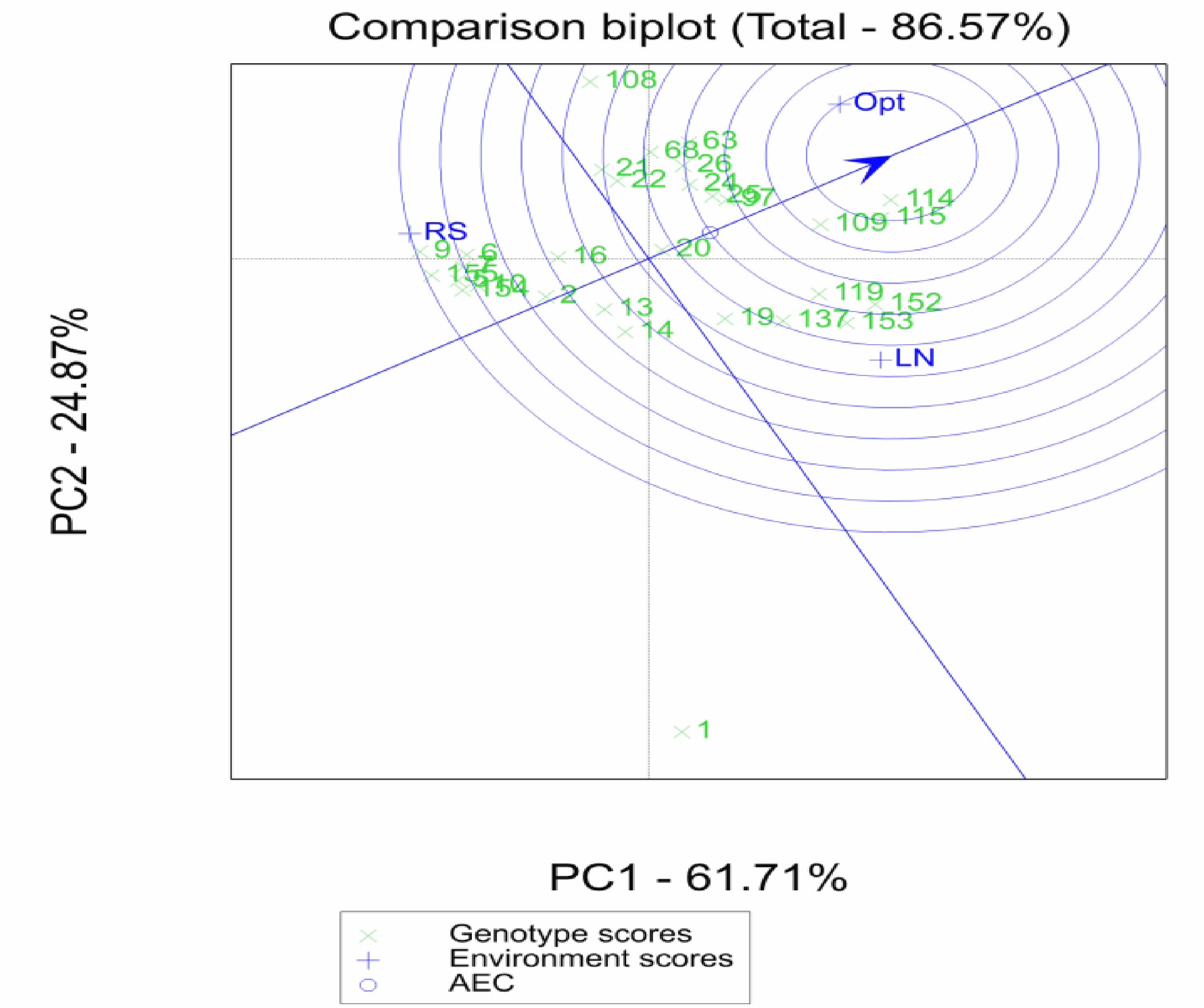

Figure 8.11 GGE biplot based on the environment-focused scaling for the comparison of genotypes with the ideal environment across three pooled management levels. RS random drought stress; LN low N stress; Opt optimum environments

8.4 Discussion

The AMMI results indicated high variability among treatments, genotypes and test environments used in the evaluations. Environment explained much of the total variation observed (80.7%) while genotypes and G x E interactions explained 5.63% and 7.95%, respectively. IPC1-8 were significant, indicating the complexity of multi-environments yield trials. These results are consistent with findings from other research groups (Yan et al., 2000; Kaya et al., 2006; Muungani et al., 2007; Sabaghnia et al., 2008; Ramburan et al., 2011; Ndhlela et al., 2014). Ababulgu (2014) also reported significant IPCA1-4 for QPM varieties.

Makumbi (2005), Menkir and Ayodele (2005), Derera et al. (2008), Sibiya et al. (2012) also reported significant G x E interactions in maize cultivars across locations. The large variability in the genotype performance was affected chiefly by varied environmental conditions included in the study. Nzuve et al. (2013), Abuali et al. (2014) and Kumar et al. (2014) also reported higher environmental and G x E interactions than genotypic effects in maize. Pooled ANOVA also indicated high variability among maize hybrids across stress management levels. Shaibu et al. (2016) reported high environmental variability in extra-early maize hybrids under varied N levels. Ababulgu (2014) also identified significant and differential responses of QPM varieties across several regions in Ethiopia. Stress factors like random drought and low N stress bring about large changes in hybid performance, and this makes mega-environments indispensable for the identification of better performing hybrids across environments.

AMMI biplots showed positive and negative IPCA scores (IPCA1 and PC2), indicating high genotypic yield differences across the environments. IPCA scores reflect stability and are indicators of adaptation over test environments (Gauch and Zobel, 1996; Purchase, 1997). Most genotypes that were high yielding contributed much to G x E interactions, as they recorded higher IPCA values. Hybrids showing positive IPCA values in a test environment have the ability to exploit the agro-ecological conditions of that particular test environment and thus are adapted to it (Kandus et al., 2010). The presence of significant G x E interactions in the AMMI analysis of hybrids indicates their differential responses (crossover interaction) (Yan and Kang, 2003; Frashadfar et al., 2012; Nzuve et al., 2013) to the test environments. Entries 109 (6.08 t ha^{-1}), 115 (6.05 t ha^{-1}), 22 (5.99 t ha^{-1}), 63 (5.91 t ha^{-1}), 1 (5.9 t ha^{-1}), 24, 21, 20, 2 (5.87 t ha^{-1}), 19 (5.8 t ha^{-1}), 5 (5.79 t ha^{-1}), 6, 10 (5.76 t ha^{-1}), 14 (5.74 t ha^{-1}), 25 (5.73 t ha^{-1}), 9, 108 (5.72 t ha^{-1}) and 108 (5.7 t ha^{-1}) had the highest mean yields for combined test environments.

The AMMI analysis identified high potential (Ivordale, Lusaka, Rattrey Arnold and Mpongwe) and lower potential (Rattrey Arnold Low N) test environments. The utility of AMMI analysis depends on its discriminating ability of high and low potential test environments and its ability to determine the extent of G x E interactions of hybrids with particular environments or management levels. AMMI analysis identified hybrids that can be utilized as potential cultivars, as they were high-yielding and stable. They offer potential in the region, which is characterised by random droughts and poor soil N fertility.

Maize yields in southern Africa vary around 2 t ha^{-1} or less (Bänziger and Diallo, 2001; FAOSTAT, 2010; Weber et al., 2012; Cairns et al., 2012; 2013) and the use of the identified potential hybrids, which yield above the global average (4 t ha^{-1}) (Pingali and Pandey, 2000) can help offset yield penalties due to the stress factors highlighted.

The GGE biplots further partition G x E interactions and give graphical presentations on aspects related to adaptiveness of a particular genotype to a given test environment. They can identify stable and unstable hybrids, ideal genotypes and ideal environments, and test environments that are discriminating and representative (Yan et al., 2000; 2007; Ezatollah et al., 2011; Tonk et al., 2011; Reza and Ahmed, 2012). In this study, the GGE biplots indicated the presence of mega-environments divided according to their relative potential, discriminativeness and representativeness. The genotypes identified within mega environments can be recommended for those particular test environments where they performed well. Sectorial divisions of test environments indicate that some genotypes performed well in certain environments and not others, suggesting a change in the ranking of the hybrids, a form of crossover G x E (Yan et al., 2007). Target mega-environments help to reduce costs of including similar test environments for future testing of hybrids across environments. The concept of mega-environments has also been a useful tool in managing G x E interactions, as good genotypes are identified for particular test environments (Gauch and Zobel, 1997). Results from this study indicated that test environments were grouped largely on the basis of management levels, with optimum test environments forming a mega-environment and low N stress environments constituting a separate major mega-environment.

The GGE biplots were also able to identify high and low yielding genotypes, as well as their relative stability as depicted by their relative deviation from the zero line of the PC. The vertices of the irregular polygon drawn on the GGE biplot indicate the yield potential of the winning genotypes (Yan et al., 2007). High yielding genotypes (from highest to lowest) included entries 19, 115, 1, 22, 114, 137, 152, 20, 63, 153, 25 and 119. These hybrids were stable, except for local checks 152, 153 and 137, which had the longest perpendicular lines from the PC2 zero line, which indicated their instability. Entries 2, 24, 10, 16 and two local checks were low yielding but stable. Hybrids that were both unstable and highly interactive with the environments included entries 108, 5, 7 and 68. Similar results were reported for differential performance of maize genotypes across multi-test environments by Tonk et al. (2011), Nzuve et al. (2013) and Nyaligwa (2014). The utility of the GGE biplots is also centred on the identification of ideal genotypes (Yan and Kang, 2003). The results indicated that entry 19 was the most ideal genotype, followed by entries 115, 22, 1, 114, 20, 137 due to their proximity to the concentric circle (Kaya et al., 2006; Choukan, 2011). Araus et al. (2008) and Rad et al. (2013) reported similar findings for high ranking and stable maize genotypes under varied test environments.

The GGE biplot results also identified winning entries specific to pooled management levels. Entries 24, 25, 97, 20, 109, 114 and 115 dominated in the optimum test environments; entries 13, 14, 19 and 137 were predominant across low N stress test environments. Under random drought stress, genotypes 9, 6, 5, local checks 154 and 155, and entries 10, 2 and 16 were dominant, indicating their adaptation to this particular test environment. The results also identified ideal test environments as optimum environments, followed by low N and lastly random drought stress test environments. An “ideal” test environment is both discriminating and representative of the average tester (Yan, 2001; Kaya et al., 2006; Yan and Tinker, 2006; Yan et al., 2007; Badu-Apraku et al., 2011). GGE biplots were able to delineate between these contrasting environments. Rattrey Arnold Research Station (low N, 14) was the most ideal test environment, followed by Art Farm (1), Rattrey Arnold Research station (optimum, 15) and Gwebi (optimum, 4). Potchefstroom (random drought, 13) and Cedara (low N) in South Africa were furthest away from the ideal test environment, indicating their poor representativeness of the average tester.

Both AMMI and GGE biplot analysis were important in identifying potential test hybrids and test environments, and thus can be used concurrently as tools for assessing G x E interactions. The utility of the AMMI is based on the additive component of the biplot analysis and the ANOVA that partitions the main effect, environments and G x E interactions. The AMMI also further partitions the G x E interactions, which makes it a powerful measure of stability. The GGE biplots, however, are useful for graphically positioning hybrids based on singular value partitioning (SVP) and can show mega-environments, ideal genotypes and environments, and winning entries in particular test environments, hence identifying which won where (adaptiveness of a particular hybrid to a given environment). Several authors have documented the usefulness of these two biplot techniques in breeding for measuring G x E interactions in multi-environment trials (Balestre et al., 2009; Dehghani et al., 2009; Habliza, 2010; Oliveira et al., 2010; Dagnachew et al., 2014).

8.5 Conclusions

The objective of this investigation was to use AMMI and GGE biplots as measures of stability and adaptiveness of potential hybrids to different production environments in southern Africa. This region is characterised by acute food shortages, malnutrition and poverty, much of which is caused by randomly occurring droughts, intrinsically low N fertility, poor access to improved infrastructures and technology, among several other constraints. CIMMYT and other stakeholders have maintained their heavy presence in southern Africa with the aim of improving food availability under these stress-prone environments. It can be concluded that both the AMMI and GGE biplot models were able to identify potential hybrids for release. They all indicated the presence of cross over interactions due to the variability of test environments. The AMMI analysis identified entries 109 (6.08 t ha^{-1}), 115 (6.05 t ha^{-1}), 22 (5.99 t ha^{-1}), 63 (5.91 t ha^{-1}), 1 (5.9 t ha^{-1}), 24, 21, 20, 2 (5.87 t ha^{-1}), 19 (5.8 t ha^{-1}), 5 (5.79 t ha^{-1}), 6, 10 (5.76 t ha^{-1}), 14 (5.74 t ha^{-1}), 25 (5.73 t ha^{-1}), 9, 108 (5.72 t ha^{-1}) and 114 (5.7 t ha^{-1}) with high mean yields across the combined test environments that were better than local commercial varieties used in the trials. These/ entries can be recommended for release as hybrids in southern Africa for production in drought prone and low N conditions. The same hybrids, though the rankings changed to some extent, were also recommended by GGE biplot analysis. Six mega-environments were identified, which can help reduce research costs for future breeding efforts.

The two models also identified mostly optimum test environments as the best for high yield (as was expected), and indicated that randomly occurring droughts cause more drastic yield reduction than low N fertility in maize in southern Africa, though both stress conditions reduced maize yields significantly.

8.6 References

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CHAPTER 9

General conclusions and recommendations

Climate changes, on-going natural resource depletion, continuing food insecurity, poverty, malnutrition, and increasing food demands due to population growth, requires combined efforts from all farming communities, international and national research organisations, policy makers, the private sector, and all stakeholders to come together to confront these challenges. Maize will continue to increase in importance, requiring doubling or even tripling food productivity per unit area. These challenges occur at a time where the fertilisers, water and labour costs are increasing. Africa is still yet to realise a Green Revolution and maize will remain a strategic crop for improvement and for the realisation of these goals.

The profitability of a breeding programme depends on the combining ability of newly developed maize inbred lines and their potential to pass their genes to their progeny (heritability). A study was conducted to assess the combining ability (GCA and SCA) and determine heritability estimates among the selected maize inbred lines and testers under stress and non-stress conditions in southern Africa. The investigation was successful in identifying suitable parents with good GCA and SCA for use in hybrid development for both early and late maturity maize lines.

For hybrids developed from early maturity inbred lines, lines 1, 3, 4, 6, 10 and 11 had significant positive GCA, indicating their potential as good combiners for grain yield. Lines 3, 4, 5, 6 and 7 contributed to earliness. Lines 1, 5, 6, 7, 8 and 9 were good combiners as they contributed to better anthesis-silking synchronization. For hybrids developed from late maturity inbred lines, lines 1, 2, 5, 15, 21, 22, 23, 25 and 26 showed positive GCA effects for grain yield across all the environments. In early maturity hybrid trials, lower heritability estimates were observed, which usually lowers selection precision, but the use of genotypic and phenotypic coefficients of variation has enabled easy inferences about the behaviour of genes in the target population. Heritability estimates for late maturity hybrid trials were high for several characteristics, indicating their potential for selection for random drought and low N tolerance. Hybrids inferring good combining ability for grain yield, those that give early attributes to hybrids in terms of flowering, and those with short plant stature can be selected and recommended for use in hybrid programmes aimed at reducing the impact of drought and low N infertility in southern Africa.

The line x tester mating design was efficient in identifying good parents and parent combinations for the formation of hybrids. The high heterotic responses and positively significant GCA and SCA effects observed, indicated the importance of additive and non-additive gene action. In maize, heterosis is often a result of mating two parents that are unrelated (originating from different heterotic groups) and the heterotic effects depend on the combining ability of these unrelated parents. Parents with significant GCA are a result of additive gene action for the observed characteristics and are good combiners. They can be successfully used as parents in hybrid development. The presence of significant SCA effects confirms the presence of non-additive gene action and potentially good hybrid combinations. The inbred lines used in this investigation had enough genetic variability that can be used for successful hybrid breeding for drought and low N prone environments.

Sub-optimal environments reduce the potential yields compared to yields under optimum conditions. Yield decreases of 52.33% (low N vs optimum), 33.24% (random drought vs optimum) and 28.6% (random drought vs. low N) environments were observed in early maturity hybrids. In late maturity hybrids, random drought stress reduced maize yield by 79% while low N stress reduced it by 61%, indicating that random drought stress effects were more severe in terms of yield reduction of late maturity hybrids. Late maturity maize hybrids face a larger risk of exposure to drought conditions that eventually reduce yields drastically. The reduced yields under random drought and low N stress observed in this study confirmed the potential threats to maize-based production systems in SSA region.

The potential of maize inbred lines is also dependent on their testcross performance in line x tester hybrid combinations. Several hybrids were identified which performed better than the local commercial checks evaluated. These testcross hybrids included (for early maturity trials) entries 46 (L6 x T2, 7.2 t ha^{-1}), 83 (L10 x T2, 6.7 t ha^{-1}), 15 (L2 x T5, 6.61 t ha^{-1}), 52 (L6 x T9), 6 (L1 x T6, 6.5 t ha^{-1}), 43 (L5 x T9), 21 (L3 x T2, 6.4 t ha^{-1}), 97 (L11 x T7), 30 (L4 x T4, 6.38 t ha^{-1}), 100 (L11 x T10) and 84 (L10 x T3) (6.36 t ha^{-1}). Among these high yielding hybrids, line 10 and tester 2 were in the highest frequency among the parents. These testcross hybrids, together with the other 68 testcross hybrids that were significantly better than the highest yielding commercial check across environments, have potential for commercial release across varied environments in southern Africa. Large variability was observed among the evaluated late maturity hybrids, with high yields observed for entries 109 (L19 x T4, 6.08 t ha^{-1}), 115 (L20 x T4, 6.05 t ha^{-1}), 22 (L4 x T4, 5.99 t ha^{-1}), 5 (L1 x T5, 5.92 t ha^{-1}), 63 (L11 x T4, 5.91 t ha^{-1}), 1 (L1 x T1, 5.9 t ha^{-1}), 24 (L4 x T6), 21 (L4 x T3), 20 (L4 x T2) and 2 (L1 x T2) (all 5.87 t ha^{-1}) across all test environments. Line 4 and tester 4 dominated in parental combinations with highest yields across combined test environments in late maturity trials. Entries that performed well across all environments have compounded enough tolerance that enables them to be cultivated across stress and non-stress conditions. The line x tester model used in this study and the multi-locations selected for testcross evaluations were successful in identifying potential hybrids for cultivation. The low genotypic and phenotypic coefficients of variation for most characteristics measured, indicated the presence of enough tolerance to both random drought and low N stress among the developed hybrids.

The occurrences of G x E interactions complicate the progress of breeding programmes in maize. This has led to the use of multi-location and multi-season trials and the development of models to explain the G x E interactions in a way to reduce their negative impact on the selection of potential hybrids for utilization. The AMMI and GGE models are currently the most important tools for quantifying and explaining these effects in maize breeding. AMMI analysis is preferred for its use of the additive ANOVA, coupled with the multiplicative explanation of the G x E interactions. The GGE also shares the advantages of effective identification of genotypes adapted to particular environments, identification of highly discriminative and representative test environments, and mega environments, which will aid in making informed decisions and inferences about the behaviour of genotypes and their interactions with the environment. AMMI analysis showed that variation in the performance of selected hybrids was due largely to the environment and it was able to identify and explain those effects. Significant differences were observed among genotypes for grain yield and measured agronomic characteristics in different test environments, which indicated the presence of high genetic variability among the hybrids that allows for selection for their improvement in breeding programmes.

For early maturity trials, test environments were the biggest source of variation (63.93%) followed by G x E interactions (16.47%), while genotypes accounted for 9.7% of the total variation. For late maturity trials, AMMI analysis identified highly significant ($P < 0.001$) differences among 15 test environments, hybrids, and G x E interactions. The effects of the test environments were very large, indicating the differences in the discriminating ability of the test environments. Random drought and low N stress environments recorded significantly lower yields than optimum environments. Several hybrids performed better than the included local commercial hyrbids, indicating their suitability as potential cultivars under stress and non-stress environments. Entries 46, 82, 32, 15, 100, 6, 21 and 83 (for early maturity hybrids) and entries 109, 115, 22, 63, 1, 24, 21, 20, 2, 19, 5, 6, 10, 14, 25, 9, 108 and 114 (late maturity hybrids) performed better than all commercial check cultivars and were consistently identified by the AMMI and GGE biplots as performing above average in terms of yield and stability, and warrant recommendations as hybrids under both stress and optimal environments in southern Africa. In southern Africa, the increase in drought conditions and unpredictability of rainfall and increase of low fertiliser inputs by the small holder communities will justify the continued improvement of genotypes for drought and low N tolerance. There is sufficient variability within CIMMYT developed inbred lines that can be useful in southern Africa and other similar sub-optimal environments in Africa.

From the results from this study, the promising inbred lines identified as having good GCA and SCA in their combinations can effectively be utilized in hybrid breeding programmes. The inbred lines with considerable levels of drought and low N stress tolerance can further be utilized as donors for stress tolerance breeding. Genotypes which performed better than local commercial checks can be further evaluated in advanced multi-location trials and across multi-seasons for stability and those that are stable can potentially be released as hybrids. Screening of these genotypes against disease pressure is further recommended, as the region is characterised by severe biotic and abiotic stresses. The ongoing climate variability and changes justifies continued research initiatives especially for drought and low N fertility. These hybrids and/or inbred lines can also be screened for trace elements like iron and zinc, which are real causes of malnutrition-related illnesses rampant in the region.