Breeding of acid soil tolerant maize genotypes for Angola

By

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DECLARATION

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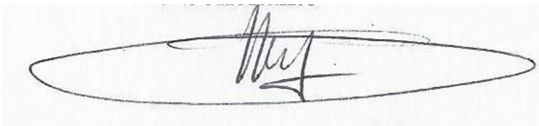

01 . 08. 2020

Dibanzilua Nginamau — Date

DEDICATION

To five glorious and beloved "ones" in my life, my lovely wife Gloria Miti, loving daughters Matondo Nginamau and Suzana Nginamau and sons Manuel Dickson Nginamau and Ndongala Nginamau, for their warm and loyal encouragement and perseverance. Special dedication is also extended to my late parents Manuel da Silva and Bibiana Diasonama, for their commitments in building my life.

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SUMMARY

Breeding efforts to develop high yielding and stable maize cultivars tolerant to soil acidity is still lacking in Angola, where the main maize production environments are characterized by acid soils. Furthermore, Angola is faced with two distinct human populations, with one favouring white kernel maize while the other prefers yellow maize, making it key to develop separate breeding programmes for these two distinct groups of people. The aim of this study was to select CIMMYT inbred lines (white and yellow kernel) adapted to the mid-altitude climatic conditions (for example from CIMMYT-Zimbabwe) and those developed for acid soil tolerance (for example from CIMMYT-Colombia), that can potentially be used in breeding programmes for acid soil tolerance in Angola. The specific objectives were to: i) assess the combining ability for grain yield performance and grain yield stability of corresponding hybrids of CIMMYT-Zimbabwe yellow elite inbred lines with CIMMYT-Colombia acid tolerance yellow donor lines under acid and non-acid soil conditions; ii) assess the combining ability for grain yield performance and grain yield stability of corresponding hybrids of the CIMMYT-Zimbabwe white elite inbred lines with CIMMYT-Colombia acid tolerance white donor lines; and, iii) to assess the *per se* grain yield performance of CIMMYT-Zimbabwe elite white and yellow lines and CIMMYT-Colombia acid tolerant donor lines. To achieve this, ten yellow kernel and eight white kernel elite inbred lines adapted to the mid-altitude climatic conditions, as well as four yellow and eight white kernel acid tolerance donors, were sourced from the CIMMYT-Zimbabwe and CIMMYT-Colombia breeding programmes, respectively. Two separate line x tester crossing nurseries for the white and the yellow kernel lines were established at the CIMMYT-Muzarabani station during the 2014 winter season, and these yielded 47 and 36 crosses with sufficient seed, respectively. The white and yellow kernel crosses (F_1s) were separately evaluated alongside eight and six check hybrids, respectively, during the 2014-2016 cropping seasons across nine acid and non-acid sites in Angola and Zimbabwe. Inbred line trials for the white kernel lines as well as the yellow kernel lines were also separately established during the same period. Multi-environmental trial data identified the most promising CIMMYT-Colombia acid tolerance donor lines as CW2, CY3 and CY1, while the most promising among the CIMMYT-Zimbabwe elite lines were ZW6, ZW8, and ZY3. These lines showed the highest positive general combining ability effects for grain yield (GY) and were involved as parents in most of the hybrids identified as the highest yielders under both acid and non-acid soil conditions. The best specific combiners that also showed yield stability, were ZW3 x CW4 and ZY10 x CY3, for the white and yellow kernel line cross hybrids, respectively. The majority of the identified high yielding crosses were also stable for yield across environments. Additionally, inbred line trial data revealed some of the CIMMYT-Zimbabwe lines (such as ZW5 and ZY3) and CIMMYT-Colombia lines (such as CW3 and CY1) as ideal for single-cross hybrid production, because of their high *per se* GY performance. Overall, the CIMMYT-Colombia acid tolerance donor lines and the elite lines from the CIMMYT-Zimbabwe breeding programme can potentially be used to develop maize inbred lines and hybrids adapted to the acid and non-acid soil conditions in Angola and elsewhere

Key words: Acid soils, non-acid soils, inbred lines, combining ability, heterotic groups, grain yield, genetic analysis

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AD	Anthesis date
Al	Aluminium
ANOVA	Analysis of variance
ASI	Anthesis-silking interval
BLUE	Best linear unbiased estimate
BLUP	Best linear unbiased prediction
Ca	Calcium
CIMMYT	International Maize and Wheat Improvement Centre
Cmol	Centimol
CSI	Cultivar stability indices
CV	Coefficient of variation
CW	CIMMYT-Colombia white inbred line
CY	CIMMYT-Colombia yellow inbred line
DF	Degrees of freedom
EH	Ear height
EPO	Ear position
ET	Leaf blight Turcicum
F_1	First filial generation
FAOSTAT	Food and Agriculture Organisation of the United Nations Statistics
Fe	Iron
GCA	General combining ability
GGE	Genotype-Genotype x Environment
GIS	Geographic information system
GLS	Grey leaf spot
GY	Grain yield
H^2	Broad sense heritability
Ha	Hectare
HG	Heterotic group
H_2O	Water
IIA	Instituto de Investigação Agronómica
IITA	International Institute of Tropical Agriculture
K	Potassium
Kg	Kilogram
LSD	Least significant difference
L x T	Line by tester
M	Metre
m.a.s.l.	Metre above sea level
Max	Maximum
MC	Moisture content
META-R	Multiple environment trial analysis package

Mg	Magnesium
Min	Minimum
MINAGRIF	Ministério da Agricultura e Florestas
MLN	Maize Lethal Necrosis
Mn	Manganese
MS	Mean square
MSV	Maize streak virus
Mo	Molybdenum
MOI	Moisture
N	Nitrogen
Na	Sodium
NA	Not analysed
NCDII	North Carolina design II
NH_2	Urea
NUE	Nitrogen use efficiency
P	Phosphorus
pH	Soil acidity or alkalinity
PH	Plant height
P_2O_5	Phosphorus pentoxide
ppm	Parts per million
QPM	Quality protein maize
QTL	Quantitative trait loci
RNRG	Relative net root growth
S	Sulphur
SD	Silking date
SCA	Specific combining ability
SSA	Sub-Saharan Africa
t ha^{-1}	Tons per hectare
TEX	Texture
UFS	University of the Free State
US$	United States Dollars
WHO	World Health Organization
WKILT	White kernel inbred line trial
YKILT	Yellow kernel inbred line trial
ZW	CIMMYT-Zimbabwe white inbred line
ZY	CIMMYT-Zimbabwe yellow inbred line
°C	Degrees Celsius
%	Percentage

CHAPTER 1

GENERAL INTRODUCTION

1.1 Global maize production trends and uses

Maize (*Zea mays* L.) is one of the most important food and feed crops in the world, grown in more than 166 countries and is adapted to different agro-ecological conditions (Udaykumar et al., 2013; Prasanna, 2011; Ahmad et al., 2011). On a global scale, maize production is constrained by a wide range of factors, including poor soil fertility, soil acidity, lack of access to key inputs (especially quality seed and fertilizers), low levels of mechanization, and poor post-harvest management.

In sub-Saharan Africa (SSA), maize is the major food crop with annual consumption averaging around 72 kg per capita (FAOSTAT, 2014), and its production is limited by several abiotic factors (Badu-Apraku et al., 2003; Vivek et al., 2010; Badu-Apraku et al., 2011), particularly drought (Zarabi et al., 2011), low soil fertility (especially, nitrogen (N) and phosphorus (P) deficiency (Ouma et al., 2012; 2013), soil acidity (Tandzi et al., 2015), heat stress (Larkindale et al., 2005; Zaidi and Singh, 2005; Cairns et al., 2013) as well as mineral toxicity, for example aluminium (Al) toxicity (Prasad et al., 2011; Mahalingam, 2015). Apart from abiotic factors, biotic stresses, such as parasitic weeds (Lagoke et al., 1991; Runo et al., 2012), foliar and cob rot diseases (Gressel et al., 2004) and insect pests (Tefera et al., 2011) also cause significant yield losses. Grain yield average in developing countries is close to 1.5 t ha^{-1}, constituting about 20% of the average yield in the developed world (Prasanna, 2011).

1.2 Crop production and consumption trends in Angola

Prior to gaining independence from Portugal in 1975, Angola was self-sufficient in all major food crops, except wheat. It was the world's fourth largest coffee exporter, employing nearly a quarter of a million people (Jover et al., 2012). The country also exported over 400 000 t of maize annually, making it one of the largest staple food producers in SSA. Other export crops included cotton, sugar cane, sisal, bananas, cassava and wood. Although farming was important in Angola during the colonial period, the sector collapsed as a result of the civil war, which resulted in a huge displacement of the rural population, many of whom still live in towns and cities. Eighteen years into peace, and despite its immense natural wealth, Angola does not yet produce enough food to meet the needs of its population (Table 1.1, Figure 1.1). The country depends heavily on expensive food imports, mainly from South Africa and Portugal, while about 90% of farming is done at family and subsistence level. According to the FAO (2017), 44% of the Angolan population (mainly children under five years and women in reproductive age) suffer from malnutrition, consequently the result of insufficient investment in domestic agricultural production and distribution, and of the continued reliance on imported goods, drive up prices and leaves many basic products out of the reach of ordinary Angolans.

Table 1.1 Maize production and productivity in some African countries during the 2017 cropping season

Country	Production (ton)	%	Ranking in Africa	Productivity (kg ha^{-1})
South Africa	16,820,000.00	19.99	1	6,398.84
Nigeria	10,420,000.00	12.38	2	1,593.27
Ethiopia	8,116,787.00	9.65	3	3.734.36
Egypt	7,100,000.00	8.44	4	7,712.35
Tanzania	5,939,737.00	7.06	5	1,450.85
Zambia	3,606,549.00	4.29	6	2,515.13
Malawi	3,464,139.00	4.12	7	2,007.77
Kenya	3,186,000.00	3.79	8	1,522.61
Uganda	3,015,316.00	3.58	9	2,544.61
Mali	2,811,385.00	3.34	10	2,280.10
Angola	**2,246,241.00**	**3.18**	**11**	**1,057.26**
Cameroon	2,246,241.00	2.67	12	1,806.57

FAOSTAT (2017)

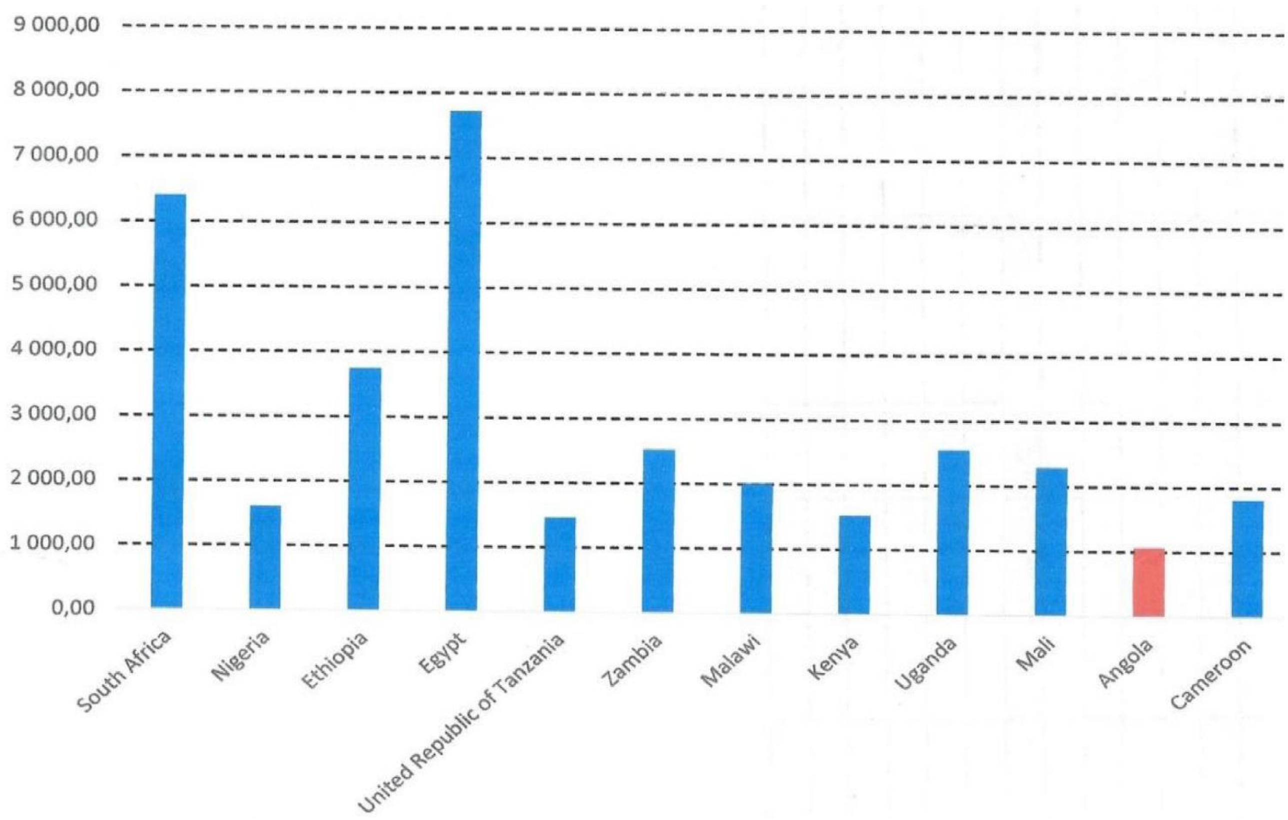

Figure 1.1 Maize productivity (kg ha^{-1}) in Africa for 2017 (FAOSTAT, 2017)

However, the cereals crops agriculture sector has seen a sustained increase in total national production in recent years, because it is specifically based in the culture of maize production. For the cereal crops, projections of total national production were made, calculated for the five-year period 2018-2022, with a total growth of 62.5%. The expected annual compound growth for 2018-2022 will be 10.2% (MINAGRIF, 2018). The growth projections for each crop are as follows: maize (63.9%), finger millet (38.6%), sorghum (26.7%) and rice (46.4%) (Table 1.2). In order to achieve these projections, it is necessary to guarantee the following annual growth composed of production by culture: maize 10.4%, finger millet 6.8%, sorghum 4.8% and rice 7.9%. However, maize production does not satisfy the projected production to respond to the consumption demand (Tables 1.1 and 1.2). To cover the gap, on average, cereal imports cover an estimated 40% of the national consumption needs (Figure 1.2).

Table 1.2 Cereal production projections (ton) in Angola for the period 2018 - 2022

Years	2018	2019	2020	2021	2022	%
Total cereal crops	**3,162,727**	**3,570,166**	**4,030,551**	**4,550,807**	**5,138,749**	**62.5**
Maize	3,007,111	3,402,456	3,849,776	4,355,906	4,928,576	63.9
Sorghum	65,923	69,940	74,200	78,721	83,516	26.7
Finger millet	59,960	65,062	70,598	76,605	83,124	38.6
Rice	29,733	32,707	35,977	39,575	43,533	46.4

MINAGRIF (2018)

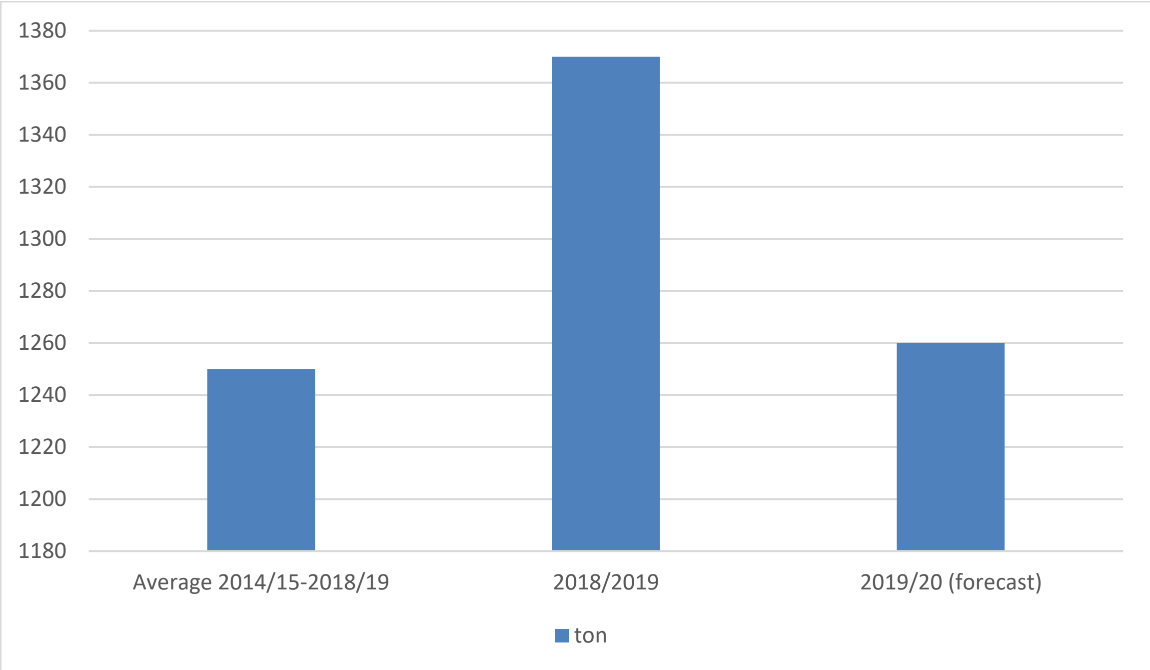

Figure 1.2 Cereal importation into Angola (FAO/GIEWS, 2020)

According to a report by MINAGRIF (2018), production of maize in Angola is not yet satisfactory, since it does not meet the country's consumption needs. In Angola, whose population is estimated at 28,000,000, about 60% of the population (~16,800,000 people) consume an average of about 0.5 kg of maize flour per day (MINAGRIF, 2018). Maize production in recent years, estimated at 2.5 million ton of grain per year, is insufficient, when consumption is closer to 5.0 million ton.

To meet this demand, for human consumption only, Angola will have to produce at least 4 million ton of maize grain annually, which, at an average of 4 t ha^{-1}, needs about 988,000 ha of land.

However, maize productivity in the country is very low, averaging 0.7-1 t ha^{-1} (MINAGRIF, 2020), thereby challenging maize breeders to holistically look at these scenarios and come up with tangible solutions that can promote food security at household and national level.

Maize varieties used for food and feed in Africa have white and yellow kernels, respectively. For example in South Africa, approximately 49% of the maize produced for human consumption is white, whereas the remaining 51% is yellow and is used for animal feed (https://www.allaboutfeed.net/Raw-Materials). This is in contrast to Angola, where both white and yellow maize are used for human consumption. This creates a huge demand for yellow/orange maize, as it is consumed by both humans and animals.

On the other hand, like most of the developing countries in Africa, a significant number of Angolans (approximately 44%) suffer nutrient-deficiency-related ailments, and the problem is prevalent mostly in pregnant woman and children below 5 years (FAO, 2017; Wirth, et al., 2017; MINAGRIP, 2020). For instance, vitamin A deficiency can result in morbidity, loss of vision or blindness and even death (Maru, 2017). In this regard, over the years, breeders in the region have responded to this challenge by developing maize varieties with enhanced vitamin A content (yellow/orange kernels), through biofortification protocols. Because of the kernel colour of these varieties, consumer acceptance in most Southern African countries, who prefer mostly white maize, has been very low (Meenakshi et al., 2010). Since yellow maize is widely accepted in Angola, it would make a lot of sense to also push for vitamin A maize varieties, in future breeding programmes.

1.3 Abiotic and biotic factors affecting maize productivity in Angola

In Angola, maize is grown over the whole country, but mainly in the high and mid-altitude geographic zones, which receive abundant annual rainfall (800 to 1200 mm) (Figure 1.3). These high rainfalls are associated with leaching, erosion of mineralized and applied nutrients, and soil acidification (Jandong et al., 2011). Because of these factors, soil acidity (Figure 1.4), toxic levels of Al and manganese (Mn), as well as deficiencies in calcium (Ca), magnesium (Mg) and P (Borreno et al., 1995) characterize soils in these zones. Over-use of inorganic nitrogenous fertilizers is also known to cause soil acidification (Guo et al., 2010; Fageria and Nascente, 2014). Soil acidity is a huge problem, limiting crop production on 30 - 40% of the world's arable land, and causing yield losses of up to 70% of the world's potentially arable land (Haug, 1983) and up to 60% in many African countries (Zeigler et al., 1995; Thé et al., 2006; Dewi-Hayati et al., 2014; Tandzi et al., 2015; 2018), including Angola.

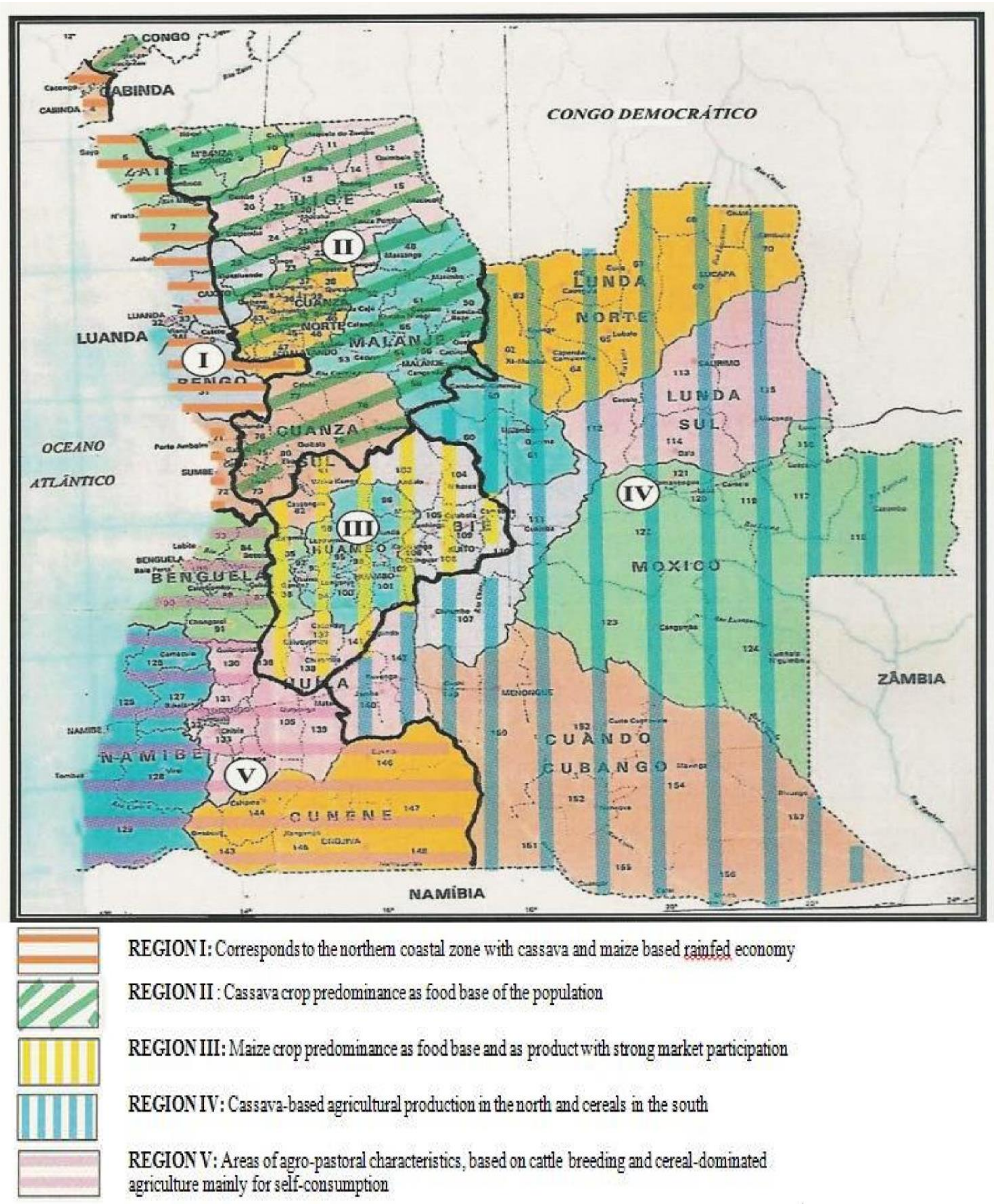

Figure 1.3 Main agriculture production regions of Angola (Agritex, 2015)

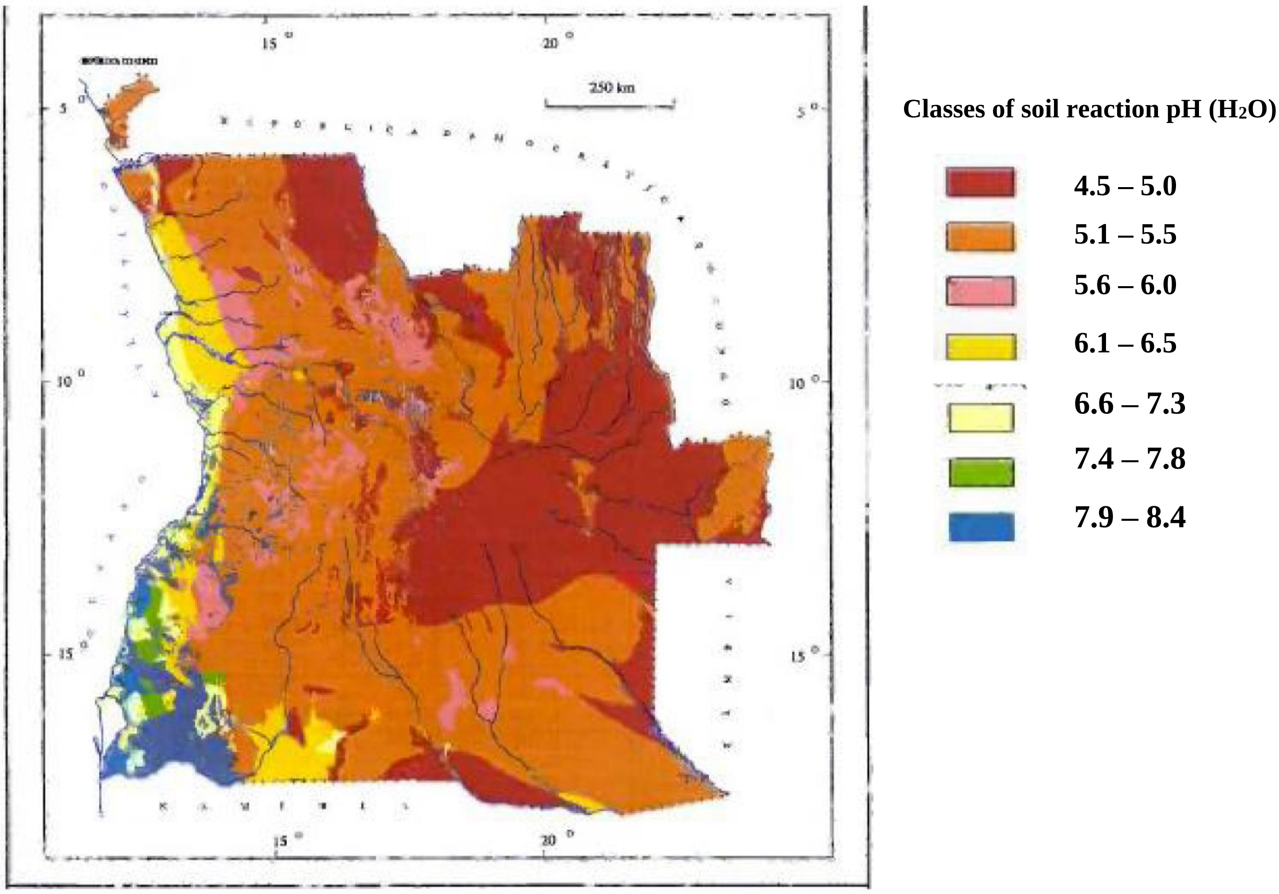

Figure 1.4 Outline of the geographic distribution in Angola of the average pH in the top 30 cm of the soil (Franco et al., 2001)

1.4 Breeding maize adapted to acid soil conditions

The development of high yielding, stress tolerant maize varieties suitable for the diverse agro-ecologies of SSA, is a major objective of public and private sectors in the region. To achieve this objective and drive increased genetic gains, efficient use of the limited resources is important. This implies the use of efficient and sustainable strategies when designing a maize breeding programme. Breeders should focus on product profiles when developing new, high yielding maize varieties, in defined environmental conditions as well as to meet farmers' and end consumers' needs and preferences for easy variety acceptance and adoption. A product profile is a set of targeted attributes, which a new plant variety is expected to meet to be released commercially and to be adopted by a specific market segment. Attributes must be understood as traits with a specific value, this value being defined either in absolute or relative terms. For instance, the product profile in this study for Angola was the mid-altitude zone and among the attributes, tolerance to soil low pH (acid soils) and high yield were targeted.

In order to solve the problem of soil acidity, farmers can use lime (Whelan, 1958; Tandzi et al., 2015) as well as other agronomic measures, such as fallowing (Robinson, 1956; Lekasi et al., 1992; Tonye et al., 1997; Mwangi et al., 2002). Liming is known to be expensive to resource poor farmers, who constitute the majority of food producers in African countries (Thé et al., 2005). On the other hand, use of this technology requires a lot of skill, which the majority of farmers do not have, and is not an economically and environmentally sustainable solution (Pandey et al., 1994; Thé et al., 2006; Krill et al., 2010; Tandzi et al., 2015; Ndeke and Tembo, 2019). Additionally, liming is only effective in the topsoil and does not neutralize acidity in the subsoil, where acidity poses a severe problem to developing roots (Toma et al., 1999; Sierra et al., 2006). On the other hand, agronomic measures, for instance fallowing, cannot be viable options, especially when the focus is on the future, where land size suitable for agriculture is expected to dwindle (Tonye et al., 1997). Developing crop varieties adapted to acid soil conditions remains the most viable and sustainable means to improve maize productivity.

Genetic variability for tolerance to acid soil exists among maize genotypes, which can be exploited in developing high-yielding, acid-tolerant maize genotypes (Tandzi et al., 2018). For instance, a study in Cameroon showed that using adapted local inbred lines and crossing them with acid tolerant inbred lines from the International Maize and Wheat Improvement Centre (CIMMYT)-Colombia, could minimize grain yield losses due to soil acidity (Tandzi et al., 2015; Petmi et al., 2016). Elsewhere, evaluation of maize single-cross hybrids on acidic soils in Indonesia showed that several hybrids, which were progeny of crosses between acid soil tolerant or moderately acid soil-tolerant inbred lines, yielded reasonably high (Dewi-Hayati et al., 2014). Although evidence suggests that maize cultivars bred to tolerate soil acidity can produce meaningful yields under acid conditions, this technology has not yet been explored in Angola. To be more precise, there is currently no breeding programme focussed on developing maize genotypes tolerant to acid soil conditions, yet this is the only viable option to increase maize productivity in the country.

It is also now widely believed that effective breeding programmes are those that have well defined aims on a particular product profile. Looking at Angola, the country can be divided into two product profiles based on preferences of kernel colour of maize. Almost half of the population prefer yellow maize, while the other half prefers white kernel maize (MINAGRIF, 2018). In this regard, breeding programmes should also be designed to cater for the needs of these two distinct groups of people.

In an effort to combat the threats posed by soil acidity, CIMMYT breeders in Colombia developed a wide range of inbred lines (both yellow and white) that are tolerant to acid soils. These materials can potentially provide a source of acid soil tolerance genes in maize breeding programmes in Southern Africa.

1.5 Main objectives of the study

The main goal of this study was to identify CIMMYT inbred lines adapted to the mid-altitude climatic conditions (such as those from CIMMYT-Zimbabwe) and those developed for acid soil tolerance (such as those from CIMMYT-Colombia), that can potentially be used in breeding for acid soil tolerance in Angola.

1.5.1 Specific study objectives

1) To assess the combining ability for grain yield performance, and grain yield stability, of corresponding hybrids of the CIMMYT-Zimbabwe yellow elite inbred lines with the CIMMYT-Colombia acid tolerance yellow donor lines under acid and non-acid soil conditions.
2) To assess the combining ability for grain yield performance, and grain yield stability of corresponding hybrids of the CIMMYT-Zimbabwe white elite inbred lines with the CIMMYT-Colombia acid tolerance white donor lines under acid and non-acid soil conditions.
3) To assess the *per se* performance of CIMMYT-Zimbabwe elite white and yellow lines and CIMMYT-Colombia acid tolerance donor lines under acid and non-acid conditions in Angola.
4) To identify the best yellow and white acid tolerant line donors
5) To identify the best yellow and white acid tolerant maize single cross hybrids for Angola

1.5.2 Hypothesis

Introducing exotic white and yellow tropical maize germplasm bred for acid soil tolerance in the mid-altitude climatic zones maize breeding programmes can improve maize productivity under both acid and non-acid soil conditions in Angola.

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CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Maize (*Zea mays* L.) is a principal cereal crop cultivated worldwide for human food, animal feed, and more recently, as a source of biofuel (Shifera et al., 2011; Ranum et al., 2014). However, as a direct consequence of water insufficiency and climate change, frequent occurrence of both biotic and abiotic stresses are a common feature in various regions around the world, and recently, this has become a constant threat in increasing global maize productivity (Kimotho et al., 2019). Maize is ranked the third most important crop in the world, with an estimated coverage of 100 million hectares in developing countries, with almost 70% of the total maize production in the developing world coming from low middle income countries (FAOSTAT, 2012).

2.2 Importance of maize in the world

Together with the other important cereals (such as rice and wheat), maize provides at least 30% of the food calories for more than 4.5 billion people in 94 developing countries. In the developed world, maize is often consumed indirectly in the form of eggs, corn syrup, milk and cheese products, beef and pork, but in the developing countries, it is a staple crop for around 900 million people who earn less than US$2 per day (Prasanna, 2011). Currently, maize is the most important food crop in SSA and Latin America, and is also a key Asian crop. In SSA, maize is consumed by at least 50% of the population and is the preferred food for one-third of all malnourished children and 900 million poor people worldwide (CIMMYT, 2019). As the world's population increases and more people begin to include higher amounts of meat, poultry and dairy into their diets, the demand for maize is expected to rise.

Demand for maize in the developing world is expected to double and by the year 2025, the crop is predicted to become the crop with the largest production globally and specifically in the developing world (Rosegrant et al., 2009). To achieve food security in SSA by 2050, it was estimated that the level of food production achieved in 1995 must be increased by 700% (du Guerny, 1999). This requires, in part, development of strategies for resource-use efficiency and sustainable production systems on acid soils. Included in these strategies are the introduction of improved acid-soil tolerant germplasm and the amelioration of soil acidity using P, lime and/or organic amendments.

Maize has unique adaptation characteristics not matched by any other crop and as a result, it is grown in a wide range of agro-climatic zones, from below sea level to altitudes higher than 3000 m, and in areas with 250 mm to more than 5000 mm of rainfall per year, and with a growing cycle ranging from 3 to 10 months (Zhang et al., 2016; Fayaz et al., 2017). This phenomenon can also point to a wide genetic variation, as the diverse geo-climatic conditions expose the crop to different types of risks during all its phenological stages of growth (Tandzi et al., 2018). This suggests that for most of the production constrains that may arise, most likely due to the impacts of climate change, opportunities to minimize the consequences of these constraints through crop improvement techniques will always remain a viable option.

2.3 Importance of maize in Angola

Angola has an economy heavily dominated by crude oil export. On the other hand agriculture, which is dominated by smallholder farming, directly contributes only 6-10% of Angola's gross domestic product (GDP). However, it is estimated that 70% of the country's population is involved in agricultural activities (Kiakanua et al., 2014). This makes the agricultural sector very important as it supports livelihood of the majority of the population. Among the many crops grown by smallholder farmers in Angola, maize is the most important agricultural commodity although production often falls below requirements due to various factors. In Angola, maize is the cereal with the highest production and one of the most consumed. An average maize yield of 640 kg/ha was reported for the period 2000-2010 (FAOSTAT, 2012).

2.4 Major abiotic stress factors affecting maize production

Drought and low N stress, soil acidity, heat stress and mineral toxicity are the major drivers of yield reductions worldwide, and as a result, yield losses of more than 50% have been reported (Prasad et al., 2011; Cairns et al., 2012; Mahalingam, 2015). Plants are continuously exposed to various changes in the environmental conditions, some of which cause negative effects on economically important crops such as maize (Ramegowda and Senthil-Kumar, 2015). Evolutionary changes have helped many plants adapt to different adverse conditions, with some species now showing a marked increase in tolerance to various abiotic stresses compared to others (Phukan et al., 2014).

Due to global warming, which is widely attributed to emission of greenhouse gases in the atmosphere, as well as the climatic abnormalities accompanying it (such as drought and heat stress), frequencies of combined biotic and abiotic stresses have increased, and the impacts on crop productivity are evident (Mittler, 2006; Pandey et al., 2015). The most sensitive stages to drought and heat stress on growth and development of maize, is the onset of flowering and the grain filling stages, although adverse effects on the other growth stages are observed when the stresses are severe (Grant et al., 1989). In the lowland tropics, drought stress was reported to have accounted for approximately 16% of maize production losses (Edmeades et al., 2006). Other studies showed similar trends (Lobell et al., 2011; Langridge and Reynolds, 2015; Obidiegwu et al., 2015).

The impact of drought is huge on drought sensitive crops (Athar and Ashraf, 2009; Huang et al., 2015), and plant breeding remains a good option to improve adaptation to this stress. Drought is coupled with heat stress in many circumstances. Heat stress can be defined as exposure to temperatures above a threshold level for a period of time, that causes irreversible damage to maize crop growth and development, and is influenced by intensity, duration and rate of increase in temperature (Larkindale et al., 2005; Zaidi and Singh, 2005).

Low potential of hydrogen (low pH) causes occurrence of acidic soils, which is one of the major abiotic constraints of maize production. Considerable grain yield reductions of maize under low soil pH were reported previously (Tandzi et al., 2018). Dewi-Hayati et al. (2014) reported that grain yield reduction under acid soils varied from 2.8 to 71%, whereas Tandzi et al. (2015a) found maize yield reduction under acid soils to be up to 69%. The variation in yield reduction under low soil pH is based on the level of acidity in the soil, the agro-climatic conditions of the environment, and the genetic potential of maize genotypes. Improving grain yield performance under acidic soil conditions is a major objective of maize breeding programmes in many regions of the world (Tandzi et al., 2015b).

Soil acidity is one of the most important factors that affect crop production worldwide. Soil acidity is a major constraint to crop production where excess of Al and Mn, hamper crop production in tropical and sub-tropical areas (Zeigler et al., 1995; Sumner and Noble, 2003).
Plants require essential nutrients for normal functioning and growth. A plant’s sufficiency range is the array of nutrient amounts necessary to meet its nutritional needs and maximize growth. Nutrient levels outside of a plant’s sufficiency range cause overall crop growth and health to decline due to either a deficiency or toxicity. Nutrient deficiency occurs when an essential nutrient is not available in sufficient quantity to meet the requirements of a growing plant. Toxicity occurs when a nutrient is in excess of plant needs and decreases plant growth or quality (McCauley et al., 2017). The combination of low pH, intoxication of heavy metals such as iron

(Fe), Al and Mn as well as deficiencies of N, P, Mg and Ca negatively affect crops growth, and reduces the yield in acid soil (Kaonga, 2015; Mutimaamba, 2015).

In Angola, maize production is constrained mostly by soil acidity, which is a common feature in most of the maize production environments in the country. Some years ago, the Angolan government developed a soil amendment programme by using lime in the communities to increase maize production and productivity. According to Kisinyo (2016), application of both lime and P-based fertilizers is important for enhanced maize productivity under acid soils. However, these interventions are not always affordable for small-scale farmers, who are primarily resource-poor, and these interventions also pose environmental risks, including contamination of underground water and disruption of aquatic ecosystems (Thé et al., 2006a; Tandzi et al., 2015a). Therefore, developing crop varieties adapted to acid soil conditions can be the most viable and sustainable means to improve maize productivity in Angola.

2.5 Concept of pH

The concept of low pH was first highlighted by a Danish chemist, Soren Peder Lauritz Sorensen in 1909. Soil pH is a measure of the acidity or basicity in soils and pH is defined as the negative logarithm of hydrogen ions (H^+ or, more precisely, H_3O^+ aq) in a solution. pH is a very important pedologic parameter, as it is fundamental for the typological characterization of soils. Each soil corresponds to a certain pH value, which unreservedly reflects the way it was formed. In contrast to this, from an agronomic point of view, it is not seen as of great importance, due to the fact that the free hydrogen ions in the soil solution, which determines pH, does not have a direct action on any plant species in that soil (Franco et al., 2001). In spite of this, it must be seen as a characteristic of some relevance, because of the influence it has on the basic soil conditions that have implications for the survival as well as development of plants. Soil pH is considered a significant variable in soils, as it dictates many chemical processes that take place in the soil. It significantly affects plant nutrient availability by determining the chemical forms of the nutrients. The optimum pH range for most plant species is between 5.5 and 7.0, however, some plants have adapted to thrive at pH values beyond this range. Its agronomic value, therefore, results from well-known correlations in soils between pH and nutrient availability.

According to Brady (1990) and Gazey (2019), the pH scale ranges from 0 to 14, with 7 being neutral, where a pH below 7 denotes acidity and above 7 denotes basicity. It has for long been known that a low soil pH (equal to or less than 5.0, for example) is not favorable to plant nutrition and development (Franco et al., 2001). This is true for one or more of the following reasons: (1)

low levels of N and Sulphur (S), due to deficient conditions for decomposition of organic matter; (2) poor assimilation of P (mostly precipitated as Fe and Al phosphates); (3) marked deficiencies of potassium (K), Ca and Mg, as it implies very leached soils; (4) lack of some micronutrients (such as molybdenum (Mo), which is quite insoluble in such pH conditions); (5) as well as excesses of Al and Fe (presenting levels that can cause toxicity). A high pH (in the order of 7.4 - 8.4), likewise involves conditions that are also not entirely favourable for most of plants. Although there are normally sufficient amounts of N, S, Ca, Mg and Mo in the soil, restrictions on other levels, namely: (1) evident deficiencies of P, (precipitated as calcium-phosphate); (2) restrictions in K nutrition due to calcium-potassium antagonism; and (3) low or very low availability of micronutrients (except for Mo). It is in the pH 6.1 - 7.3 zone, without a doubt, that the plants find the largest and most balanced availability of the various plant nutrients in the soil.

2.6 Soil acidification and soil acidity effects on maize production

Acidic soils are defined as soils with pH < 5.5 in the top layer (Wambeke, 1976; Dalovic et al., 2012) and acidic soils are usually prone to Al (Al saturation > 35%) and Mn toxicity, and are deficient in Ca, Mg, P (P < 16 ppm) and Fe (Granados et al., 1993; Duque-Vargas et al., 1994;). The extent of hydrogen cation (H^+) activity in the soil solution determines soil pH and is influenced by edaphic, climatic, and biological factors. High rainfall affects the rate of soil acidification, particularly when rainfall washes away bases [such as Ca^{2+}, Mg^{2+}, K^+, sodium (Na^+) and carbonate ions (CO_3^{-2})] from the soil.

Other factors that are known to cause soil acidity are: acidic precipitation (H^+ ions in precipitation); input of acidifying gasses or particles (such as sulphite gas); nitric and hydrochloric acids (such as hydrogen chloride) from the atmosphere; poor agricultural practices such as application of elemental S; use of ammonium-based fertilizers (NH_4^+); nutrient uptake by leguminous crop, and mineralization of organic matter (Rowell, 1988; Dashuan and Shuli, 2015; Singh et al., 2017).

Over the years, farmers have been responding in different ways to the challenge of soil acidity. One of the most common and efficient intervention strategies is liming, and has a direct effect on soil pH. Application of lime commonly results in significant reduction of exchangeable Al (Thompson and Troech, 1978; Moody et al., 1998), thereby allowing for a more efficient uptake of N and P (Raij and Quaggio, 1997; Novak et al., 2009; Goulding, 2016). In a study by Kisinyo (2016), application of both lime and P fertilizer was shown to be important for P and N fertilizer recovery efficiencies necessary for healthy maize growth in acid soils. However, these interventions are not always affordable for small-scale farmers, who are predominantly resource-poor, and are also not environmentally friendly (Thé et al., 2006a; Tandzi et al., 2015b). Additionally, liming affects the topsoil and does not remove acidity in the subsoil, where it poses a severe problem to developing roots (Toma et al., 1999; Sierra et al., 2006).

2.6.1 Effects of low pH on maize performance

For the maize crop, acid soils increase Al solubility, which in subsoils, is particularly harmful, because it causes shallow rooting, drought susceptibility, and poor use of subsoil nutrients, thereby decreasing maize production (Lidon and Barreiro, 2002).

2.6.2 Effects of Al toxicity in plants grown on acidic soils

Several mineral-related factors limit crop production on acid soils, mainly the combination of phytoxic levels of heavy metals, which include Al and Mn, and a deficiency of P, Ca and Mg. (Mutimaamba, 2015). Al is one of the major factors constraining crop production on at least 67% of the total acid soil areas in the world. High Al concentration presents an important growth and yield limiting factor for crop production in acid soils (pH < 5.5). Al toxicity is known to limit nutrient use efficiency (NUE) and crop production through reducing root growth, which greatly restricts the ability of the plant to explore the soil volume for nutrients and water. The scenario also culminates in restriction of uptake of P, Ca and Mg by plant roots, and deficiencies of these nutrients are common in plants suffering from Al toxicity (Foy and Fleming, 1978; Foy, 1984; Haynes, 2001). The most recognized effect of Al toxicity in plants is observed in roots. Inhibition of root tip growth or root elongation, is the most common symptom of Al toxicity, but damage in the upper plant parts (including stems, leaves and fruits) are a lot evident (Vitorello et al., 2005; Miyasaka et al., 2007; Mariño-Gergichevich et al., 2010).

A recent study revealed that when soil pH drops below 5.5, soluble Al^{3+} concentrations increase in the soil (Gazey, 2019). In this form, Al retards root growth, restricting access to water and nutrients. Poor crop growth, yield reduction and smaller grain size occur as a result of inadequate water and nutrition.

2.6.3 Effects of soil-acidity related to P deficiency on plants

In plants, P is considered second to N as the most essential nutrient to ensure health and function. P is used by plants in numerous processes such as photophosphorylation, genetic transfer, nutrient transfer and phospholipid cell membranes (International Plant Nutrition Institute, 1999).

P availability is crucial, especially during the early stages of maize growth, as the nutrient promotes root development. Soil acidity is one of the main factors, which control P availability in soil. For instance, when P-based fertilizer is applied to acid soils, 70-90% of the nutrient will be locked up and become unavailable for plant absorption (Fageria et al., 2008). In almost all soils, P is usually the most limiting mineral nutrient (Thé et al., 2006b).

P availability to plants may be limited by its low abundance in the soil, but also in some instances, by its adsorption onto various soil minerals. In acid soils, P may be adsorbed by Fe or Al oxides as well as by various clay minerals. In most soils, P that is available to plants, is predominantly present in the upper soil horizons and its availability decreases with soil depth (Chu and Chang, 1966; Enwezor and Moore, 1966; Keter and Ahn, 1986; Pothuluri et al., 1986).

Application of lime usually is a common remedy that results in a drastic reduction of exchangeable Al (Thompson and Troech, 1978; Moody et al., 1998), allowing for a more efficient uptake of N and P (Raij and Quaggio, 1997). Soil P availability during maize seedling development is an important determinant of growth and grain yield. For example, a study by Barry and Miller (1989) detected a significant increase in maize yield in response to P fertilization before the six-leaf stage (V6) compared to addition of P after the V6 stage. Root growth and development are critical for early P uptake in maize, since P is relatively unavailable and immobile in many soils (Barber, 1984).

2.6.4 Agricultural practices that contribute to increased soil acidity

Approximately 30% of the world's ice-free soils are acidic, 17% of which are considered as arable. Maize has become one of the most important grain crops grown on acidic soils due to its demand as a food crop, coupled with its ability to tolerate, to some extent, Al toxicity (Uexküll and Mutert, 1995). Yield reductions of approximately 70% have been recorded in these regions due to Al toxicity (Uexküll and Mutert, 1995; Welcker et al. 2005). Leaching of the soil profile naturally encourages soil acidification, but the phenomenon can be accelerated by certain farming practices such as continuous maize cultivation on acid soils (Thé et al., 2006a), and over-application of ammonia fertilizers, especially in the tropical and subtropical regions (Rao et al. 1993). Since N-fixing legumes, release H^+ in the root zone, farming practices that encourage continuous cultivation of leguminous crops (such as green manure cover crops), may increase acidity of acid soils (Brett and James, 1995). Therefore, farmers should always be cautious in the agronomic decisions they make, as some of them have negative implications in cropping cycles.

2.7 Mechanisms of tolerance to low soil pH

For development of maize, which is acid soil-tolerant, maize breeders need to have an understanding of the mechanisms employed by the plant to withstand Aluminium (Al), Iron (Fe), and manganese (Mn) toxicities. Al toxicity tolerant plants are known to respond in two ways, namely the symplastic and the exclusion (or apoplastic) strategy. In the symplastic response, immobilisation or neutralization of Al occurs within the cell where Al reacts with several entities, forming complexes with organic acids (Foy, 1988; Taylor, 1988), or proteins or other compounds (Suhayda and Haug, 1995). The exclusion strategy involves deterrence of Al from penetrating into the cell and this is achieved through immobilisation or neutralisation of the toxic ions within the rhizosphere (Kochian, 1995; Samac and Tesfaye, 2003). Inactivation of Al already within the plant tissues, specifically in the cytoplasm or in the vacuoles, is important, since it prevents its toxic effects on cellular processes. The Al exclusion and symplastic mechanism is well documented (Yang et al., 2011; Bojorquez-Quintas et al., 2017) and is considered an important mechanism for Al tolerance in maize (Kochian et al., 2015; Delhaize and Ryan, 1995). Plants that harbour Al exclusion capacity as a defence mechanism are known to have the ability to excrete organic acids and phenolics from their root apex (Pellet et al., 1995; Zheng et al., 1998; Kochian et al., 2004a) and others release chelating compounds in the rhizosphere environment, which form non-toxic compounds with Al, and as result, avoiding entry of this toxic element into cells (Kaonga, 2015).

Physiological, molecular and biochemical studies by Levesque-Tremblay et al. (2015), Zhang et al. (2016) and Bojorquez-Quintal et al. (2017) demonstrated that the modification of cell wall composition imparts resistance to Al toxicity in some genotypes. On the other hand, organic acids, especially citrate and malate, form stable complexes with Al^{3+} ions in the rhizosphere, thereby reducing its toxic effects in the root system (Kochian et al., 2004a; 2004b).

2.8 Breeding for acid soil tolerance in maize

Maize grain yield reduction in acid soils was reported to vary from 2.8 to 71% (Dewi-Hayati et al., 2014), and in a separate study, yield reductions of up to 69% were recorded (Tandzi et al., 2015a). The variation identified in grain yield reductions under acid soils can be explained either by the level of acidity in the soil; the agro-climatic conditions of the environment; or the genetic potential of maize genotypes. Improving grain yield performance under acid soil conditions is a major goal of maize breeding programmes in many regions of the world. Some progress has been made in maize breeding for tolerance to acid soils. For example, grain yield improvements of some maize genotypes were observed under acidic soils in Latin America and Asia and Cameroon (Pandey et al., 1994; Thé et al., 2006b). Tolerance to mineral elements can be defined as the ability of a plant to grow better, produce dry matter, develop fewer deficiency symptoms when grown at low or toxic levels of the mineral element, and give better yield (Graham et al., 2002; Hacisalihoglu and Kochian, 2003). Genetic variability for tolerance to low soil pH exists among maize genotypes, hence can be exploited in developing high-yielding, acid-tolerant maize genotypes (Tandzi et al., 2015b).

Conventional breeding, based on testcross data, has been widely used to estimate heterosis between populations or inbred lines, and used to assign inbreds to heterotic groups (Menkir et al., 2004; Welcker et al., 2005; Thé et al., 2006b; Badu-Apraku et al., 2013; Qurban et al., 2014; Tandzi et al., 2015b). Furthermore, combining ability analyses assesses the potential value of inbred lines and identifies the nature of gene action controlling various quantitative characters. This information is essential for maize breeding focusing on developing hybrids, synthetics, and improved open pollinated varieties adapted to acid soil conditions (Gowda et al., 2013).

2.8.1 Secondary traits related to yield under acid soil condition in maize

Identification of secondary traits is very useful in breeding maize for tolerance to acid soils due to their correlations with yield. Since yield is mostly controlled by non-additive gene action, secondary traits could be used as indirect predictors of yield in acid soil environments. In addition, secondary traits can also be useful for the genotypic characterization of plants in response to low soil pH stress.

Several studies have pointed to traits that could possibly be used as secondary traits for grain under acid soils. For instance, Welcker (2000) found leaf area and photosynthetic rate as highly and positively correlated with grain yield. On the other hand, studies by Thé et al. (2006a) and Welcker (2000) showed seminal root length which was measured at the 4^{th} leaf stage, to be the most sensitive trait for tolerance to low pH under laboratory conditions. Elsewhere, relative net root growth (RNRG) was found to be able to predict field performance under Al toxic soil conditions (Ouma et al., 2013).

2.8.2 Heterotic patterns groups

One of the most important limiting factors, which is a bottleneck in any breeding programme for yield improvement, is a narrow genetic base (Meena et al., 2017). Information on genetic diversity and heterotic groups is very useful in inbred line development. It helps breeders to utilize their germplasm in a more efficient and consistent manner through exploitation of complementary lines for maximization of outcomes of a hybrid development programme. Therefore, for any maize breeding programme to be successful, classification of elite germplasm and inbred lines into heterotic groups should always be at the centre of a breeding strategy (Hallauer et al., 1998).

The concept of heterotic patterns includes the subdivision of the germplasm available in a hybrid breeding programme into at least two divergent populations, which are improved with inter-population selection methods. Two populations of a specific heterotic pattern are typically improved as follows: the progenies are generated within the same heterotic pool; these progenies are then evaluated for their yield performance when test-crossed with a tester from the opposite heterotic pool. Lines showing superior test-cross performance are inter-mated to form the next cycle of selection. Heterosis has been extensively studied in maize because of its expression for grain yield; its intensive exploitation in hybrid breeding of maize; and the ease of both self and controlled cross-fertilization.

Shull (1908; 1909) conducted experiments on heterosis and inbreeding. Result of these experiments provided the origin of the pure-line hybrid concept. They observed that when maize plants are selfed, their vigour and grain yield decline rapidly. However, when two inbred lines are crossed, both vigour and grain yield of the F_1 hybrid often exceeds the mean of the two parents (i.e., heterosis). To exploit heterosis in hybrid breeding, the concept of heterotic groups and patterns was suggested. Heterotic groups consist of related or unrelated genotypes from the same or different populations, which display a similar combining ability and heterotic response when crossed with genotypes from other genetically distinct germplasm groups. Heterotic pattern is a specific pair of two heterotic groups, which may be populations or lines that express in their crosses high heterosis, and consequently high hybrid performance.
Various methods to develop heterotic groups were previously described. Quantitative genetic analysis was widely used to classify and identify heterotic groups (Moreno-Gonzalez et al., 1988; Ordas, 1991; Melchinger, 1999; Vasal, 1999). In other studies, methods such as the geographical isolation inference (Moll et al., 1965), molecular markers (Camussi et al., 1985; Hoisington et al., 1994; Yu et al., 2000; Mohammadi and Prasanna, 2003; Badu-Apraku et al., 2006; 2013) were also exploited.

From the evaluation of tropical maize germplasm, several promising heterotic patterns have been described by Wellhausen (1978), Goodman (1985) and Vasal (1999). These include Tuxpeno, N3, Kitale II, Pool 9A, ETO, Eucador 573, SC, Cuban Flint, Caribbean Flint, Katumani, K64R, Tiko, and Suwan. Maize programme in Angola uses the herotic grouping A and B, based on CIMMYT heterotic group standard

2.8.3 Combining ability and heritability of maize genotypes for tolerance to soil acidity

All breeding programmes focus on distinguishing lines that can be used in future crosses as parents and determining the best performing lines for commercial use (Fasahat et al., 2016). Sprague and Tatum (1942) introduced the concept of combining ability and its mathematical model was set by Griffing (1956). Combining ability analysis is the procedure used by plant breeders to identify the best performing lines and to make decisions on the lines that can be used as parents in future crosses.

Kambel and Webster (1965) defined combining ability as the performance of a line in a cross. Some recent studies explained combining ability as the ability of parental lines to combine among each other during the hybridization process such that desirable genes or characters are transmitted to their progenies (Singh et al., 2013; Fasahat et al., 2016). There are two types of combining ability: general (GCA) and specific combining ability (SCA). SCA is the interaction of genes of two parents involved in a cross with a specific inbred in relation to its contributions in crosses with an array of other inbred lines. It relates to non-additive gene effects and is dependent on how genes from each inbred complement those from the other inbred (Sprague and Tatum, 1942). GCA refers to the average performance of a given genotype or parent in a series of hybrid combinations. GCA measures the additive effect while SCA measure dominant and interaction effects (Kulembeka et al., 2012).

GCA is used in selection of parents based on their progeny performance, commonly in the F_1 generation, though it can be used in later generations as well. Low GCA values (positive or negative) show that the mean of a particular inbred line, when crossed with all the parents, deviates very little from the grand mean of all the crosses that would have been made. On the other hand, a high GCA value (negative or positive) tells the breeder that the mean of the parent is superior or inferior to the grand mean of all crosses, which shows evidence of a high intensity gene flow from the parents to the offspring (Franco et al., 2001). SCA evaluates the non-additive gene action and is used in the identification of superior hybrids. GCA is considered more important than SCA, but they are used together in breeding programmes (Hallauer et al., 2010), but parental choices based on SCA effects have limited value in breeding programmes.

Combining ability analyses are usually used in maize breeding programmes to obtain GCA and SCA information from a population for genetic diversity evaluation, hybrid development, heterosis estimation, inbred line selection and heterotic pattern classification (Fan et al., 2008). In order to assess the potential of an inbred line as well as to identifying the nature of gene action involved in various quantitative characters, combining ability remains a viable option for breeders (Gowda et al., 2013; Singh et al., 2013). All this information is valuable to plant breeders to formulate an efficient hybrid breeding programme. Information on the genetic structure and mode of inheritance of different characteristics helps breeders to employ appropriate breeding procedures for improvement of these characteristics (Kambe et al., 2013).

Genetic effects for maize tolerance to soil acidity were reported previously. Studies revealed the importance of both additive and non-additive gene effects for yield and yield components under acid soil environments (Borrero et al., 1995; Salazar et al., 1997; Welcker, 2000; Kwena, 2008). Some studies using F_1 progenies showed the importance of both additive and non-additive gene actions, but with a predominance of non-additive effects (Magnavaca et al., 1987; Pandey et al., 1994; Borrero et al., 1995; Thé et al., 2007). Ceballos et al. (1998) reported that epistasis accounted for the highest proportion of the total variability (from total sum of squares) in maize populations evaluated under acid soil conditions. Furthermore, tolerance to Al toxicity was noted in some maize hybrids growing under acid soil conditions and the tolerance was shown to be controlled by additive as well as non-additive gene effects, with a predominance of additive effects (Magnavaca et al., 1987; Lima et al., 1992; Duque-Vargas et al., 1994; Borrero et al., 1995; Thé et al., 2007; Tekeu et al., 2015; Petmi et al., 2016). Other studies observed a greater contribution of non-additive than additive gene effects in tolerance exhibited by some single-cross maize hybrids to Mn toxicity (Tekeu et al., 2015; Petmi et al., 2016). At Nkolbisson in Cameroon, where acid soils contain high levels of Mn, additive genes effects were more important that non-additive gene effects in determining Mn tolerance (Qurban et al., 2014).

2.8.4 Mating designs in maize breeding

Mating designs can be defined as procedures or protocols that are followed in producing progenies. Plant breeders and geneticists, theoretically and practically, use different mating designs and arrangements, depending on the desired set objectives (Nduwumuremyi et al., 2013). Mating designs are important because they (i) provide information about the genetic control of the characters under investigation; ii) help in the generation of breeding populations to be used as a basis for selection and development of potential varieties; iii) provide estimates of genetic gain; and, iv) also provide information on performance of parents used in the breeding programme (Acquaah, 2012). After a well-defined hybridization programme, breeders will be concerned about getting answers related to the significance of the genetic variation among the available genotypes and of the available variation, the extent to which the traits are heritable, as well as understanding the type of gene action affecting the most important traits (Kearsey and Pooni, 1996). In addition, the breeder will also be interested in determining the breeding value of the genotypes (inbred lines). Breeding value of a genotype can be defined as its superiority, judged by the performance of its progeny. The best inbred lines are selected based on combining ability effects as well as better mean performance (Nduwumuremyi et al., 2013).

Choosing of a suitable mating design for selection and identification of the best inbred lines depends on various considerations. Acquaah (2012) and Nduwumuremyi et al. (2013) highlighted some of the points to be considered in selection of an appropriate mating design and these include: (i) the type of pollination (self- or cross-pollinated); (ii) the type of crossing to be used (artificial or natural); (iii) the type of pollen dissemination (wind or insect); (iv) the presence of a male-sterility system; (v) the purpose of the project (for breeding or genetic studies); and (vi) the size of the population required. But as a general guide, the choice of a mating design for estimating genetic variances is determined by the objectives of the study, time, space, cost and other biological limitations (Nduwumuremyi et al., 2013). There are several studies that have been done that described and contrasted different mating designs. They considered at least six mating designs including bi-parental progenies, polycross, topcross, North Carolina (I, II, III), diallel (I, II, III, IV) and line x tester design, which are commonly used in maize breeding (Griffing, 1956; Kearsey and Pooni, 1998; Hallauer et al., 2010; Acquaah, 2012).

The diallel mating design is the most popular with many plant breeders, but it requires extensive labour, although more information about combining ability is obtained. Apart from the diallel design, the North Carolina designs, particularly design II (NCDII) as well as the line x tester (LxT) design, where each member of a group of parents which is used as males is mated to each member of another group of parents used as females, are also very commonly used by maize breeders (Comstock and Robinson, 1952; Acquaah, 2012; Nduwumuremyi et al., 2013). For both NCII and LxT designs, variation is partitioned into males (m) (i.e., testers) and females (f) (i.e., lines) and their interactions (i.e., line x tester interaction). Analysis of the NCDII or LxT crosses provide estimates of both GCA and SCA effects (Comstock and Robinson, 1948). For its simplicity and estimating the combing ability of parents and gene effects, L x T was used in current study

2.9 Other areas that require urgent attention in maize breeding research in Angola

2.9.1 Diseases and pests

Apart from abiotic stress factors, biotic stresses, such as parasitic weeds (Lagoke et al., 1991; Runo et al., 2012), foliar and cob rot diseases (Gressel et al., 2004) and insect pests (Tefera et al., 2011) also cause significant yield losses. Recently, fall armyworm (FAW), *Spodoptera frugiperda* (Lepidoptera: Noctuidae), one of the new migratory pests, has become the most important maize pest in SSA, with Angola not being an exception (Figure 2.1; Goergen et al., 2016, Cock et al., 2017). FAW, a polyphagous pest, affects not only maize, but can feast on over 80 other crop species (Day et al., 2017). The insect pest is native to the Americas, and was first confirmed in West Africa in early 2016 (Goergen et al., 2016; Cock et al., 2017) and has since spread across of some african countries where it is significantly affecting crop yields. Although application of insecticides is commonly used to control this devastating pest, this is not always effective (Fatoretto et al., 2017). Through development of maize varieties resistant to FAW, the devastating effects of this pest on maize can be reduced in Angola as well as in the region. Diseases in Angola are not different from those targeted in SSA, and these include maize lethal necrosis disease (MLN), maize streak virus (MSV), grey leaf spot (GLS), and rust and leaf blight (ET). On the other hand, the parasitic weeds, *Striga asiatica*, which is predominant in the central plateau of Angola (Dovala, 2014) and *Striga hermothica*, will also need to be monitored closely.

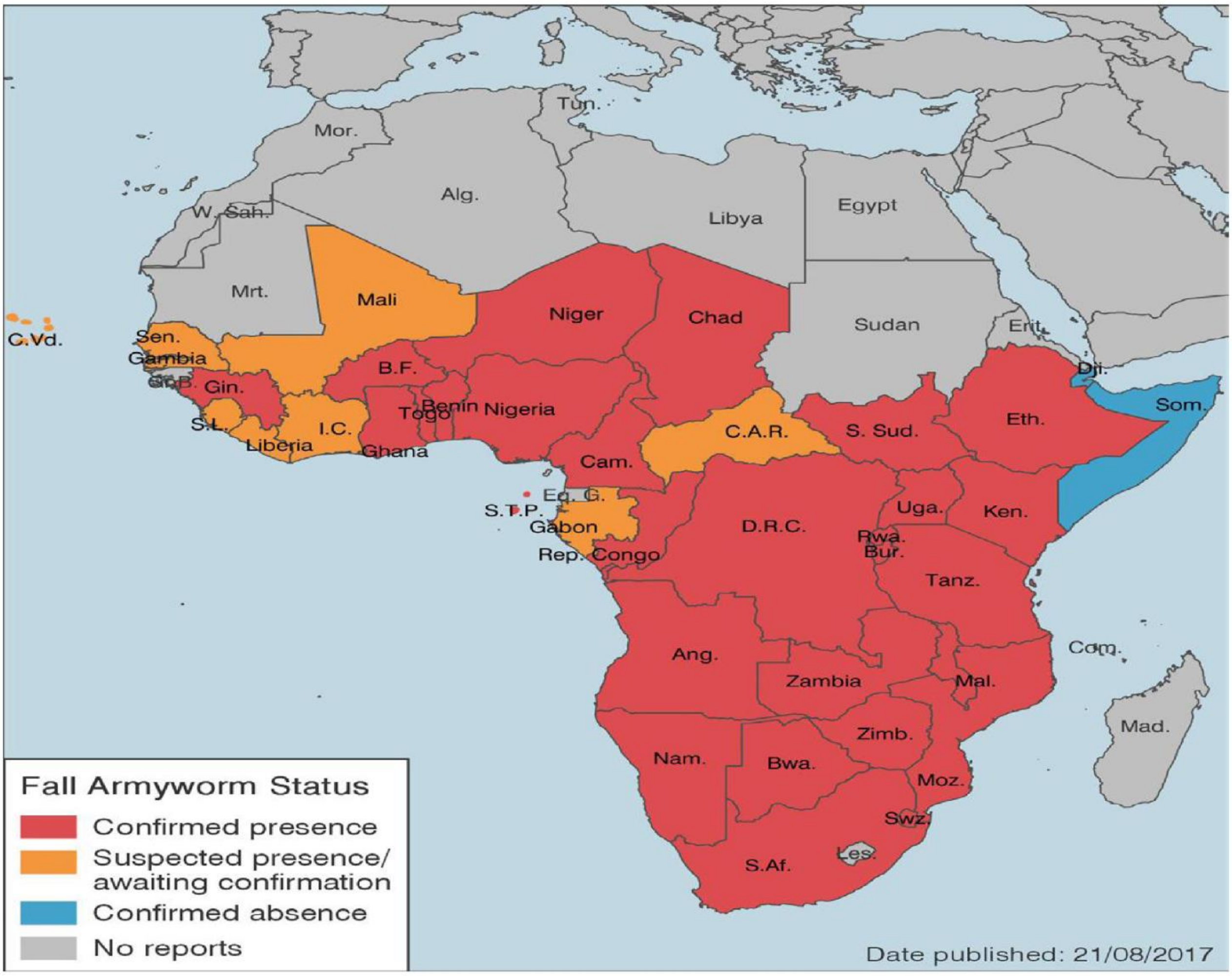

Figure 2.1 Map of current fall armyworm distribution in Africa (Day et al., 2017)

2.8.2 Biofortification for enhanced nutrition security

Nutritional insecurity is a major challenge in most low-income countries globally (Black et al., 2013; Kondwakwenda et al., 2018). At least 44% of the Angolan population suffer from malnutrition, with vitamin A deficiency being one of the major public health problems affecting mostly children under five years and women of reproductive age (FAO, IFAD, UNICEF, WFP, and WHO, 2017; Wirth et al/. 2017; MINAGRIP, 2020). Vitamin A deficiency can result in morbidity, loss of vision or blindness, and even death (Maru, 2017). According to With et al., 2017, 64.3% of Angolan population face vitamin A deficiency. Angola harbours a significant number of people that favour yellow maize over white maize. Developing and releasing biofortified provitamin A maize genotypes (with yellow-orange kernels) can be a viable option in this country, since market resistance is likely to be low. Provitamin A maize contains vitamin A precursors (provitamin A) in the form of carotenoids (Wurtzel et al., 2012). Provitamin A biofortification is the process of increasing the provitamin A density in maize kernels through conventional breeding and/or biotechnology (Kondwakwenda et al., 2018).

Other nutrients in maize are essential amino acids such as lysine and tryptophan, and minerals such as zinc, iodine and iron (Figure 2.2). Nearly a third of the Southern African population is exposed to the risk of nutritional insecurity (Figure 2.3), because their diets are dominated by maize, which is very rich in carbohydrates but poor in the other essential macro- and micro-nutrients required for normal body functioning (World Health Organization, 2009). Research on quality protein maize (QPM) has shown good results in SSA where protein deficiency is prevalent. QPM has twice the amount of the essential amino acids; lysine and tryptophan compared to conventional maize, and has been developed to reduce human malnutrition in various parts of SSA (Krivanek et al., 2007).

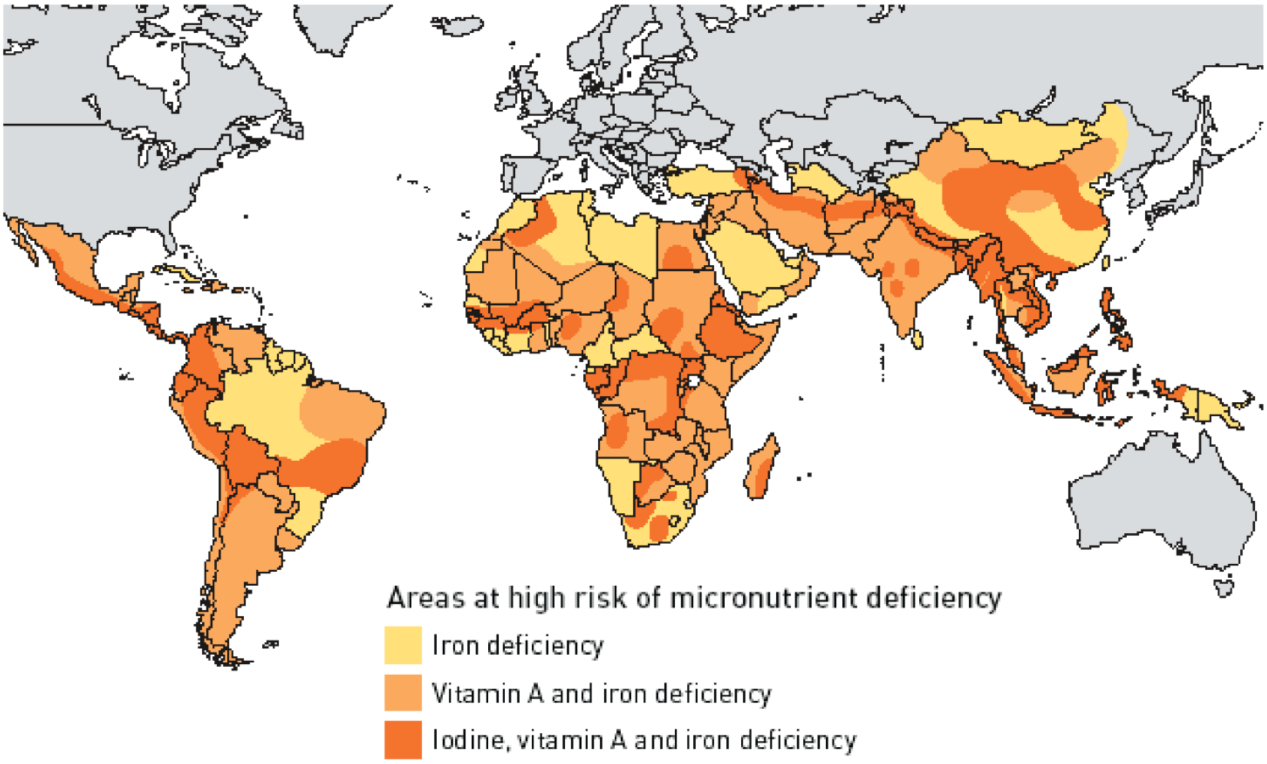

Figure 2.2 Widespread micronutrient deficiencies in developing countries (Bhutta et al., 2013)

On another note, maize varieties enhanced with Zn and Fe are still under development within the CIMMYT and International Institute of Tropical Agriculture (IITA) maize breeding programmes. The establishment of breeding programmes for nutrient enhancement is key in Angola, going forward, since its people are also at risk from malnutrition challenges.

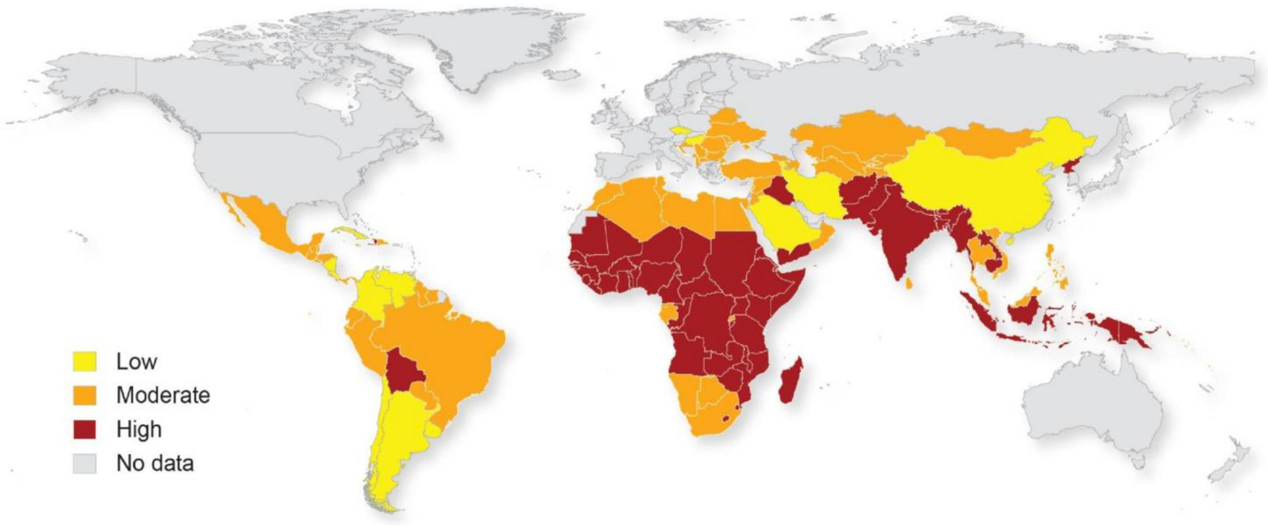

Figure 2.3 Severity of the most common micronutrient deficiencies (http://www.harvestplus.org)

2.10 Conclusions

Maize is a key food security crop in Angola, but its production is limited mostly by soil acidity, which is a common feature in most of the maize production environments. Although agronomic measures such as the use of lime may improve maize productivity in this country, this solution is not sustainable as most of the farmers are subsistent with limited access to resources. Since genetic variation exists in maize for adaptation to various stress factors, including soil acidity, a breeding programme should be developed in order to develop varieties that can produce reasonable yields under the maize production environments of Angola. Apart from soil acidity tolerance breeding, FAW and biofortification need to be considered in maize breeding strategies in Angola.

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CHAPTER 3

COMBINING ABILITY AND GRAIN YIELD STABILITY OF CIMMYT-ZIMBABWE YELLOW ELITE INBRED LINES WITH CIMMYT-COLOMBIA ACID TOLERANCE DONOR YELLOW LINES UNDER ACID AND NON-ACID SOIL CONDITIONS

Abstract

Acid soil is one of the most important constraints to maize production in Angola. This study was conducted to assess the general (GCA) and specific combining ability (SCA). Four yellow acid soil tolerant lines from CIMMYT-Colombia were crossed with ten yellow elite lines adapted to the mid-altitude climatic conditions from CIMMYT-Zimbabwe, to identify donor lines, which can be potential sources of acid tolerance genes in breeding programmes in Angola and elsewhere within the mid-altitude climatic zone. The two groups of parents were crossed using a line by tester design. The 36 single cross hybrids were evaluated during the 2014 - 2016 cropping seasons at nine sites (six with acid soils and three with non-acid soils) in Angola and Zimbabwe. There was a highly significant ($p<0.001$) genotype effect for grain yield performance across all environments. Under acid soil conditions, the effects of the genotype and GCA were highly significant ($p<0.001$), whereas non-significant SCA effects for grain yield were observed. The experimental hybrids CH142464 (ZY2 x CY3) and CH142447 (ZY2 x CY1) were the best hybrid combinations under acid and non-acid soil conditions, respectively. Combining ability analysis (GCA and SCA) and Best Linear Unbiased Estimators (BLUEs) identified the best yellow specific combiners for grain yield performance under acid soil as crosses ZY10 x CY3, ZY1 x CY1 and ZY4 x CY4. Beside check 5 hybrid, which was ranked as the highest yielding and most stable genotype, the experimental hybrids CH142442 (ZY7 x CY1), CH142464 (ZY2 x CY3) and CH142444 (ZY3 x CY1) were more stable and high yielding than most of the other checks. Under non-acid conditions, hybrid CH142447 (ZY2 x CY1) was the highest yielding and stable. CY3 and CY1 were the best acid tolerant inbred line donors and identified as the potential donors to use in the breeding programme

Keywords: Acid soil, maize, combining ability, genotype, acid soil tolerance

3.1 Introduction

Angola can be classified into two major maize product profiles based on taste preferences. Almost half of the population prefers yellow maize while the other half prefers white maize. These differences are usually based on custom and eating habits. Although acid soil is the most critical abiotic stress factor constraining maize productivity in Angola, breeding programmes focussing on acid soil tolerance should aim to develop varieties that are acceptable to these two distinct groups of people.

With this in mind, exotic yellow acid donor inbred lines were sourced from CIMMYT-Colombia, which needed to be assessed for their combining ability with germplasm adapted to the mid-altitude climatic conditions, under acid and non-acid conditions in Angola. The majority of countries in eastern and southern Africa are classified in this mega-environment, hence germplasm selected anywhere within this climatic zone can potentially do well in any other location within the zone (Chapman et al., 2003; Abate et al., 2013). Additionally, stability of the corresponding single-cross hybrids between the yellow acid donor lines and the elite yellow mid-altitude adapted lines under acid and non-acid conditions remains unexplored. Assessing the combining ability (both the GCA and the SCA) between these two groups of parental lines, will help in identifying acid tolerant donor lines that can be potential sources of acid tolerance genes in breeding programmes in Angola and elsewhere within the mid-altitude climatic zone. Also, potential crosses that can be used as pedigree starting populations for developing new inbred lines adapted to soil acidity and other stress factors common in Angola, can be identified. On the other hand, stability analysis will help in assessing and identifying crosses that can be targeted for commercial release.

Therefore, the specific objectives of this study were: (i) to identify acid donor lines from CIMMYT-Colombia that can potentially improve adaptation of mid-altitude adapted CIMMYT-Zimbabwe maize germplasm under acid conditions and non-acid conditions in Angola; and, (ii) to identify high yielding CIMMYT-Zimbabwe x CIMMYT-Colombia hybrids with stable grain yield performance under acid and non-acid conditions in Angola.

The hypothesis is that the yellow donor lines from CIMMYT-Colombia can improve maize productivity under acid and non-acid soil conditions in Angola.

3.2 Materials and methods

3.2.1 Germplasm description and F_1 formation

Ten elite yellow lines adapted to the mid-altitude climatic conditions were sourced from CIMMYT-Zimbabwe. Four were classified into heterotic group A and the other six into heterotic group B. These were crossed with three heterotic group A and one heterotic group B yellow donor lines sourced from the CIMMYT-Colombia breeding programme (Table 3.1), using a LxT design. Crossing nurseries were planted in Muzarabani in Zimbabwe (latitude 16°19’60 S, longitude 31°10 0 E) during the winter season of the year 2014. Hand pollinations were performed. The LxT nursery yielded a total of 40 F_1s, but four of them were discarded because they had insufficient seed for at least nine locations (Table 3.2).

Table 3.1 Mid-altitude adapted yellow inbred lines used as female parents in a line x tester design with yellow acid tolerant donor lines as testers

#	Code	Origin	Parental category	Heterotic group
Lines				
1	ZY1	Zimbabwe	Line	B
2	ZY2	Zimbabwe	Line	B
3	ZY3	Zimbabwe	Line	B
4	ZY4	Zimbabwe	Line	B
5	ZY5	Zimbabwe	Line	B
6	ZY6	Zimbabwe	Line	B
7	ZY7	Zimbabwe	Line	A
8	ZY8	Zimbabwe	Line	A
9	ZY9	Zimbabwe	Line	A
10	ZY10	Zimbabwe	Line	B
Testers				
11	CY1	Colombia	Tester	A
12	CY2	Colombia	Tester	A
13	CY3	Colombia	Tester	A
14	CY4	Colombia	Tester	B

Table 3.2 Line x tester F_1s developed in a nursery established in Muzarabani during the 2014 winter season in Zimbabwe

Entry	Cross	Name	Entry	Cross	Name
1	ZY5 x CY2	CH142431	19	ZY6 x CY1	CH142449
2	ZY7 x CY2	CH142432	20	ZY9 x CY1	CH142450
3	ZY8 x CY2	CH142433	21	ZY5 x CY4	CH142451
4	ZY3 x CY2	CH142434	22	ZY7 x CY4	CH142452
5	ZY4 x CY2	CH142435	23	ZY8 x CY4	CH142453
6	ZY1 x CY2	CH142436	24	ZY3 x CY4	CH142454
7	ZY2 x CY2	CH142437	25	ZY4 x CY4	CH142455
8	ZY10 x CY2	CH142438	26	ZY1 x CY4	CH142456
9	ZY6 x CY2	CH142439	27	ZY2 x CY4	CH142457
10	ZY9 x CY2	CH142440	28	ZY6 x CY4	CH142458
11	ZY5x CY1	CH142441	29	ZY5 x CY3	CH142459
12	ZY7 x CY1	CH142442	30	ZY7 x CY3	CH142460
13	ZY8 x CY1	CH142443	31	ZY3 x CY3	CH142461
14	ZY3 x CY1	CH142444	32	ZY4 x CY3	CH142462
15	ZY4 x CY1	CH142445	33	ZY1 x CY3	CH142463
16	ZY1x CY1	CH142446	34	ZY2 x CY3	CH142464
17	ZY2 x CY1	CH142447	35	ZY10 x CY3	CH142465
18	ZY10 x CY1	CH142448	36	ZY6 x CY3	CH142466

3.2.2 Hybrid evaluation and description of the sites

The 36 LxT hybrids which had sufficient seed, were evaluated alongside six acid tolerant commercial check hybrids at nine locations in Angola and Zimbabwe (Table 3.3), thereby making up a total of 42 hybrids per trial. Trials were established during the 2014-2016 cropping seasons under acid and non-acid soil conditions. Sites with sandy soils, but with a historic record of receiving normal to above normal rains, and those known to be acid (such as low P and low pH) were chosen as acid soil sites. On the other hand, optimal and random stress sites were classified as non-acid sites. Briefly, low P sites were those where non-leguminous crops were repeatedly grown without use of phosphate fertilizers, and crop residues were removed from the field immediately after harvesting. Optimal sites were those where the crop was subjected to all the recommended agronomic measures including fertilization and supplemental irrigation during water-deficit periods. These sites also occurred naturally in environments where the climatic conditions are suitable for maize production. The random stress sites were those where chances of mid-season drought were close to 100% during the rainy season and if drought occurred, no supplemental irrigation was given. These sites represented the real conditions to which maize is subjected in the small-scale farming sector, where most of the crop production is done in many countries in Africa.

Soil sampling was done at the beginning of the experiments. Samples were collected using the Horneck et al. (2011) method, from the top 30 cm of the soil profile at all the nine sites. Six soil samples were collected per site, and were bulked. A representative sub-sample from the bulked four samples collected in Angola was taken and submitted for chemical analysis at the Chianga Experimental Station soil laboratory of the Agricultural Research Institute (IIA). Similarly, representative samples from five bulk samples gathered in Zimbabwe were analysed. Samples were analysed for pH and available P, K, Ca and Mg (Table 3.3).

3.2.3 Experimental design and trial management

The 42 yellow hybrids (Appendix 3.1) were laid out at each of the nine sites in Angola and Zimbabwe using an alpha (0,1) lattice design (Patterson and Williams, 1976) with two replications at each site. Each replication accommodated seven incomplete blocks, with each incomplete block containing six hybrids. Randomization was done differently across replications and across sites. Each hybrid was planted in a single row plot of 4 m length, having a uniform inter- and intra-row spacing of 0.75 m and 0.25 m, respectively. Two seeds were hand-planted on each hill, and the trials were later thinned to one plant on each planting station, 3-5 weeks after crop emergence, in order to have an optimum plant population of 53,333 plants per hectare. Border rows were planted to avoid border effects. A total of 400 kg ha^{-1} of Compound D (N_{12} P_{24} K_{12}) was applied as basal dressing and 250 kg ha^{-1} of urea (NH_2; N = 46 %) was split-applied as top-dressing fertilizer at all sites in Angola. In Zimbabwe, the same quantity of 400 kg ha^{-1} of compound D (N_7 P_{14} K_7) was applied as basal dressing at most of the sites, except for the low P site. Ammonium nitrate (N = 34.5%) was split-applied as top-dressing at a rate of 400 kg ha^{-1} at the sites used in Zimbabwe.

Table 3.3 Climatic, geographical and soil chemical characteristics of the top 30 cm of the soil profile at nine sites in Angola and Zimbabwe, used to evaluate 42 yellow hybrids during the 2014-2016 cropping seasons

Parameter	Angola				Zimbabwe			
	Chianga 1&2	SEDIAC	Chianga	Alto-Kapaka	CIMMYT Harare1	CIMMYT Harare2	Chibero	Marondera
	Low pH	Random stress	Optimal	Random stress	Optimal	Low P	Sandy soil	Sandy soil
Classification	Acid	Non-acid	Non-acid	Non-acid	Non-acid	Acid	Acid	Acid
Geographic Information System (GIS) position	S 12º44´27´´, E 15º49´36´´	S11º 19´44´´ E 14º 59´21´´	S 12º44´27´´, E 15º49´36´´	S 12º57´15´´ E14º25´45´´	S 17º438´, E 31º05´	S 17º438´, E 31º05´	S 18º40´ E 30º39´	S 18º10´, E 31º29´
Altitude (m.a.s.l)	1600	1400	1600	1300	1500	1500	1341	1617
Soil pH (H_2O)	4.75	5.90	6.05	5.76	5.80	5.40	-	5.10
Available P_2O_5 (ppm)	33.14	32.86	61.62	20.30	21.70	10.20	-	45.00
Potassium (ppm)	0.16	0.81	0.66	0.30	0.30	0.30	-	0.10
Calcium ($cmol_{(+)}$ kg^{-1})	0.20	4.42	3.19	1.37	8.10	5.10	-	1.00
Magnesium ($cmol_{(+)}$ kg^{-1})	0.09	0.62	2.36	0.74	3.80	2.50	-	0.50
Organic carbon (%)	1.20	1.99	2.89	1.51	Na	na		Na
Total N	0.07	0.14	0.22	0.09	Na	na		Na

Changa1&2 = Chianga 1 and Chianga 2, Soil pH < 5.1; strongly acidic, 5.2 – 6.0; moderately acidic, 6.1 -6.5 slightly acidic (Horneck et al., 2011)

3.2.4 Data collection

Data collection followed the CIMMYT (1985) standard procedures. Grain yield (GY), was measured on a whole plot basis. Shelled grain weight per plot was adjusted to 12.5% grain moisture and converted to ton per hectare using the following formula:

GY (t ha^{-1}) = [Grain weight (kg $plot^{-1}$) x 10 x (100-MC)/(100-15)/(plot area)],

where MC = grain moisture content
plot area = row length x 0.75 (4 x 0.75 = 3 m)

3.2.5 Statistical analysis

Across-site ANOVA was performed using the 'aov' function in the Agricolae R package. The treatments (crosses/hybrids) were considered as fixed

The model for combined ANOVA was:
$Y_{ij(k)(l)} = b_j(r_k)(E_l) + r_k(E_l) + g_i + E_l + gE_{(il)} + e_{ij(k)}(l)$

where $Y_{ij(k)(l)}$ is the response of the i^{th} genotype in the j^{th} incomplete block nested within the k^{th} replication nested in the l^{th} environment; $b_j r_{(k)} E_{(l)}$ is the effect of the j^{th} incomplete block nested in the k^{th} replication also nested in the l^{th} environment and j = 1, 2, 3, 4; $r_k(E_l)$ is the effect of the k^{th} replication nested in the l^{th} environment and k = 1, 2, 3; g_i is the effect of the i^{th} genotype and I = 1, 2, 3,...10; E_l is the effect of the l^{th} environment and l = 1, 2, 3,...6; $gE_{(il)}$ is the interaction effect of the i^{th} genotype and the l^{th} environment; and $e_{ij(k)(l)}$ is the random error term.

Broad-sense heritability estimates, best linear unbiased estimators (BLUPS), as well as genetic correlations between grain yield and the other agronomic traits were calculated using the Multi-Environment Trial Analysis with R (META-R) version 5.0 (Alvarado et al., 2015). Mean comparisons were performed using Fisher's Protected Least Significance Difference (LSD) (Little and Hills, 1978) at 5% significance level. Crosses of temperate by mid-altitude adapted inbred lines with superior grain yield performance, but harbouring other desirable agronomic traits that are of importance in the sub-tropical regions, were visualised on scatter plots using the 'ggplot' function in the ggplot2 R package (Wickham, 2016). Stability of the top performing temperate by tropical inbred lines, selected within the A- and B-heterotic groups, was assessed using ranking, and Genotype-Genotype x Environment (GGE) Biplot in the GenStat Software, 17^{th} Edition (Payne et al., 2009).

Preliminary data checking and individual site ANOVA were performed using CIMMYT Fieldbook software (Bänziger and Vivek, 2007). LxT analysis was performed for grain yield across the acid and non-acid sites, as well as for acid and non-acid sites, separately. The LxT procedures in the R software v3.0.1 (RDevelopmentCoreTeam, 2013), embedded in the CIMMYT Fieldbook software were followed. Briefly, the procedure uses functions in the lme4 (Chang, 2010; Bates et al., 2015; 2019), lattice (Deepayan, 2018) and matrix (Yau, 2016) R packages, to estimate GCA and SCA effects for lines and testers. The model for the combined sites LxT was as follows:

$$Y_{ijkp} = \mu + g_i + g_j + s_{ij} + E_p + r_k (E_p) + (gE)_{ip} + (gE)_{jp} + (sE)_{ijq} + e_{ijkp} \qquad (2)$$

where, i = 1, 2, 3, …10, j = 1, 2, 3,4, k = 1, 2, and Y_{ijkp} represented the value of the progeny of a mating of the i^{th} CIMMYT-Zimbabwe elite yellow inbred line (i.e., line), the j^{th} CIMMYT-Colombia yellow acid donor inbred line (i.e. tester), in the k^{th} replication, and in the p^{th} environment (site). The μ represents grand mean, g_i is the GCA effect common to all progeny of the i^{th} line, g_j is the GCA effect common to all progeny of the j^{th} tester, s_{ij} is the SCA effect specific to the progeny of mating the i^{th} line and the j^{th} tester, Ep is the average effect of the p^{th} environment, $r_k (E_p)$ is the effect of the k^{th} replication that was nested within the p^{th} environment, $(gE)_{ip}$ and $(gE)_{jp}$ are the interactions between the GCA effects and the environment, $(sE)_{ijq}$ is the interaction between the SCA effect and environment, and e_{ijkp} is the random experimental error. This model was adopted from Lee et al. (2005).

The BLUEs were calculated following the procedures of Puntanen and Styan (2011) and the broad-sense heritability (H^2) estimates were calculated using the Multi-Environment Trial Analysis with R (META-R) software v5.0 (Alvarado et al., 2015). The following model was used to calculate H^2:

$$H^2 = \left(\frac{\sigma^2 g}{\frac{\sigma^2 g}{re} + \frac{\sigma^2 ge}{e} + \sigma^2 p} \right) * 100$$

Where; $\sigma^2 g$ is genotypic variance, $\sigma^2 ge$ is genotype x environment variance, $\sigma^2 p$ is phenotypic variance, e represents sites and r represents the replications.

Mean comparisons were performed using the Fisher's Protected LSD (Little and Hills, 1978) at 5% significance level. To identify the best yielding, and stable genotypes across the acid sites and across the non-acid sites, a stability coefficient method known as superiority performance, which calculates cultivar superiority indices according to Lin and Binns (1988), was performed in GenStat Software, 17th Edition (Payne et al., 2009). GCA and SCA of CIMMYT Zimbabwe and

CIMMYT Colombia inbred lines involved in the highest grain yielding LxT crosses under acid, non-acid and across acid and non-acid sites, were visualized using a scatter plot. The most stable, but high yielding LxT crosses under acid and non-acid soil conditions were also visualized using a scatter plot. The scatter plots were graphed using the 'ggplot' function in the ggplot2 R package (Wickham, 2016).

3.3 Results

3.3.1 Hybrid grain yield performance under acid and non-acid soil conditions

Highly significant ($p < 0.001$) genotype effect for GY performance was noted across soil conditions (Tables 3.4 and 3.5). LxT analysis across acid soil sites revealed significant genotype and GCA effects of lines. Additive variance was more important than dominance variance, with genotypic variance also beeing more important than environmental variance. Across non-acid sites, LxT data showed significant ($p < 0.05$) genotype x site effects, and GCA of line x site effects for GY, apart from significant genotypic and GCA of line effects for GY. SCA effects for GY were also significant. Genotypic variance was less important than environmental variance, but additive variance was more important than dominance variance under the non-acid conditions. The L x T analysis results were similar for the acid and the non-acid conditions. Broad- and narrow-sense heritability estimates for GY were more than 50% under both the acid and non-acid soil conditions.

Table 3.4 Individual site analysis of variance for grain yield performance of the CIMMYT-Zimbabwe elite lines x CIMMYT-Colombia acid tolerance donor line hybrids evaluated across nine sites in Zimbabwe and Angola during the 2014-2016 cropping seasons

Location	Management	Soil type	GY (t ha^{-1})			Error variance	Genotype variance	Heritability	LSD
			Mean	Min	Max				0.05
CIMMYT Harare1	Optimal	Non-acid	8.93	0.48	14.19	2.08	3.87	0.79	2.83
CIMMYT Harare2	Low P	Acid	8.53	5.05	14.38	2.80	0.97**	0.41	3.28
Chibero	Sandy soil	Acid	2.47	0.13	7.11	0.70	0.70***	0.67	1.64
Marondera	Sandy soil	Acid	2.82	1.26	5.23	1.95	0.00	0.00	2.74
SEDIAC	Random stress	Non-acid	3.05	1.75	4.45	0.53	0.15	0.36	1.42
Chianga1	Low pH	Acid	4.57	1.64	6.87	1.56	0.36	0.32	2.45
Chianga3	Optimal	Non-acid	6.74	0.51	13.61	8.64	1.80***	0.29	5.76
Alto-Kapaca	Random stress	Non-acid	2.64	1.28	4.52	0.65	0.27**	0.46	1.59
Chianga2	Low pH	Acid	1.86	0.41	3.74	0.41	0.25	0.55	1.25

GY: Grain yield, Min: Minimum, Max: Maximum, LSD: Least significant difference, CV: Coefficient of variation, ***p<0.001, **p<0.01

Table 3.5 Grain yield combined analysis of variance of CIMMYT-Zimbabwe elite lines x CIMMYT-Colombia acid tolerance donor line F_1s, evaluated under acid and non-acid soil conditions in Angola and Zimbabwe

	Acid soil		Non-acid soil		Across acid and non-acid	
	DF	MS	DF	MS	DF	MS
Replication (Site)	5	7.41**	4	1.18	9	4.71*
Site	4	466.80***	3	518.53***	8	458.02***
Genotype	35	3.30**	35	7.85***	35	6.88***
GCA_{Line}	9	5.77***	9	12.14***	9	13.22***
GCA_{Tester}	3	4.02	3	3.63	3	5.10
SCA	23	2.38	23	5.80**	23	4.38**
Genotype x Site	131	1.52	97	4.27***	263	2.89**
GCA_{Line} x Site	36	1.71	27	8.08**	72	4.47***
GCA_{Tester} x Site	12	1.79	9	6.94	24	3.79
SCA x Site	83	1.35	61	2.49	167	2.11
Residuals	158	1.72	126	2.44	284	2.04
Line variance		0.03		0.11		0.13
Tester variance		1.50		0.00		0.001
Line x Tester variance		2.07		0.31		0.102
Genotypic variance		11.19*		0.34		0.22
Additive variance		44.78***		1.35*		0.88***
Dominance variance		8.26*		1.23*		0.41**
Environmental variance		0.00		0.57		0.16
Broad sense heritability		1.00		0.82		0.89
Narrow sense heritability		0.84		0.43		0.61
Grand mean		4.02		5.17		4.55
LSD		2.51		3.43		2.98
CV		31.92		33.84		33.37

***p<0.001, **p<0.01, *p<0.05, DF: degrees of freedom, MS: mean squares, LSD: least significant degree, CV: coefficient of variation

3.3.2 Grain yield performance of the CIMMYT-Zimbabwe elite lines x CIMMYT-Colombia acid tolerance donor line F1s in comparison with commercial checks under acid and non-acid soil conditions

Comparing the five highest yielding experimental hybrids with the highest yielding commercial check hybrids, the results showed the potential of the CIMMYT-Zimbabwe elite lines and the CIMMYT-Colombia acid tolerance donor lines to promote maize productivity under acid and non-acid soil conditions in Angola (Table 3.6 and Fig. 3.1). Firstly, it was interesting to note that the best five experimental hybrids yielded more than the five highest yielding commercial checks under both the acid (average $GY_{Experimental}$ = 4.81 t ha^{-1} > GY_{Checks} = 4.61 t ha^{-1}) and the non-acid soil conditions (average $GY_{Experimental}$ = 6.61 t ha^{-1} > GY_{Checks} = 6.46 t ha^{-1}). Similar trends were also observed for the hybrids selected across the acid and non-acid sites (average $GY_{Experimental}$ = 5.40 t ha^{-1} > GY_{Checks} = 5.31 t ha^{-1}). CIMMYT-Zimbabwe elite lines, ZY2 (GCA_{acid} = 0.17; $GCA_{non\text{-}acid}$ = 0.636; $GCA_{acid+non\text{-}acid}$ = 0.398), ZY1 (GCA_{acid} = 0.018; $GCA_{non\text{-}acid}$ = 0.636; $GCA_{acid+non\text{-}acid}$ = 0.318) and ZY3 (GCA_{acid} = 0.626; $GCA_{non\text{-}acid}$ = 0.68; $GCA_{acid+non\text{-}acid}$ = 0.66), were involved in the three highest grain yielding experimental hybrids under all conditions. The inbred line, ZY3, consistently showed the highest positive GCA effects for GY, and was involved as a parent in more than one cross among the five highest grain yielding experimental hybrids under all conditions (Table 3.6; Figure 3.1) and was ranked the best line under acid conditions and across acid and non-acid conditions (Appendix 3.1).

On the other hand, the CIMMYT-Colombia donor lines CY3 (GCA_{acid} = 0.143; $GCA_{non\text{-}acid}$ = -0.032; $GCA_{acid+non\text{-}acid}$ = 0.019) and CY1 (GCA_{acid} = 0.17; $GCA_{non\text{-}acid}$ = 0.053; $GCA_{acid+non\text{-}acid}$ = 0.114) were parents in the two highest grain yielding hybrids under all conditions (Table 3.6). More interestingly, the yellow acid donor line, CY1, was a parent in three of the five highest yielding hybrids under the acid soils and across the acid and non-acid conditions (Table 3.6; Figure 3.1) and was also ranked the best tester under the acid and across acid and non-acid conditions (Appendix 3.2). The CIMMYT-Zimbabwe elite inbred line, ZY8 was ranked the highest under non-acid conditions, whilst the CIMMYT-Colombia acid donor line, CY4, was ranked the best tester under non-acid conditions (Appendix 3.1 and 3.2).

The best specific combiners for GY performance under acid soil conditions were ZY10 x CY3 (Entry 35; SCA = 0.802, $BLUE_{GY}$ = 3.78 t ha^{-1}), ZY1 x CY1 (Entry 16; SCA = 0.645, $BLUE_{GY}$ = 4.86 t ha^{-1}) and ZY4 x CY4 (Entry 25; SCA = 0.545, $BLUE_{GY}$ = 4.32 t ha^{-1}). Under non-acid soil conditions, the best yellow specific combiners for GY performance were ZY6 x CY3 (Entry 36; SCA = 3.29, $BLUE_{GY}$ = 4.15 t ha^{-1}), ZY2 x CY1 (Entry 17; SCA = 1.44, $BLUE_{GY}$ = 7.01 t ha^{-1}) and ZY10 x CY3 (Entry 35 SCA = 1.05, $BLUE_{GY}$ = 4.76 t ha^{-1}). Lastly, across acid and non-acid conditions, the best specific combiners for GY were ZY6 x CY3 (Entry 36; SCA = 0.995, $BLUE_{GY}$ = 4.23 t ha^{-1}), ZY10 x CY3 (Entry 35; SCA = 0.927, $BLUE_{GY}$ = 4.19 t ha^{-1}) and ZY7 x CY1 (Entry 12; SCA = 0.586, $BLUE_{GY}$ = 5.27 t ha^{-1}) (Appendix 3.4 and 3.5).

3.3.3 Grain yield stability of the five highest grain yielding experimental hybrids and checks under acid and non-acid conditions

A check hybrid identified as Check 5 (Entry 41; BLUE_GY = 5.85 t ha^{-1}) was ranked as the highest yielding and stable genotype under acid conditions (Table 3.7 and Fig. 3.2). Experimental hybrids CH142442 (Cross = ZY7 x CY1; GY = 4.74 t ha^{-1}), CH142464 (Cross = ZY2 x CY3; GY = 5.05 t ha^{-1}), and CH142444 (Cross = ZY3 x CY1; GY = 4.65 t ha^{-1}) were more stable and high yielding than most of the other checks. Under non-acid conditions, the experimental genotype CH142447 (Cross = ZY2 x CY1; GY = 7.01 tha^{-1}) was the most stable and was slightly outperformed by the genotype Check 3 (Entry 38; GY = 7.15 t ha^{-1}), in terms of GY performance (Figure 3.2; Table 3.7).

Table 3.6 Grain yield performance of the top five yellow maize hybrids and their lines and testers compared to the top five check hybrids under acid and non-acid soil conditions and across the two conditions

#	Hybrid Name	Hybrid Type	Line	Tester	BLUE Grain yield	GCA Line	GCA Tester	SCA
					t ha^{-1}			
A. Acid soils								
34	CH142464	Experimental	ZY2	CY3	5.51	0.170	0.143	0.343
16	CH142446	Experimental	ZY1	CY1	4.86	0.018	0.170	0.645
24	CH142454	Experimental	ZY3	CY4	4.76	0.626	0.077	0.017
12	CH142442	Experimental	ZY7	CY1	4.74	0.093	0.170	0.456
14	CH142444	Experimental	ZY3	CY1	4.65	0.626	0.170	0.037
Average grain yield					**4.81**			
41	Check5	Check	–	–	5.85	–	–	–
42	Check6	Check	–	–	4.54	–	–	–
37	Check1	Check	–	–	4.28	–	–	–
38	Check2	Check	–	–	4.19	–	–	–
40	Check4	Check	–	–	4.18	–	–	–
Average grain yield					**4.61**			
B. Non-acid soils								
17	CH142447	Experimental	ZY2	CY1	7.01	0.636	0.053	1.439*
31	CH142461	Experimental	ZY3	CY3	6.65	0.680	-0.032	0.789
26	CH142456	Experimental	ZY1	CY4	6.53	0.636	0.075	0.532
4	CH142434	Experimental	ZY3	CY2	6.53	0.680	-0.032	0.579
3	CH142433	Experimental	ZY8	CY2	6.30	0.717	-0.032	0.313
Average grain yield					**6.61**			
39	Check3	Check	–	–	7.15	–	–	–
41	Check5	Check	–	–	6.77	–	–	–
38	Check2	Check	–	–	6.41	–	–	–
42	Check6	Check	–	–	6.40	–	–	–
37	Check1	Check	–	–	5.57	–	–	–
Average grain yield					**6.46**			
C. Across acid and non-acid soils								
31	CH142461	Experimental	ZY3	CY3	5.54	0.660	0.019	-0.147
17	CH142447	Experimental	ZY2	CY1	5.45	0.398	0.114	0.491
16	CH142446	Experimental	ZY1	CY1	5.41	0.318	0.114	0.383
4	CH142434	Experimental	ZY3	CY2	5.34	0.660	-0.206	0.288
12	CH142442	Experimental	ZY7	CY1	5.27	-0.021	0.114	0.586
Average grain yield					**5.40**			
Checks								
41	Check5	Check	–	–	6.26	–	–	–
42	Check6	Check	–	–	5.37	–	–	–
38	Check2	Check	–	–	5.19	–	–	–
39	Check3	Check	–	–	4.90	–	–	–
37	Check1	Check	–	–	4.85	–	–	–
Average grain yield					**5.31**			

* $p<0.05$, BLUE: best linear unbiased estimates

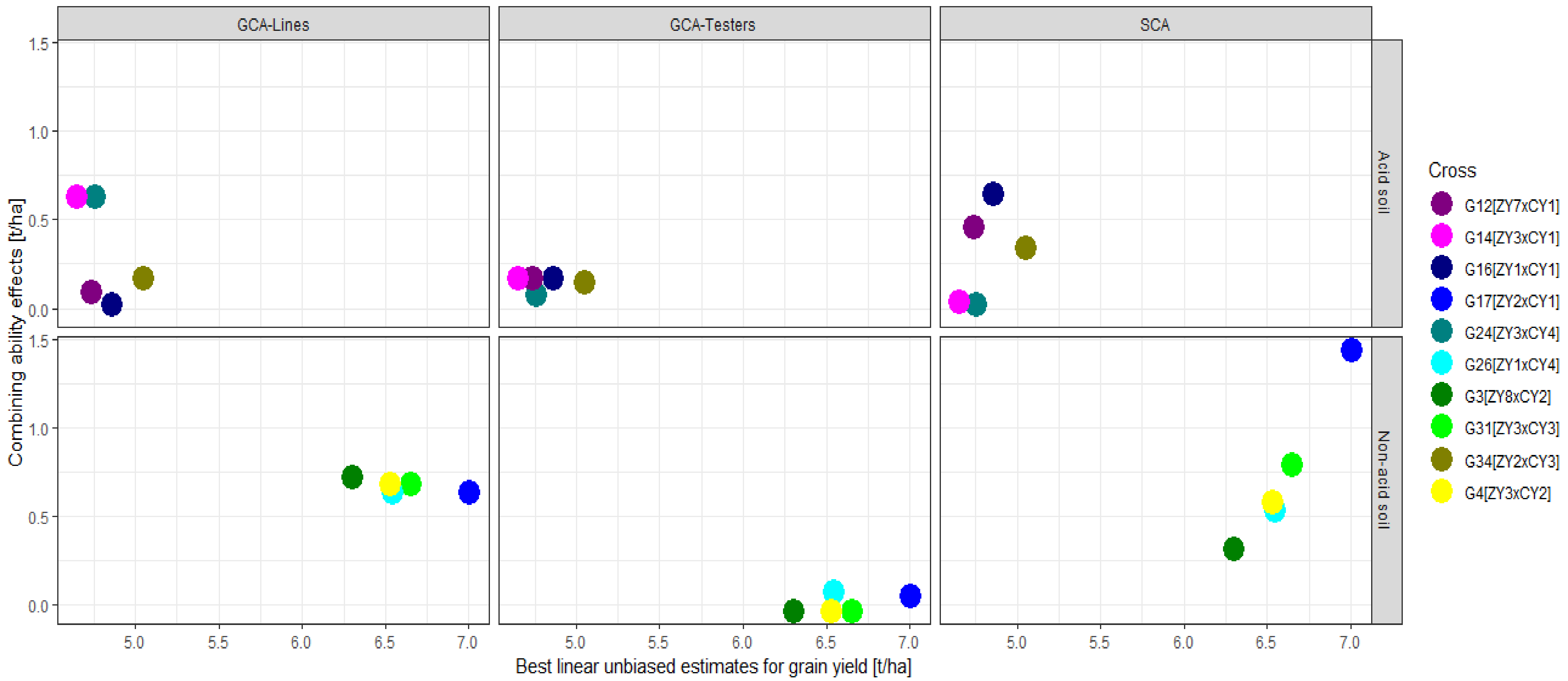

Figure 3.1 Best linear unbiased estimates for combining ability for grain yield performance (t ha^{-1}) of the top five experimental yellow maize hybrids under acid and non-acid soil conditions and across the two conditions

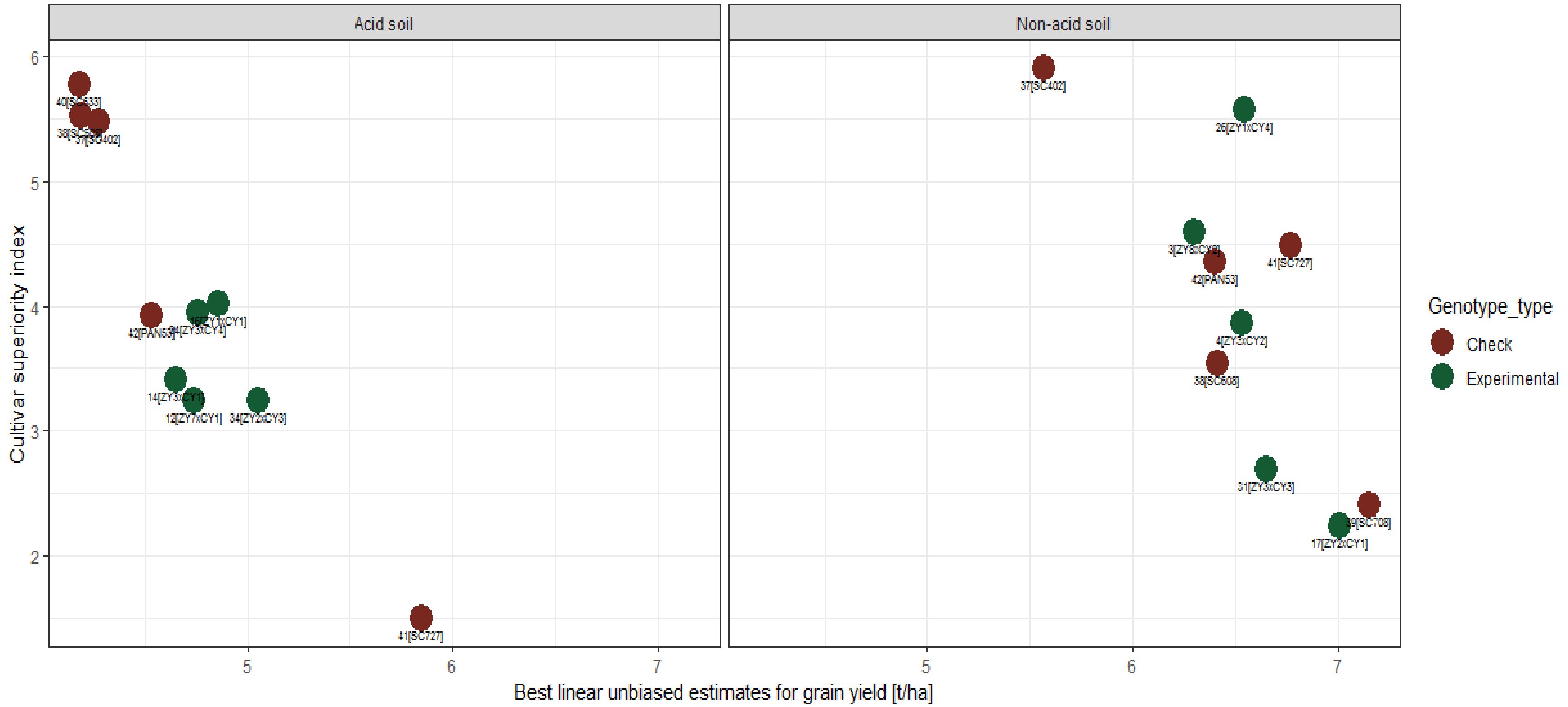

Figure 3.2 Cultivar superiority indices (CSI) of the top five experimental yellow maize hybrids and commercial check hybrids under acid and non-acid soil conditions

Table 3.7 Mean grain yield and cultivar stability indices of the top five experimental hybrids and commercial check hybrids under acid and non-acid soil conditions

Genotype					GY BLUE ($t\ ha^{-1}$)	CSI (1 = best)	Rank
Entry	Name	Cross	Type	Soil type			
12	CH142442	ZY7xCY1	Experimental	Acid soil	4.74	3.24	2
14	CH142444	ZY3xCY1	Experimental	Acid soil	4.65	3.42	4
16	CH142446	ZY1xCY1	Experimental	Acid soil	4.86	4.02	7
24	CH142454	ZY3xCY4	Experimental	Acid soil	4.76	3.94	6
34	CH142464	ZY2xCY3	Experimental	Acid soil	5.05	3.24	3
37	Check1	Check1	Check	Acid soil	4.28	5.47	13
38	Chek2	Chek2	Check	Acid soil	4.19	5.53	14
40	Check4	Check4	Check	Acid soil	4.18	5.77	16
41	Check5	Check5	Check	Acid soil	5.85	1.49	1
42	Check6	Check6	Check	Acid soil	4.54	3.92	5
3	CH142433	ZY8xCY2	Experimental	Non-acid soil	6.30	4.59	8
4	CH142434	ZY3xCY2	Experimental	Non-acid soil	6.53	3.86	5
17	CH142447	ZY2xCY1	Experimental	Non-acid soil	7.01	2.24	1
26	CH142456	ZY1xCY4	Experimental	Non-acid soil	6.55	5.57	10
31	CH142461	ZY3xCY3	Experimental	Non-acid soil	6.65	2.69	3
37	Check1	Check1	Check	Non-acid soil	5.57	5.91	12
38	Chek2	Chek2	Check	Non-acid soil	6.41	3.54	4
39	Check3	Check3	Check	Non-acid soil	7.15	2.41	2
41	Check5	Check5	Check	Non-acid soil	6.77	4.48	7
42	Check6	Check6	Check	Non-acid soil	6.40	4.36	6

GY: Grain yield, BLUE: best line unbiased estimate, CSI: cultivar stability indices

3.4 Discussion

Highly significant differences ($p<0.001$) among maize genotypes were evident, which indicates the presence of considerable variation within and among sites for genotype performance. High broad sense heritability (H^2) values were observed for grain yield at most of the sites. Similar results were reported by Yadav et al. (2002), Rafique et al. (2004), Seanki et al. (2005), Akbar et al. (2006), Dagne et al. (2007), Nesir (2007), Ali et al. (2010), Vashistha et al. (2013), Abdel Moneam et al. (2014), Sudika et al. (2015) and Andayani et al. (2018). One of maize breeders' main objectives is grain yield enhancement (Hussain et al., 2004) which is a result of complex interaction of genotypes and environmental conditions. These results indicated that sufficient genetic variability is present in the studied germplasm for grain yield, which can be exploited in future breeding programmes in Angola.

Under acid soil conditions, significant genotypic and GCA line mean squares indicated the importance of additive gene effects in grain yield, whereas non-significant SCA mean squares for grain yield supported this finding. Pswararyi and Vivek (2008) in their research on combining ability amongst CIMMYT's early maturing maize germplasm under stress and non-stress conditions and identification of tester performance in a diallel analysis, also reported significant GCA mean squares and non-significant SCA for grain yield. Similarly, Piovarci (1973) noted that GCA was more important than SCA for yield. The results from this study are in accordance with results published by Bhatnagar et al. (2004), Pswararyi and Vivek, (2008), and Taminat et al. (2014). Contrary to this, Dagne et al. (2007) previously reported a dominant role of SCA gene action in grain yield, as well as Strube (1967), who reported that SCA effects were larger than GCA effects for yield. Additive variance was more important than dominance variance, with genotypic variance also more important than environmental variance. Genotypic variance was less than environmental variance, but additive variance was more important than dominance variance under the non-acid conditions and this affirmation is in accordance with Ertiro et al. (2017) findings. The results were similar to those observed across non-acid sites. Broad- and narrow-sense heritability estimates were more than 50% under both the acid and non-acid soil conditions.

Comparing the highest yielding five experimental hybrids with the highest yielding commercial check hybrids under acid, non-acid and across both soil conditions, showed that the top five highest yielding experimental hybrids had high average mean GY compared to the top five highest yielding check hybrids. This translated to good yield potential of the inbred lines used in hybrid combinations, which can be exploited in high yielding hybrid formation in different environments in Angola. The experimental hybrid CH142464 (ZY2 x CY3) with 5.05 t ha^{-1} was the best hybrid combination under acid soil conditions, while in non-acid soil conditions, hybrid CH142447 (ZY2 x CY1) with 7.01 t ha^{-1} showed superiority amongst the top five highest yielding experimental hybrids. Combining the two environments (acid and no-acid soil conditions), the experimental hybrid CH142461 (ZY3 x CY3) with 5.54 t ha^{-1} was the best of the top five highest yielding experimental hybrids.

The lines involved in the highest yielding hybrids had positive GCA effects for grain yield in the two testing environments (acid and non-acid soil conditions), separately and combined. This indicated that there was high genetic variability among the lines used in this study. Similar results were reported by Egesel et al. (2003), Bhatnagar et al. (2004), Fan et al. (2007), and Bello and Olaoye (2009). Lines ZY1, ZY2 and ZY3 were involved in the three highest grain yielding experimental hybrids and line ZY3 with the highest positive GCA effect for grain yield, was the best line and involved as parent in more than one cross among the top five yielding experimental hybrids. Presence of highly significant GCA variances for grain yield also indicated the importance of additive genes in the expression of grain yield (Hefny, 2010). Having significantly positive GCA line effects for grain yield and for at least two yield component traits (Fan et al., 2007), these lines could be used directly in high grain yielding yellow maize hybrid development programmes in Angola.

On the other hand, donor lines (testers) CY1 and CY3 were identified as the best lines due to their parentage in the two highest yielding experimental hybrids, and tester CY1 ranked the highest under acid, non-acid and across acid and non-acid soil and was a parent in three of the five highest yielding experimental hybrids. This indicated that these two testers had good potential and could be used mainly in high yielding hybrid formation under acid soil conditions in Angola.

The CIMMYT-Zimbabwe elite inbred line, ZY8 was the best line under non-acid conditions, whilst the CIMMYT-Colombia yellow acid donor line, CY4, was the best tester under non-acid conditions. These two inbred line can be used specifically in high yielding hybrid formation under non-acid soil conditions in Angola.

Under acid soil conditions, hybrids ZY10 x CY3, ZY1 x CY1 and ZY4 x CY4 were identified as the best combiners. Exploiting their potential, these inbred lines and their combinations could significantly contribute in maize breeding programmes for high yield and tolerance to acid soils in Angola. These results are in accordance with Mutimaamba et al. (2020) findings. Hybrids ZY6 x CY3, ZY2 x CY1 and ZY10 x CY3 were the best combiners under non-acid soil conditions. These crosses are suitable for developing high yielding yellow maize hybrids for other environments than acid soil. Finally, across acid and non-acid soil conditions, two of the three crosses selected in non-acid soil (ZY6 x CY3 and ZY10 x CY3) had the same tester (CY3). Of these, cross ZY10 x CY3 was the best hybrid in this study, because it was top yielding under acid and non-acid soil conditions.

CY3 was the best tester, which was a parent in the best hybrids more than once, followed by CY1. ZY6 and ZY10 were the best lines for the same reason.

Assessing genotype grain yield stability is one of the key attributes for variety recommendation. High yield stability usually refers to a genotype's ability to maintain a constant yield across different environments (Falconer, 1990; Dyke et al., 1995). Cultivar superiority indices were used in this study to identify the most stable of the five highest yielding experimental hybrids against the five highest grain yielding checks.

Under acid soil conditions, except for hybrid check 5 which was ranked as the highest yielding and stable genotype, the experimental hybrids CH142442 (ZY7 x CY1), CH142464 (ZY2 x CY3) and CH142444 (ZY3 x CY1) were more stable and high yielding than most of the other checks. Under non-acid conditions, hybrid CH142447 (ZY2 x CY1) was the most stable genotype and was slightly outperformed by check 3, in terms of GY. The highest yielding and stable experimental hybrids could be tested in large-scale trials across environments for adaptation in diverse agro-ecological regions. Improved hybrids can stabilize the production level of the crop and it could improve the national production and productivity since in Angola, production and productivity levels are very low.

3.5 Conclusions

The most outstanding hybrid in this study was ZY10 x CY3. This hybrid has the potential for production across all environments and should therefore be tested further in multiple environments to confirm consistency of its high yield performance to facilitate its release as a commercial hybrid. Hybrids which were selected as high yielding, but were not stable across environments cannot be recommended for specific environments where they performed well. CY3 and CY1 were the best acid tolerant inbred line donors. The results of this study should therefore be confirmed through further evaluation of hybrids at different locations in Angolan maize productions agro-ecological zones. The results from further evaluation will without doubt, form the foundation for low soil pH tolerance breeding in the Angolan breeding programme

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CHAPTER 4

COMBINING ABILITY AND GRAIN YIELD STABILITY OF CIMMYT-ZIMBABWE WHITE ELITE INBRED LINES CROSSED WITH THE CIMMYT COLOMBIA ACID TOLERANCE DONOR WHITE INBRED LINES UNDER ACID AND NON-ACID SOIL CONDITIONS

Abstract

Breeding efforts to develop high yielding and improved maize varieties tolerant to acid soils has not been done in Angola as yet, although the main maize production areas are characterized by acid soils. To overcome this situation, a study was carried out on eight elite white lines adapted to the mid-altitude climatic conditions from CIMMYT-Zimbabwe and eight acid soil tolerance donors (testers) from CIMMYT-Colombia, which were crossed using a line x tester design. The 47 F_1 single cross hybrids were evaluated during the 2014-2016 cropping seasons at nine sites (five with acid soils and four with non-acid soils) in Angola and Zimbabwe. The aim of this study was identification of the white acid tolerant donor inbred lines that can potentially be sources of acid tolerance genes in breeding programmes in Angola, and elsewhere within the mid-altitude climatic regions of Africa. Crosses with high grain yield potential can be identified, and these can either be used as starting populations in pedigree breeding programmes. Combined analysis of variance showed highly significant differences ($p<0.001$) among the nine test sites for grain yield, indicating the presence of considerable variation among sites for genotype performance. Inbred lines ZW6 and ZW8 were the best general combiners under acid soil conditions and under non-acid conditions, respectively. Inbred line CW2 was the best acid tolerant donor line (tester) which can be used for hybrid maize generation under acid soil conditions. The best specific cross for acid soil conditions was ZW1 x CW8 (CH142512, and for non-acid conditions, ZW3 x CW4 (CH142500). They exhibited excellent SCA values for yield, and can be considered for commercial release. Assessment of stability and adaptability identified hybrids CH142480, CH142497, CH142501 and CH142512 as the most stable among the 10 top highest yielding hybrids under acid soil conditions. Under non-acid soil conditions, the most stable hybrids among the 10 top highest yielding were CH142472, CH142500, CH142512 and CH142491. Hybrid CH142512 was stable under both acid and non-acid soil conditions, and could be recommended for commercial release in Angola.

4.1 Introduction

Maize is the most important energy source for almost every household in Angola. Although maize is grown around the country, its production is mainly confined to the high and mid-altitude zones of the country, where abundant rainfall is received yearly (Acidri et al., 2013). Because of the high rainfall, soils in these geographic zones are mainly acidic, characterized by low pH and mineral toxicity, as well as deficiencies of essential macro- and micro-nutrients such as Ca, Mg and P (Borreno et al., 1995). Developing maize genotypes adapted to stress factors is regarded as the most sustainable and cost-effective method of promoting crop productivity worldwide.

However, as new germplasm that is adapted to the present and future climatic scenarios is developed, the social and market dynamics should also be taken into consideration. This is because, at the end of the day, the new variety developed should be acceptable to the end users and should be equally competitive against the already commercialized similar products in the market (Hellin et al., 2014). For instance, although Angolans depend on maize as a staple crop, some of the groups prefer white kernelled maize while the others prefer the yellow types (Agritex, 2015). Hence, breeding programmes should be designed carefully to cater for the needs of these two distinct groups of people in the country. Breeding programmes where a breeder develops a product specifically suitable to a specific group of people or geographical area are now commonly referred to as, 'product-profile-based breeding', and is postulated as key in developing genotypes that make a significant impact in the market.

In order to conform to the needs of those consumers who prefer white kernel maize, but also not shifting away from the main target, which is developing maize adapted to acid and non-acid soils in Angola, exotic white acid donor inbred lines were sourced from the CIMMYT-Colombia breeding programme. However, these exotic lines are yet to be assessed for combining ability with white germplasm adapted to the mid-altitude climatic conditions under acid and non-acid conditions in Angola. Likewise, grain yield stability of crosses between these divergent gene pools under acid and non-acid conditions is still not known. Both the GCA and the SCA effects between the white acid tolerance donor inbred lines from Colombia and the elite white inbred lines adapted to the mid-altitude climatic zones will be key in identification of the white acid donor inbred lines that can potentially be sources of acid tolerance genes in breeding programmes in Angola, and elsewhere within the mid-altitude climatic regions of Africa. Crosses with high grain yield potential can be identified, and these can either be used as starting populations in pedigree breeding programmes, if the parents fall in the same heterotic group (Meena et al., 2017; Annor et al., 2020), or if stable across diverse environments, can be advanced for commercialization.

Therefore, the specific objectives of this study were to: (i) identify the white-kernelled acid tolerance donor lines from CIMMYT-Colombia that can potentially improve adaptation of the mid-altitude adapted CIMMYT, white-kernelled elite inbred lines under acid and non-acid conditions in Angola; and, (ii) identify high yielding CIMMYT-Zimbabwe x CIMMYT-Colombia F_1s with stable grain yield performance under the acid and non-acid soil conditions in Angola. The hypothesis is that the white acid tolerance donor inbred lines from CIMMYT-Colombia can improve maize productivity under acid and non-acid conditions in Angola.

4.2 Materials and methods

4.2.1 Germplasm description and F_1 formation

A total of eight white-kernelled acid tolerance donor inbred lines were sourced from CIMMYT-Colombia during 2014. Four of these lines are classified into heterotic group A, while the rest were in heterotic group B. In the same year, white-kernelled inbred lines adapted to the mid-altitude climatic conditions were sourced from CIMMYT-Zimbabwe. Six of these are classified in heterotic group A, whereas the rest are in heterotic group B (Table 4.1). A LxT design crossing nursery was established for these two groups of germplasm in Muzarabani (latitude 16°19’60 S, longitude 31°10 0 E), during the winter season (May - August) of 2014. In the crossing design, CIMMYT-Zimbabwe lines were used as female parents (lines), and the CIMMYT-Colombia acid tolerance donor lines as male parents (testers) (Table 4.1). The LxT nursery yielded a total of 64 F_1s, but 17 of them were discarded because they did not have sufficient seed for multi-environmental trial evaluations (Table 4.2).

Table 4.1 White lines and testers used in developing single cross hybrids

#	Code	Origin	Parental category	Heterotic group
Lines				
1	ZW1	Zimbabwe	Line	A
2	ZW2	Zimbabwe	Line	A
3	ZW3	Zimbabwe	Line	B
4	ZW4	Zimbabwe	Line	A
5	ZW5	Zimbabwe	Line	A
6	ZW6	Zimbabwe	Line	B
7	ZW7	Zimbabwe	Line	A
8	ZW8	Zimbabwe	Line	A
Tester				
9	CW1	Colombia	Tester	B
10	CW2	Colombia	Tester	B
11	CW3	Colombia	Tester	B
12	CW4	Colombia	Tester	A
13	CW5	Colombia	Tester	A
14	CW6	Colombia	Tester	A
15	CW7	Colombia	Tester	A
16	CW8	Colombia	Tester	B

Table 4.2 Line x tester F_1s developed between CIMMYT-Zimbabwe white elite inbred lines and CIMMYT-Colombia white acid tolerance donor lines

Entry	Hybrid name	Crosses	Entry	Hybrid name	Crosses
1	CH142471	ZW7 x CW1	25	CH142495	ZW5 x CW4
2	CH142472	ZW5 x CW1	26	CH142496	ZW4 x CW4
3	CH142473	ZW4 x CW1	27	CH142497	ZW1 x CW4
4	CH142474	ZW4 x CW8	28	CH142498	ZW2 x CW4
5	CH142475	ZW1 x CW2	29	CH142499	ZW8 x CW4
6	CH142476	ZW2 x CW1	30	CH142500	ZW3 x CW4
7	CH142477	ZW8 x CW2	31	CH142501	ZW6 x CW4
8	CH142478	ZW3 x CW1	32	CH142502	ZW7 x CW5
9	CH142479	ZW6 x CW1	33	CH142503	ZW5 x CW5
10	CH142480	ZW5 x CW3	34	CH142504	ZW4 x CW5
11	CH142481	ZW1 x CW3	35	CH142505	ZW1 x CW5
12	CH142482	ZW2 x CW3	36	CH142506	ZW2 x CW5
13	CH142483	ZW8 x CW3	37	CH142507	ZW8 x CW5
14	CH142484	ZW3 x CW3	38	CH142508	ZW3 x CW5
15	CH142485	ZW6 x CW3	39	CH142509	ZW6 x CW5
16	CH142486	ZW7 x CW7	40	CH142510	ZW7 x CW8
17	CH142487	ZW5 x CW6	41	CH142511	ZW5 x CW8
18	CH142488	ZW4 x CW7	42	CH142474	ZW4 x CW8
19	CH142489	ZW1 x CW7	43	CH142512	ZW1 x CW8
20	CH142490	ZW2 x CW7	44	CH142513	ZW2 x CW8
21	CH142491	ZW8 x CW7	45	CH142514	ZW8 x CW8
22	CH142492	ZW3 x CW6	46	CH142515	ZW3 x CW8
23	CH142493	ZW6 x CW7	47	CH142516	ZW6 x CW8
24	CH142494	ZW7 x CW4			

4.2.2 F_1 hybrid evaluation and sites description

The 47 LxT F_1s which had sufficient seed for evaluation across nine sites (Table 4.2), were evaluated alongside eight commercial check hybrids at nine locations in Zimbabwe and Angola (Table 4.3), thereby making a total of 55 hybrids per trial (Appendix 4.1). Trials were established during the 2014-2016 cropping seasons under acid and non-acid conditions as described in Chapter 3. Soil analysis was done as described in Chapter 3.

4.2.3 Experimental design and trial management, data collection and statistical analysis

The 55 white hybrids (Appendix 4.1) were planted using an alpha (0,1) lattice design (Patterson and Williams, 1996) with two replications at each site. Each replication accommodated a total of 11 incomplete blocks with a block size of five plots each. Randomization was done differently across replications and across sites. Each white hybrid was planted in a single row of 4 m length, having a uniform inter- and intra-row spacing of 0.75 m and 0.25 m, respectively. Two seeds were hand-planted on each hill, and later thinned to one plant on each hill, 3-5 weeks after crop emergence, in order to have an optimum plant population of 53,333 plants per hectare. Border rows were planted. Trial fertilisation was as described in Chapter 3. Data collection followed CIMMYT (1985) standard procedures and grain yield was determined as described in Chapter 3 and statistical analyses were done as described in Chapter 3.

4.3 Results

4.3.1 White F_1 hybrid yield performance on individual sites and across acid and non-acid conditions

Significant ($p<0.05$) genotype effects for GY were seen at four of the acid soil sites (Chibero, Marondera, Chianga1 and Chianga2) as well as at two non-acid soil sites (Chianga3 and Alto- Kapaca). Most of the acid soil types showed mean grain yields less than 3.5 t ha^{-1}, while the CIMMYT-Zimbabwe low P site, surprisingly had a mean GY of 8.82 t ha^{-1}, which was comparable to yields observed under an optimally managed site (Chinga3), which had a mean of 9.77 t ha^{-1} . Broad sense heritability (H^2) of above 10% was observed at most of the sites, except for SEDIAC (random stress management) and CIMMYT-Harare2 (low P management), which showed heritability of zero (Table 4.4).

Across acid soil sites genotypic, GCA_{lines}, $GCA_{testers}$ and SCA effects for GY performance were significant. Similar results were observed for non-acid soils as well as for combined acid and non-acid soils. Significant genotype x site interaction effects were also noted for GY under acid and non-acid soil conditions and the same was seen in the combined trial analysis.

Genotypic variance was more important than environmental variance under acid soil conditions and across the acid and non-acid soil conditions, but the opposite was true under non-acid conditions. Additive variances under the acid, non-acid, and combined conditions, were more important than dominance variance. Both H^2 and narrow-sense (h^2) heritability estimates (Robison et al., 1949) were above 90% under acid soil conditions and across acid and non-acid conditions, but were lower under non-acid conditions (Table 4.5).

Table 4.3 Individual site analysis of variance for grain yield performance of the white CIMMYT-Zimbabwe elite lines x CIMMYT-Colombia acid tolerance donor lines F_1s, evaluated across nine sites in Zimbabwe and Angola during the 2014-16 cropping seasons

Location	Management	Soil type	Grain yield (t ha^{-1})			Error variance	Genotype variance	H^2	LSD
			Mean	Min	Max				
CIMMYT Harare	Low P	Acid	8.82	5.68	13.41	2.21	1.94	0.64	2.92
Chibero	Sandy Soil	Acid	2.98	1.40	6.85	0.91	0.44**	0.50	1.86
Marondera	Sandy Soil	Acid	3.34	1.31	6.52	1.52	0.55*	0.42	2.42
SEDIAC	Low Ph	Acid	1.27	0.51	2.55	0.31	0.02	0.12	1.09
SEDIAC	Random Stress	Non-acid	2.27	0.95	3.65	0.84	0.00	0.00	1.80
Chianga1	Low pH	Acid	3.31	1.81	5.32	0.69	0.23**	0.40	1.63
Alto-Kapaca	Random Stress	Non-acid	2.85	0.81	4.36	0.52	0.14***	0.34	1.41
Chianga2	Low pH	Acid	1.75	0.58	3.38	0.49	0.00*	0.00	1.37
Chianga3	Optimal	Non-acid	9.77	3.89	16.22	6.72	2.87**	0.46	5.08

*** p< 0.001, ** p< 0.01, * p< 0.5, Min: Minimum, Max: Maximum, H^2: heritability, LSD: Least significant difference, CV: Coefficient of variation

Table 4.4 Grain yield LxT analysis of white CIMMYT-Zimbabwe elite lines x CIMMYT-Colombia white acid tolerance donor lines F_1s, evaluated at nine locations during the 2014-2016 cropping seasons under acid and non-acid soil conditions in Angola and Zimbabwe

	Acid soil		**Non-acid soil**		**Across**	
	Df	**MS**	**Df**	**MS**	**Df**	**MS**
Replication (Site)	6	13.82***	3	0.33	9	9.24****
Site	5	633.81***	2	1110.36***	8	690.87***
Genotype	54	3.02***	45	6.25***	54	4.08***
GCA_{Line}	7	6.03***	7	7.41**	7	9.97***
GCA_{Tester}	7	4.84***	7	2.81	7	6.66***
$SCA_{Line\ x Tester}$	31	2.80***	30	8.19***	31	3.66***
Genotype x Site	209	2.10***	75	4.42**	329	3.03***
GCA_{Line} x Site	35	2.63***	14	3.07	56	2.83***
GCA_{Tester} x Site	35	3.42***	14	1.094	56	2.57***
SCA x Site	131	1.672**	45	5.00***	206	3.22***
Residuals	244	1.18	98	2.36	342	1.52
Line variance		5.09**		0.03		6.28**
Tester variance		118.89***		0.00		138.58***
Line x Tester variance		6.67**		0.17		6.822**
Genotype variance		119.63***		0.23		138.30***
Additive variance		478.51***		0.91		553.19***
Dominance variance		26.50*		0.68		27.29*
Environmental variance		8.06*		0.73		3.38
Broad sense heritability		0.98		0.69		0.99
Narrow sense heritability		0.93		0.39		0.95
Grand mean		3.58		5.02		4.04
LSD		2.01		3.01		2.34
CV		28.64		30.58		29.51

*** p< 0.001, ** p< 0.01, * p< 0.5, GCA: general combining ability; SCA: specific combining ability; LSD: Least significant difference; CV: coefficient of variation, Df: degrees of freedom, MS: mean squares

4.3.2 The best grain yield performing CIMMYT-Zimbabwe white lines and CIMMYT-Colombia white acid tolerance donor lines in hybrid combinations under acid and non-acid soil conditions

Making comparisons between the highest yielding five experimental white kernel F_1 hybrids with the highest five grain yielding commercial check hybrids, showed the potential of CIMMYT-Zimbabwe and CIMMYT-Colombia inbred lines in enhancing maize productivity under acid and non-acid soil conditions in Angola (Table 4.5 and Fig. 4,1). The five highest yielding experimental hybrids yielded more than the five highest yielding commercial checks under acid (average $GY_{Experimental}$ = 4.43 t ha^{-1} > average GY_{Checks} = 4.14 t ha^{-1}); non- acid (average $GY_{Experimental}$ = 8.56 tha^{-1} > average GY_{Checks} = 5.816 tha^{-1}); and combined acid and non-acid conditions (average $GY_{Experimental}$ = 4.87 t ha^{-1} > average GY_{Checks} = 4.60 t ha^{-1}). Although there is no significant difference for mean grain yield between the experimental and commercial hybrids in acid and non-acid soil conditions, but the results demonstrated the potential of the new hybrids compared to the commercial hybrids. The highest potential of the white experimental hybrids was observed under the non-acid soil conditions where the two highest yielding F_1s, Entry 30 (CH142500; $BLUE_{GY}$ = 12.69 t ha^{-1}) and Entry 26 (CH142496; $BLUE_{GY}$ = 9.35 t ha^{-1}) significantly out yielded all five the highest yielding commercial checks.

To understand the parental contributions in the high yields observed in some of the experimental hybrids, individual contributions of lines were evaluated (Table 4.5 and Fig. 4.1). It was seen that the CIMMYT-Zimbabwe white inbred lines: ZW1 (GCA_{acid} = 0.421; $GCA_{non-acid}$ = 0.28); ZW4 (GCA_{acid} = -0.011; $GCA_{non-acid}$ = -0.475); and, ZW5 (GCA_{acid} = 0.071; $GCA_{non-acid}$ = 0.256), were involved as parents in the highest yielding experimental hybrids under both acid and non-acid soil conditions. On the other hand, the CIMMYT-Colombia white acid tolerance donor lines involved as parents in the highest grain yielding genotypes were: CW4 (GCA_{acid} = 0.263; $GCA_{non-acid}$ = 0.571) and CW8 (GCA_{acid} = -0.405; $GCA_{non-acid}$ = -0.059) (Figure 4.1; Table 4.6).

The best CIMMYT-Zimbabwe white elite line combiner under acid soil conditions was ZW6 (GCA = 0.578) and under non-acid conditions, ZW8 (GCA = 0.49) (Appendix 4.2). As for the CIMMYT-Colombia white acid tolerance donor lines, the inbred line, CW2 was prominent in hybrids under both soil conditions (GCA_{acid} = 0.346; $GCA_{non-acid}$ = 1.19) (Appendix 4.3). The best specific cross for acid soil conditions was ZW1xCW8 (SCA =

0.927; $BLUE_{GY}$ = 4.34 t ha^{-1}), and for non-acid soil conditions, it was ZW3xCW4 (SCA = 11.90; $BLUE_{GY}$ = 12.69 t ha^{-1}) (Appendix 4.4 and 4.5).

Table 4.5 Grain yield performance (t ha^{-1}) of the top five experimental white maize hybrids and their lines and testers compared to the top five check hybrids under acid and non-acid soil conditions and across the two conditions

Entry number	Hybrid Name	Type of hybrid	Line	Tester	BLUE_grain yield (t ha^{-1})	SCA	Line GCA	Tester GCA
A. Acid soils								
	Experimental genotypes							
31	CH142501	Experimental	ZW6	CW4	4.57	0.578*	0.263	0.723
27	CH142497	Experimental	ZW1	CW4	4.49	0.421	0.263	0.687
10	CH142480	Experimental	ZW5	CW3	4.43	0.071	0.266	0.31
43	CH142512	Experimental	ZW1	CW8	4.34	0.421	-0.405	0.927*
18	CH142488	Experimental	ZW4	CW7	4.33	-0.011	0.141	0.597
Average GY					**4.43**			
Checks								
52	Check5	Check			4.54			
49	Check2	Check			4.50			
48	Check1	Check			3.95			
55	Check8	Check			3.92			
53	Check6	Check			3.73			
Average GY					**4.14**			
B. Non-acid soils								
	Experimental genotypes							
30	CH142500	Experimental	ZW3	CW4	12.69	-0.13	0.571*	11.899***
26	CH142496	Experimental	ZW4	CW4	9.35	-0.475	0.571*	8.907***
43	CH142512	Experimental	ZW1	CW8	7.09	0.28	-0.585*	1.632
2	CH142472	Experimental	ZW5	CW1	6.88	0.256	0.698**	0.161
21	CH142491	Experimental	ZW8	CW7	6.81	0.49	-0.059	1.676
Average GY					**8.56**			
Checks								
49	Check2	Check			6.24			
51	Check4	Check			6.23			
52	Check5	Check			6.13			
54	Check7	Check			5.24			
48	Check1	Check			5.24			
Average					**5.82**			
C. Across acid and non-acid soils								
Experimental genotypes								
43	CH142512	Experimental	ZW1	CW8	5.13	0.382	-0.458*	1.130**
30	CH142500	Experimental	ZW3	CW4	5.12	-0.193	0.326	1.700***
9	CH142479	Experimental	ZW6	CW1	4.73	0.343	0.404*	0.703
10	CH142480	Experimental	ZW5	CW3	4.70	0.130	0.079	0.110
31	CH142501	Experimental	ZW6	CW4	4.68	0.382	0.326	0.782
Average GY					**4.87**			
Checks								
52	Check5	Check			5.07			
49	Check2	Check			5.02			
51	Check4	Check			4.45			
48	Check1	Check			4.32			
53	Check6	Check			4.15			
Average GY					4.60			

*p< 0.05; ** p< 0.01; *** p< 0.001; CA: Combining ability, SCA: specific combining ability

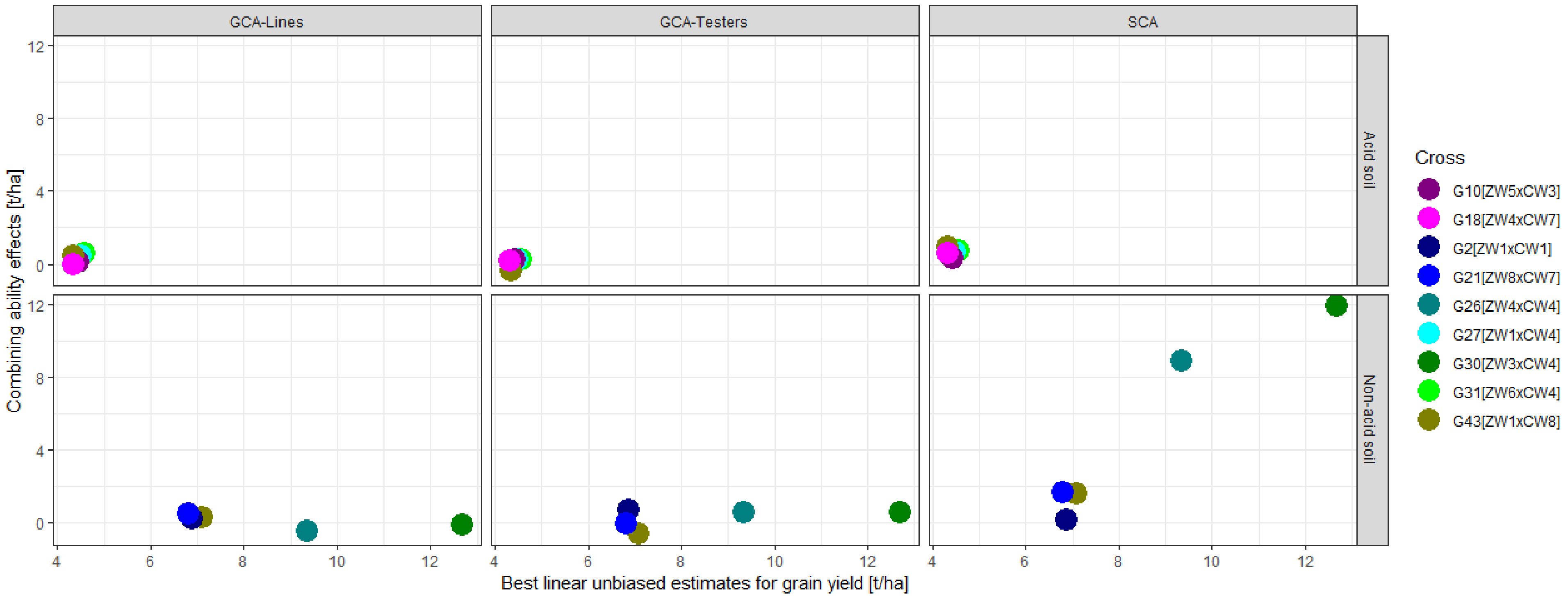

Figure 4.1 Best linear unbiased estimates for combining ability for grain yield performance (t ha-1) of the top five experimental white maize hybrids under acid and non-acid soil conditions and across the two conditions (Puntanen and Williams, 2011)

4.3.3 Grain yield stability of the five highest grain yielding white kernel experimental hybrids and checks under acid and non-acid soil conditions

Cultivar superiority indices also revealed encouraging results. First, four experimental genotypes [Hybrids: CH142480, entry 10 (Rank = 1); CH142497, entry 27 (Rank =3); CH142501, entry 31 (Rank = 6); and, CH142512, entry 43 (Rank = 8)] out of the five selected as the best grain yielding genotypes under acid soil conditions were all ranked in the top 10 most stable genotypes. Similar results were observed under non-acid soil conditions, where hybrids: CH142472, entry 2 (Rank = 10); CH142491, entry 21 (Rank = 7); CH142500, entry 30 (Rank = 1.5); and, CH142512, entry 43 (Rank = 9), all appeared in the top 10 most stable genotypes group. It was interesting to note that only one check (Check5, entry 52; GY_BLUE = 4.54 t ha^{-1}; Rank = 4) ranked amongst the top 10 most stable genotypes under acid soil conditions. On the other hand, under non-acid soil conditions, only two check genotypes, entry 49 (GY_BLUE = 6.24 t ha^{-1}; Rank = 3) and entry 51 (GY_BLUE = 6.23 t ha^{-1}; Rank = 8), ranked in the top 10 most stable genotypes (Figure 4.2; Table 4.6).

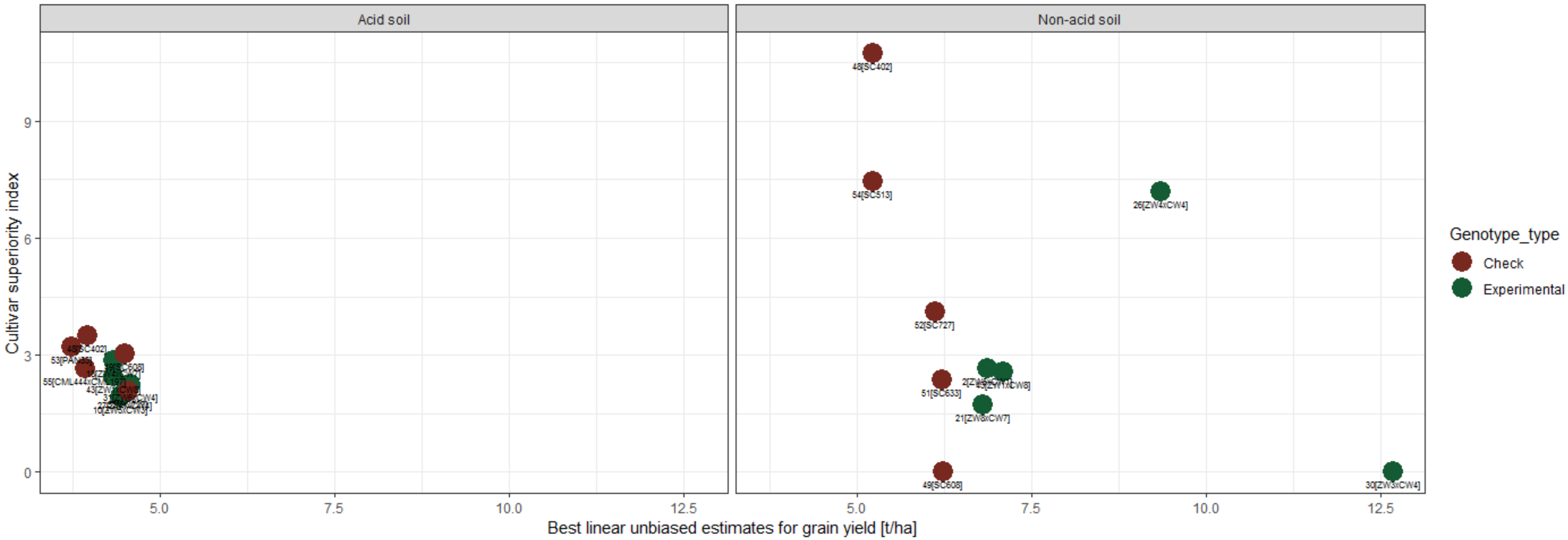

Figure 4.2 Best linear unbiased estimates (BLUEs) for grain yield and cultivar superiority indices of the top five experimental maize hybrids and commercial check hybrids under acid and non-acid soil conditions

Table 4.6 Mean grain yield and cultivar superiority indices for the top five experimental white kernel hybrids and commercial checks under acid and non-acid soil conditions

Genotype				GY_BLUE	Cultivar superiority indices (CSI)	Rank
#	Name	Cross	Type	t ha^{-1}		
A. Acid soils						
10	CH142480	ZW5 x CW3	Experimental	4.43	1.944	1
18	CH142488	ZW4 x CW7	Experimental	4.33	2.873	14
27	CH142497	ZW1 x CW4	Experimental	4.49	2.055	3
31	CH142501	ZW6 x CW4	Experimental	4.57	2.241	6
43	CH142512	ZW1 x CW8	Experimental	4.34	2.469	8
48	Check1	Check1	Check	3.95	3.506	19
49	Check2	Check2	Check	4.50	3.034	15
52	Check5	Check5	Check	4.54	2.067	4
53	Check6	Check6	Check	3.73	3.204	16
55	Check8	Check8	Check	3.92	2.667	11
B. Non-acid soils						
2	CH142472	ZW5 x CW1	Experimental	6.88	2.67	10
21	CH142491	ZW8 x CW7	Experimental	6.81	1.72	7
26	CH142496	ZW4 x CW4	Experimental	9.35	7.2	17
30	CH142500	ZW3 x CW4	Experimental	12.69	0.00	1.5
43	CH142512	ZW1 x CW8	Experimental	7.09	2.57	9
48	Check1	Check1	Check	5.24	10.74	27
49	Check2	Check2	Check	6.24	0.00	3
51	Check4	Check4	Check	6.23	2.38	8
52	Check5	Check5	Check	6.13	4.1	13
54	Check7	Check7	Check	5.24	7.45	19

GY-Grain yield, BLUE-best line unbiased estimates, CSI-cultivar stability indices

4.4. Discussion

Combined ANOVA showed highly significant differences among the nine test sites for grain yield, indicating the presence of considerable variation among sites for genotype performance. This result is in agreement with Apala Mafouasson et al. (2018) who, in their study on genotype x environment interaction of maize single cross hybrids developed from tropical inbred lines, found that environment contributed more to variation than genotype and genotype x environment interaction. Similarly, Badu-Apraku et al. (2012) reported that the contribution of the test environments were much greater than from the other sources of variation in most multi-environmental trials. The effects of genotype were highly significant for grain yield under acid and non-acid soil conditions and in combined analysis, which could be explained by the inherent genetic variation in the germplasm studied. Desired genes from this germplasm can effectively be utilized to develop high performing and adapted hybrids to the local conditions in Angola.

The significant site effect on GY performance (Table 4.4) was evident as seen in most breeding results. In a recent study by Apala Mafouasson et al. (2018), the variation of the test environments was due to the greater variation contributed by environment than those from genotype and genotype x environment interaction. Similarly, Badu-Apraku et al. (2012) reported that the contribution of the test environments is much greater than the other sources of variation in most multi-environmental trials. The highly significant genotypic, GCA of lines and testers effects on GY under acid and non-acid soil conditions can point to high inherent genetic variation among the germplasm studied.

Desired genes from this germplasm can effectively be utilized to develop high performing and adapted hybrids to the local conditions in Angola. It was also interesting to note from the results that both additive and non-additive gene actions were important in expression of grain yield under acid soil conditions (Table 4.5). A study by Martin et al. (2017) also reported on the importance of both additive and non-additive gene actions for the expression of grain yield under stressed environments. In addition, the high broad and narrow heritability estimates observed under the acid and the non-acid soil conditions indicates the possibility of effective selection for genetic improvement of GY for the maize production environments in Angola. High heritability estimates for maize grain yield are not surprising, as they were reported elsewhere by Kashiani et al. (2008), Rafique et al. (2004), and Wannow et al. (2010). The results also provide the evidence that a large proportion of phenotypic variance was attributed to genotypic variance, and reliable selection could be made for these traits on the basis of phenotypic expression (Salani et al., 2007).

Selection was done for the five top grain yielding experimental white grain hybrids and their grain yield potential was compared against the commercial check hybrids. It was so encouraging to note that experimental hybrids showed GY superiority over the commercial checks under acid and the non-acid soil environments (Table 4.6). For instance, under non-acid conditions, the crosses, ZW3 x CW4 (12.69 t ha^{-1}) and ZW4 x CW4 (9.35 t ha^{-1}) significantly out yielded the five highest grain yielding commercial checks. On the other hand, the crosses, ZW6 x CW4 (4.57 t ha^{-1}) and ZW1 x CW4 (4.49 t ha^{-1}) also outperformed commercial checks under acid soil conditions. Most of these superior crosses (such as ZW4 x CW4) were formed by parents residing within the same heterotic group (see Table 4.1), hence are good targets for pedigree starting populations for development of new lines adapted to conditions in Angola. A cross such as ZW3 (heterotic group B) x CW4 (heterotic group A) can be subjected to further testing for yield stability and can be targeted for release.

The search to really understand parental contributions to the high yields observed in some of the experimental hybrids did not disappoint, as it revealed that the CIMMYT-Zimbabwe white elite inbred lines as well as the CIMMYT-Colombia acid tolerance white kernelled donor lines could potentially be useful in breeding programmes for acid tolerance adaptation and wide adaption of maize in Angola. From the CIMMYT-Zimbabwe breeding programme, the inbred lines identified as ZW1, ZW4 and ZW5, together with the CIMMYT-Colombia white acid tolerance donor lines noted as CW4 and CW8 seemed to be ideal parents for crosses that can do well under both the acid and non-acid soil conditions in Angola (Figure 4.1). This finding was not surprising, since in previous genetic studies, inbred lines with highly positive GCA effects for GY were found to have contributed to high GY performance in maize hybrids (Egesel et al., 2003; Bhatnagar et al., 2004; Fan et al., 2007; Bello and Olaoye, 2009).

Breeders should also consider those lines that do well in specific combinations, as these can be potential single-cross testers or potential targets for pedigree starting populations, or can be potential targets for commercial release. In this study, the best specific combination was identified as ZW1 x CW8 and for the non-acid conditions, the cross, ZW3 x CW4 was noted. Results met expectations, as the parents making up these two specific crosses lie in opposite heterotic groups where heterosis is always expected to be high. Therefore, if, after further evaluation, mainly for GY stability, these hybrids continue to show GY superiority, they can be key targets for commercialization in Angola.

Lastly, some of the new crosses need to be recommended for production in different environments of Angola. However, before commercialization, assessment of yield stability and adaptability is an important factor, particularly for recommendation purposes (Liu et al., 2011, Eberhart and Russell, 1966). Cultivar superiority indices were used to determine grain yield stability and adaptability of the five highest grain yielding white kernel experimental hybrids and checks under acid and non-acid soil conditions. The hybrids: CH142480, CH142497, CH142501 and CH142512 were selected as the most stable among the 10 top highest grain yielding under acid soil condition. Under non-acid soil conditions, the most stable hybrids among the 10 top highest grain yielding were CH142472, CH142500, CH142512 and CH142491. The hybrid CH142512 seemed to be stable in both conditions (acid and non-acid soil conditions) and could be immediately be further evaluated and recommended for commercial release in Angola.

4.5 Conclusions

The differences in the classification of the cultivars in the various environments indicated the presence of genotype by environment interactions. This was confirmed by the significant effect of the cultivar x environment interaction in the joint analysis of variance and indicated the need to assess the response of the cultivars to environmental variation. Combined ANOVA showed highly significant differences among the nine test sites for grain yield, indicating the presence of considerable variation among sites for genotype performance. This study demonstrated the combining ability of maize inbred lines in acid and non-acid soil conditions in Angola and Zimbabwe. Thirty six single cross hybrids were generated through line by tester analysis for each environment, along with six commercial hybrids as checks. Inbred lines ZW6 and ZW8 were the best combining lines under acid soil conditions and under non-acid conditions, respectively, while inbred line CW2 was the best acid tolerant tester that can be pursued for hybrid maize generation under acid soil conditions. Furthermore, combined analysis of SCA effects showed that the best specific cross for acid soil conditions was ZW1 x CW8 (CH142512), and for non-acid conditions, ZW3 x CW4 (CH142500) that can be advanced for commercial release.

Hybrids CH142480, CH142497, CH142501 and CH142512 were the most stable among the 10 top highest yielding hybrids under acid soil conditions, and under non-acid soil conditions, the most stable hybrids among the 10 top highest grain yielding were CH142472, CH142500, CH142512 and CH142491. Hybrid CH142512 seemed to be stable under both acid and non-acid soil conditions, and could immediately be evaluated and recommended for commercial release in Angola.

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CHAPTER 5

PER SE GRAIN YIELD PERFORMANCE OF THE CIMMYT-COLOMBIA ACID TOLERANCE DONOR WHITE AND YELLOW INBRED LINES UNDER ACID AND NON-ACID SOIL CONDITIONS

Abstract

Identification of inbred lines with unique traits for hybrid development is key in any maize breeding programme. Apart from desirable genetic attributes, for example, positive and significant GCA effects for GY performance, high *per se* GY performance, coupled with other ideal agronomic traits, for instance, plant height and ear position, which reflects on standing ability, are often used to make decisions on inbred lines ideal as parents in hybrid development. The objective of this study was to identify the ideal traits for superior inbred lines which can be used as parents in the future in hybrid development in Angola. To do this, 16 white kernel and 14 yellow kernel inbred lines from the CIMMYT-Zimbabwe and CIMMYT-Colombia breeding programmes were separately evaluated under acid and non-acid soil conditions in Angola and Zimbabwe, during the 2014-2016 rainy seasons, in order to identify those with unique traits suitable for hybrid development. White kernel inbreds were planted together with four inbred line checks, whereas six checks were used for the yellow inbred line trial. Results showed highly significant genotypic effects for GY performance across the acid and non-acid soil environments for the white kernel inbred lines only, but heritability for GY was above 20% in both cases. The CIMMYT-Colombia white kernel inbred lines, identified as CW3 (3.20 t ha^{-1}) and CW4 (3.90 t ha^{-1}) showed superior GY performance across acid and non-acid soil conditions, whereas the inbred lines CY1 (3.2 t ha^{-1}) and CY3 (3.9 t ha^{-1}) were the best lines from CIMMYT-Colombia for the yellow maize breeding programme. From the CIMMYT-Zimbabwe breeding programme, the white kernel inbred lines identified as ZW5 (4.16 t ha^{-1}) and ZW2 (3.68 t ha^{-1}), together with the yellow kernel inbreds (ZY3; 4.16 t ha^{-1} and ZY2; 3.68 t ha^{-1}), performed the best. Overall, although the findings provide insights into inbred lines most likely suitable for hybrid development in Angola, more work should be done in developing yellow and white kernelled lines specifically adapted to the different maize growing environments of Angola.

5.1 Introduction

In SSA, maize productivity is very low, averaging 1 t ha^{-1} (Thierfelder and Wall, 2012) and soil acidity is one of the major constraints known to be negatively impacting food security in the region. Liming is a practice which has been traditionally used by the farmers to improve crop adaption to soil acidity (Bossuet et al., 2019), but, due to its high costs, the technology is not feasible for resource poor farmers and it is not economical, and neither is it environmentally friendly (Pandey and Gardner, 1992; Krill et al., 2010; Ndeke and Tembo, 2019). Breeding programmes for acid-soil tolerance are desirable as a relatively inexpensive and sustainable way for increasing maize yields on these soils. Genetic variation for tolerance to soil acidity has been reported in several studies using different germplasm, different traits and different genetic analyses (Velásquez et al., 2008), hence prompting the need to utilize this variation to develop adapted maize genotypes for the region.

Quality breeding materials developed for acid soil tolerance exist and can be successfully used in a wide range of production environments. For example, the Colombia Agriculture and Livestock Research Corporation used two of CIMMYT's acid soil tolerant inbred lines, ClA176 and CLA215 in crosses, and the single cross hybrid developed yielded more than 9 t ha^{-1} on average in different test environments (CIMMYT, 2006). However, for positive outcomes in hybrid development, agronomic information on parental lines is very important in choosing the best lines to be used as male and female parents (Zhang et al., 2015). Parental inbred lines should show good seed production and stable performance across testing environments (Worku et al., 2016; Troyer and Wellin, 2009).

The objective of this study was to evaluate the *per se* grain yield performance of the CIMMYT-Colombia acid tolerance donor white and yellow inbred lines under acid and non-acid soil conditions in Angola and Zimbabwe. The hypothesis was that some of the CIMMYT-Colombia acid tolerant donor lines may be suitable as parental lines in hybrid development in Angola.

5.2 Materials and Methods

5.2.1 Description of the germplasm

Two separate inbred line trials were designed for the white kernel inbreds and the yellow kernel inbred lines, respectively and were evaluated at Chianga Experimental research station in Angola and at Harare CIMMYT research station in Zimbabwe. The white kernel inbred line trial (WKILT) consisted of eight acid tolerance donor lines sourced from CIMMYT-Colombia and eight elite lines from the CIMMYT-Zimbabwe breeding programme. In this trial, four lines from the CIMMYT-Zimbabwe programme were used as checks, thereby making up a total of 20 inbred lines in the trial (Table 5.1). The yellow kernel inbred line trial (YKILT) comprised of four acid tolerance donor lines obtained from CIMMYT-Colombia and 10 elite lines from the CIMMYT-Zimbabwe breeding programme, and these were evaluated together with six check inbred lines from the CIMMYT-Zimbabwe programme, therefore, the entire trial consisted of 20 inbred lines (Table 5.2).

5.2.2 Description of the test locations and experimental design

For the WKILT, a total of 16 inbred lines and four checks (Table 5.1) were arranged in the field at five testing locations, using an alpha (0.1) lattice design with two replications, with each replication accommodating four incomplete blocks, with a block size of five entries (genotypes). In a separate experiment (YKILT), 14 yellow inbred lines and six checks (Table 5.2) were laid out in the field at two locations, again using an alpha (0.1) lattice design with two replications, with four incomplete blocks of size five entries (genotypes), nested in each of the replications.

Evaluation sites are shown in Chapter 3, Table 3.3. Details on site management were presented in the materials and methods section of Chapter 3.

Table 5.1 White kernel maize inbred lines evaluated during the 2014-16 cropping seasons in Angola and Zimbabwe under acid and non-acid soil conditions

#	Code	Origin	Parental category	Heterotic group
1	CW1	Colombia	Tester	B
2	CW2	Colombia	Tester	B
3	CW3	Colombia	Tester	B
4	CW4	Colombia	Tester	A
5	CW5	Colombia	Tester	A
6	CW6	Colombia	Tester	A
7	CW7	Colombia	Tester	A
8	CW8	Colombia	Tester	B
9	ZW1	Zimbabwe	Line	A
10	ZW2	Zimbabwe	Line	A
11	ZW3	Zimbabwe	Line	B
12	ZW4	Zimbabwe	Line	A
13	ZW5	Zimbabwe	Line	A
14	ZW6	Zimbabwe	Line	B
15	ZW7	Zimbabwe	Line	A
16	ZW8	Zimbabwe	Line	A
17	Check 1	Zimbabwe	Check	-
18	Check2	Zimbabwe	Check	-
19	Check3	Zimbabwe	Check	-
20	Check4	Zimbabwe	Check	-

Table 5.2 Yellow kernel maize inbred lines evaluated during the 2014-16 cropping seasons in Angola and Zimbabwe under acid and non-acid soil conditions

#	Code	Origin	Parental category	Heterotic group
1	CY1	Colombia	Tester	A
2	CY2	Colombia	Tester	A
3	CY3	Colombia	Tester	A
4	CY4	Colombia	Tester	B
5	ZY1	Zimbabwe	Line	B
6	ZY2	Zimbabwe	Line	B
7	ZY3	Zimbabwe	Line	B
8	ZY4	Zimbabwe	Line	B
9	ZY5	Zimbabwe	Line	B
10	ZY6	Zimbabwe	Line	B
11	ZY7	Zimbabwe	Line	A
12	ZY8	Zimbabwe	Line	A
13	ZY9	Zimbabwe	Line	A
14	ZY10	Zimbabwe	Line	B
15	Check 1	Zimbabwe	Check	-
16	Check2	Zimbabwe	Check	-
17	Check3	Zimbabwe	Check	-
18	Check4	Zimbabwe	Check	-
19	Check5	Zimbabwe	Check	-
20	Check6	Zimbabwe	Check	-

5.2.4 Agronomic management

Each yellow and white kernel inbred line was planted in a single row plot of 4 m length, having a uniform inter- and intra-row spacing of 0.75 m and 0.25 m, respectively. Two seeds were hand-planted on each hill, and the trials were later thinned to have one plant on each planting station, 3-5 weeks after crop emergence, in order to have an optimum plant population of 53,333 plants per hectare. Border rows were planted to avoid border effect. A total of 400 kg ha^{-1} of Compound D (N_{12} P_{24} K_{12}) was applied as basal dressing and 250 kg ha^{-1} of urea ($NH_{2;}$ N = 46 %) was split-applied as top-dressing fertilizer at all sites in Angola. In Zimbabwe, the same quantity of 400 kg ha^{-1} of compound D (N_7 P_{14} K_7) was applied as basal dressing at most of the sites, except for the low P site. Ammonium nitrate (N = 34.5 %) was split-applied as top-dressing at a rate of 400 kg ha^{-1} at the sites used in Zimbabwe.

5.2.5 Data collection

Data collection followed CIMMYT (1985) standard procedures. Briefly, pre-harvest observations recorded were plant height (PH), measured as as the height between the base of a plant and the insertion of the first tassel branch, ear height (EH), measured as the height between the base of a plant to the insertion of the top ear and ear position (EPO), obtained by dividing EH/PH. Post-harvest observations recorded were grain moisture (MOI), percent water content of grain as measured at harvest; GY, measured on a whole plot basis, shelled grain weight per plot adjusted to 12.5% grain moisture and converted to ton per hectare using the following formula:

GY (t ha^{-1}) = [Grain Weight (kg $plot^{-1}$) x 10 x (100-MC) / (100-15) / (Plot Area)].

Where MC = Grain Moisture Content, and plot area = row length x 0.75 (4 x 0.75 = 3 m); ear position (EPO, calculated as EH divided by PH).

5.2.6 Data analysis

Preliminary data checking and individual site ANOVA were performed using the CIMMYT FieldBook software (Bänziger and Vivek, 2007). Data gathered was subjected to across site ANOVA using Genstat Software v17 (Payne et al., 2009). The best linear unbiased estimators (BLUEs) and the best linear unbiased predictors (BLUPs) were calculated using the procedures of Puntanen and Styan (2011) and the broad-sense heritability (H^2) estimates were calculated using the Multi-Environment Trial Analysis with R (META-R) version v5.0 (Alvarado et al., 2015). The following model was used to calculate (H^2):

$$H^2 = \left(\frac{\sigma^2 g}{\frac{\sigma^2 g}{re} + \frac{\sigma^2 ge}{e} + \sigma^2 p} \right) * 100$$

Where; σ^2g is genotypic variance, σ^2ge is GEI variance, σ^2p is phenotypic variance, e represents sites and r represents the replications.

Mean comparisons were performed using the Fisher's Protected Least Significance Difference (LSD) (Little and Hills, 1978) at 5% significance level.

5.3 Results

5.3.1 *Per se* grain yield performance of the white CIMMYT-Colombia acid tolerance donor inbred lines under acid and non-acid conditions

Combined ANOVA for WKILT showed highly significant ($p<0.001$) site effects on GY, and selected agronomic traits include; PH, EH and EPO. The effects of entries (inbred lines) were highly significant for GY, and significant inbred line x site interaction effects on GY were also seen (Table 5.3). The CIMMYT-Colombia white maize inbred lines, CW4 (GY = 3.90 t ha^{-1}), CW3 (GY = 3.20 t ha^{-1}) and CW7 (GY = 2.97 t ha^{-1}) showed grain yields above the grand mean of all the inbred lines studied, but not significantly different from the checks. The CIMMYT-Zimbabwe elite inbred lines identified as ZW5 (GY = 4.16 t ha^{-1}) and ZW2 (GY = 3.68 t ha^{-1}) exhibited similar high yields (Table 5.4). Much more interestingly, performance of the identified superior acid tolerance donor lines did not significantly differ from the best check inbred (Entry 20).

Table 5.3 Combined analysis of variance of white kernel maize inbred lines for grain yield and other agronomics traits evaluated under acid and non-acid soil conditions during the 2014-2016 cropping seasons in Angola and Zimbabwe

	Grain yield	Plant height	Ear height	Ear position
Site	78.60***	437788.48***	97800.30***	0.090***
Replication (Site)	0.18	59.27	94.80	0.008
Block (Replication x Site)	2.46*	575.65***	632.30**	0.013*
Entry	5.44***	304.82*	142.30	0.009
Entry x Site	4.55***	100.99	104.00	0.003
Residual	0.86	94.04	140.70	0.005
Total	4.58	6978.86	1724.50	0.009

***$p<0.001$, ** $p<0.01$, * $p<0.05$

Table 5.4 Best linear unbiased estimates for grain yield and other important agronomic traits for the CIMMYT-Colombia acid tolerance donor and CIMMYT-Zimbabwe elite white kernel inbred lines evaluated under acid and non-acid soil conditions in Zimbabwe and Angola during the 2014-2016 cropping season

#	Code	Name	Origin	HG	GY ($t\ ha^{-1}$)	Plant height (cm)	Ear height (cm)	Ear position (scale: 0-1)
1	CW1	CL137781	CIMMYT-Colombia	B	1.97	121.05	67.01	0.57
2	CW2	CL137781-1	CIMMYT-Colombia	B	0.52	115.20	34.46	0.34
3	CW3	CL137786	CIMMYT-Colombia	B	3.20	164.09	67.47	0.33
4	CW4	CL137788	CIMMYT-Colombia	A	3.90	126.17	93.36	0.59
5	CW5	CL137789	CIMMYT-Colombia	A	1.39	95.37	56.95	0.51
6	CW6	CL137787	CIMMYT-Colombia	A	1.51	104.67	65.57	0.61
7	CW7	CL137787-1	CIMMYT-Colombia	A	2.97	116.00	75.82	0.61
8	CW8	CL137790	CIMMYT-Colombia	A	2.21	128.98	67.94	0.55
9	ZW1	CL106683	CIMMYT-Zimbabwe	B	3.26	122.23	60.63	0.60
10	ZW2	CL115803	CIMMYT-Zimbabwe	A	3.68	146.05	72.43	0.61
11	ZW3	CL115811	CIMMYT-Zimbabwe	A	1.86	148.80	91.29	0.66
12	ZW4	CL115801	CIMMYT-Zimbabwe	B	3.19	115.65	54.07	0.49
13	ZW5	CL115795	CIMMYT-Zimbabwe	A	4.16	128.10	67.80	0.58
14	ZW6	CZL0815	CIMMYT-Zimbabwe	A	2.02	122.45	54.24	0.56
15	ZW7	CL106622	CIMMYT-Zimbabwe	B	2.29	119.25	61.93	0.58
16	ZW8	CZL1014	CIMMYT-Zimbabwe	A	0.85	89.67	35.57	0.38
17	Check1	Check1	CIMMYT-Zimbabwe	-	2.04	106.11	79.12	0.64
18	Check2	Check2	CIMMYT-Zimbabwe	-	3.06	126.48	68.44	0.61
19	Check3	Check3	CIMMYT-Zimbabwe	-	3.19	114.09	62.47	0.53
20	Check4	Check4	CIMMYT-Zimbabwe	-	4.25	139.40	83.64	0.64
Error variance					1.25	375.49	170.73	0.01
Genotypic variance					0.19	58.22	0.00	0.00
Genotype x Environment variance					0.31	0.00	111.47	0.01
Location variance					1.84	412.51	261.68	0.06
Heritability					0.28	0.38	0.00	0.00
Grand mean					2.58	122.49	66.01	0.55
LSD					2.19	37.98	25.61	0.18
CV					43.34	15.82	19.79	16.96

GY: grain yield, HG: heterotic group

5.3.2 *Per se* grain yield performance of the yellow CIMMYT-Colombia acid tolerance donor inbred lines under acid and non-acid conditions

Combined ANOVA for the YKILT showed highly significant site effects on GY, PH, EH and EPO. Effects of entries were only significant for ear height and entry x site interaction effects on GY were not present (Table 5.5). BLUEs indicated two CIMMYT-Colombia yellow acid tolerant donor lines, CY3 (3.90 t ha^{-1}) and CY1 (3.20 t ha^{-1}), with yields above the trial mean. Grain yield performance of these two lines did not significantly differ from the best check inbred line (Entry 19; GY = 4.25 t ha^{-1}). Some CIMMYT-Zimbabwe elite white kernel lines (ZW3: GY = 4.16 t ha^{-1} and ZW2: GY = 3.68 t ha^{-1}) also showed superior performance for GY (Table 5.6).

Table 5.5 Combined analysis of variance of yellow kernel maize inbred lines for grain yield and other agronomic traits evaluated under acid and non-acid soil conditions during the 2014-2016 cropping seasons in Angola and Zimbabwe

	Grain yield	Plant height	Ear height	Ear position
Site	45.52***	9885.90***	6095.07***	1.332***
Replication (Site)	1.48	541.50	124.22	0.012
Block (Replication x Site)	1.11	852.20	477.68*	0.0173
Entry	2.55	472.00	396.33*	0.029
Entry x Site	1.551	449.30	119.87	0.006
Residual	0.62	197.30	75.87	0.007
Total	2.70	745.60	452.71	0.047

***:p<0.001, *: p<0.05

Table 5.6 Best linear unbiased estimates for grain yield and other important agronomic traits for the CIMMYT-Colombia acid tolerance donor and CIMMYT-Zimbabwe elite yellow kernel inbred lines evaluated under acid and non-acid soil conditions in Zimbabwe and Angola during the 2014-2016 cropping season

#	Code	Name	Origin	HG	GY ($t\ ha^{-1}$)	Plant height (cm)	Ear height (cm)	Ear position (scale: 0-1)
1	CY1	CL137785	CIMMYT-Colombia	A	3.20	164.09	67.47	0.33
2	CY2	CL137782	CIMMYT-Colombia	A	1.97	121.05	67.01	0.57
3	CY3	CL137793	CIMMYT-Colombia	A	3.90	126.17	93.36	0.59
4	CY4	CL137792	CIMMYT-Colombia	B	1.51	104.67	65.57	0.61
5	ZY1	CL1012033	CIMMYT-Zimbabwe	B	3.26	122.23	60.63	0.60
6	ZY2	CL1012034	CIMMYT-Zimbabwe	B	3.68	146.05	72.43	0.61
7	ZY3	CL1012035	CIMMYT-Zimbabwe	B	4.16	128.10	67.80	0.58
8	ZY4	CL1012051	CIMMYT-Zimbabwe	B	3.19	115.65	54.07	0.49
9	ZY5	CL1012062	CIMMYT-Zimbabwe	B	1.39	95.37	56.95	0.51
10	ZY6	CL1012080	CIMMYT-Zimbabwe	B	1.86	148.80	91.29	0.66
11	ZY7	CL1012097	CIMMYT-Zimbabwe	A	2.21	128.98	67.94	0.55
12	ZY8	CL1012110	CIMMYT-Zimbabwe	A	2.29	119.25	61.93	0.58
13	ZY9	CL1012121	CIMMYT-Zimbabwe	A	2.02	122.45	54.24	0.56
14	ZY10	CL1012134	CIMMYT-Zimbabwe	B	0.85	89.67	35.57	0.38
15	Check1	Check1	CIMMYT-Zimbabwe	-	2.97	116.00	75.82	0.61
16	Check2	Check2	CIMMYT-Zimbabwe	-	2.04	106.11	79.12	0.64
17	Check3	Check3	CIMMYT-Zimbabwe	-	3.06	126.48	68.44	0.61
18	Check4	Check4	CIMMYT-Zimbabwe	-	3.19	114.09	62.47	0.53
19	Check5	Check5	CIMMYT-Zimbabwe	-	4.25	139.40	83.64	0.64
20	Check6	Check6	CIMMYT-Zimbabwe	-	2.08	115.20	34.46	0.34
Error variance					0.31	0.00	111.47	0.01
Genotypic variance					1.84	412.51	261.68	0.06
Genotype x location variance					0.31	0.28	0.38	0.00
Location variance					2.58	122.49	66.01	0.55
Heritability					0.28	0.38	0.25	0.18
Grand mean					2.65	122.49	66.01	0.55
LSD					1.25	375.49	170.73	0.01
CV					43.34	15.82	19.79	16.96

GY: grain yield, HG: heterotic group, LSD: least significant difference, CV: coefficient of variation

5.4 Discussion

Identification of inbred lines with unique traits for hybrid development remains a very vital step in any maize breeding programme. In this study, 16 white kernelled and 14 yellow kernelled inbred lines from the CIMMYT-Zimbabwe and CIMMYT-Colombia breeding programmes were separately evaluated under acid and non-acid soil conditions in Angola and Zimbabwe, during the 2014 - 2016 rainy seasons, in order to identify those with unique traits suitable for hybrid development. Data revealed CIMMYT-Colombia acid tolerance white- and yellow kernel donor lines that can potentially be used in hybrid seed production in Angola.

The most common traits considered in selecting inbred lines suitable for hybrid production are *per se* GY yield performance (Worku et al., 2016; Pinnisch et al., 2012), flowering synchronization (Worku et al., 2016) and shorter plant heights as well as medium ear placement (Andayi et al., 2018). In some cases, grain yield components, for example, ear length and thousand kernel weight (Pinnisch et al., 2012), and seed quality traits such as oil content (Munamava et al., 2004), are also considered. These traits are important in different ways. For example, an inbred line that produces grain yields almost comparable to hybrids can be an ideal female parent for profitability in a single-cross hybrid production system. On the other hand, an inbred line with a shorter ear placement is usually less prone to lodging, therefore no yield loses will be encountered in seed production systems where mechanical harvesting is practiced. It was so encouraging to note that some of the acid tolerance white kernel and yellow kernel donor lines from the CIMMYT-Colombia breeding programme harboured some of these key traits mentioned in previous studies. For instance, the white donor lines identified as CW3 and CW4, as well as the yellow donor lines, CY1 and CY3, showed yields above the WKILT and the YKILT means, respectively (Tables 5.5 and 5.7), and their performance was not significantly different from that of the best checks identified in these two trials.

5.5 Conclusions

Inbred line trial data demonstrated the potential that the CIMMYT-Colombia acid tolerance donor lines have for use as parents in hybrid production in Angola. However, developing new lines from CIMMYT-Colombia acid tolerance donor lines and CIMMYT-Zimbabwe elite lines crosses will be ideal in production of hybrids with stable performance across the different agro-ecological regions of Angola. For the current study the lines with GY above 2 t ha^{-1} are recommended for initiating breeding for acid soil tolerance.

5.6 References

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CHAPTER 6

GENERAL CONCLUSIONS AND RECOMMENDATIONS

Maize is a key food security crop in Angola, but its production is limited mostly by soil acidity, which is a common feature in most of the maize production environments. Although agronomic measures such as use of lime may alleviate maize productivity in acid soil areas, the solution remains unsustainable as most of the farmers are subsistent with limited access to resources. Since genetic variation exists in maize for adaptation to various stress factors, including soil acidity, a breeding programme should be established to develop varieties that can produce reasonable yields under the maize production environments of Angola.

The study demonstrated the potential of the CIMMYT-Colombia acid tolerance white and yellow kernel donor lines and the CIMMYT-Zimbabwe elite lines in improving grain yield performance and stability under the maize production environments of Angola. Furthermore, opportunities to use these materials in future breeding programmes as well as in seed production systems were also identified.

The CIMMYT-Colombia acid tolerance white kernel (CW2) and the yellow kernel (CY1 and CY2) donor lines, which showed the highest positive GCA effects for GY performance, under acid and non-acid conditions can further be used in developing better inbred lines adapted to maize production environments of Angola. These identified potential lines can be used in combination with the best general combiners from the CIMMYT-Zimbabwe breeding programme. For instance, from the CIMMYT-Zimbabwe programme, key lines for breeding for maize productivity in Angola will be ZW6 and ZW8 (for the white kernel program), while ZY3 will be the most ideal for the yellow maize breeding programme. However, for breeding progress, breeders should always be mindful on how they make decisions on which lines to cross when developing new breeding populations. For example, a cross between CW2 [heterotic group (HG) B] and ZW6 (HG B) will be ideal for developing a population for the white kernel programme, because these lines fall in the same heterotic group. From this cross, heterotic group B inbred lines adapted to different production environments of Angola can be extracted, and high heterosis will be achieved if these extracted HG B lines are crossed with lines extracted from HG A breeding populations.

Since Angola is already suffering heavily from food insecurity as a result of soil acidity, quick fix solutions are also required. For example, development of new inbred lines which will be used for hybrid formation will only produce desired results after at least six years. From this study, both white (ZW3 x CW4) and yellow (ZY10 x CY3) maize specific crosses were identified and these were shown to yield reasonably high under both the acid and non-acid soil conditions. Based on performance of the single cross hybrids generated and the lines used in this study, three- way cross hybrids will be developed. These crosses can be further tested across many locations in Angola, specifically for grain yield stability, targeting their immediate release. At the same time, seed production experiments can be done in order to generate data that can be used to economically produce the hybrid, because at the end of the day, the seed companies should also make profits from selling the hybrids. In the same vein, the inbred line trials identified some other CIMMYT-Colombia and CIMMYT-Zimbabwe lines that can potentially be used economically as female parents in single-cross hybrid combinations in Angola. Examples of these inbred lines are CW3, CY1, ZW5 and ZY3. Some of these lines (ZY3 and CY3), already showed their prowess in specific hybrid combinations mentioned above.

In conclusion, maize breeders in Angola really have to make use of resources from the CIMMYT-Zimbabwe and CIMMYT-Colombia breeding programmes in order to develop inbred lines suitable to their local conditions.

APPENDICES

Appendix 3.1 The 36 line x tester yellow F_1s evaluated together with six commercial check hybrids under acid and non-acid soil condition during the 2015-2016 cropping seasons in Angola and Zimbabwe

Entry	Name	Cross	Entry	Name	Cross
1	CH142431	ZY5 x CY2	22	CH142452	ZY7 x CY4
2	CH142432	ZY7 x CY2	23	CH142453	ZY8 x CY4
3	CH142433	ZY8 x CY2	24	CH142454	ZY3 x CY4
4	CH142434	ZY3 x CY2	25	CH142455	ZY4 x CY4
5	CH142435	ZY4 x CY2	26	CH142456	ZY1 x CY4
6	CH142436	ZY1 x CY2	27	CH142457	ZY2 xCY4
7	CH142437	ZY2 x CY2	28	CH142458	ZY6 x CY4
8	CH142438	ZY10 x CY2	29	CH142459	ZY5 x CY3
9	CH142439	ZY6 x CY2	30	CH142460	ZY7 x CY3
10	CH142440	ZY9 x CY2	31	CH142461	ZY3 x CY3
11	CH142441	ZY5xCY1	32	CH142462	ZY4 x CY3
12	CH142442	ZY7 x CY1	33	CH142463	ZY1 x CY3
13	CH142443	ZY8 x CY1	34	CH142464	ZY2 x CY3
14	CH142444	ZY3 x CY1	35	CH142465	ZY10 x CY3
15	CH142445	ZY4 x CY1	36	CH142466	ZY6 x CY3
16	CH142446	ZY1 x CY1	37	Check1	Check1
17	CH142447	ZY2 x CY1	38	Check2	Check2
18	CH142448	ZY10 x CY1	39	Check3	Check3
19	CH142449	ZY6 x CY1	40	Check4	Check4
20	CH142450	ZY9 x CY1	41	Check5	Check5
21	CH142451	ZY5 x CY4	42	Check6	Check6

Appendix 3.2 Estimates of grain yield (t ha^{-1}) and general combining ability for yellow maize lines under acid, non-acid and across acid and non-acid soil conditions

Line	Line Mean	Grain Yield	GCA Line	GCA_SE Line	T_Value GCA	Prob_T GCA	GCA Rank
A. Acid soils							
ZY1	4.046	4.027	0.018	0.360	0.051	0.960	5
ZY2	4.560	4.027	0.533	0.360	1.480	0.145	2
ZY3	4.653	4.027	0.626	0.360	1.738	0.088	1
ZY4	3.698	4.027	-0.330	0.360	-0.916	0.364	9
ZY5	3.709	4.027	-0.319	0.360	-0.885	0.380	8
ZY6	4.056	4.027	0.029	0.360	0.080	0.937	4
ZY7	4.121	4.027	0.093	0.360	0.259	0.797	3
ZY8	3.929	4.027	-0.099	0.360	-0.274	0.786	6
ZY9	3.145	4.027	-0.882	0.360	-2.450	0.018	10
ZY10	3.760	4.027	-0.268	0.360	-0.743	0.461	7
B. Non-acid soils							
ZY1	5.940	5.304	0.636	0.584	1.089	0.283	3
ZY2	5.516	5.304	0.212	0.584	0.362	0.719	5
ZY3	5.984	5.304	0.680	0.584	1.164	0.251	2
ZY4	4.535	5.304	-0.769	0.584	-1.317	0.195	9
ZY5	5.030	5.304	-0.274	0.584	-0.469	0.642	7
ZY6	4.691	5.304	-0.613	0.584	-1.050	0.300	8
ZY7	5.109	5.304	-0.195	0.584	-0.333	0.741	6
ZY8	6.021	5.304	0.717	0.584	1.227	0.227	1
ZY9	4.181	5.304	-1.124	0.584	-1.923	0.062	10
ZY10	5.607	5.304	0.302	0.584	0.517	0.608	4
C. Across acid & non-acid soils							
ZY1	4.912	4.593	0.318	0.406	0.783	0.435	3
ZY2	4.991	4.593	0.398	0.406	0.978	0.331	2
ZY3	5.253	4.593	0.660	0.406	1.624	0.108	1
ZY4	4.070	4.593	-0.524	0.406	-1.289	0.201	9
ZY5	4.288	4.593	-0.305	0.406	-0.751	0.455	8
ZY6	4.319	4.593	-0.275	0.406	-0.676	0.501	7
ZY7	4.573	4.593	-0.021	0.406	-0.051	0.959	6
ZY8	4.814	4.593	0.221	0.406	0.543	0.589	4
ZY9	3.605	4.593	-0.988	0.406	-2.432	0.017	10
ZY10	4.576	4.593	-0.018	0.406	-0.043	0.966	5

GCA: general combining ability, SE: square error

Appendix 3.3 Estimates of grain yield (t ha^{-1}) and general combining ability effects for GY of the yellow maize testers under acid, non-acid and across acid and non-acid soil conditions

Tester	Tester mean	Grain Yield	GCA Tester	GCA_SE Tester	T_Value GCA	Prob_T GCA	GCA Rank
A. Acid soils							
CY1	4.1972	4.0274	0.1698	0.1732	0.9804	0.3386	1
CY2	3.6612	4.0274	-0.3662	0.1732	-2.1139	0.0473	4
CY3	4.1706	4.0274	0.1432	0.1732	0.8265	0.4182	2
CY4	4.1044	4.0274	0.0770	0.1732	0.4442	0.6616	3
B. Non-acid soils							
CY1	5.3571	5.3042	0.0529	0.1839	0.2875	0.7774	2
CY2	5.2726	5.3042	-0.0316	0.1839	-0.1716	0.8659	3
CY3	5.1848	5.3042	-0.1193	0.1839	-0.6488	0.5257	4
CY4	5.3796	5.3042	0.0754	0.1839	0.4101	0.6872	1
C. Across acid & non-acid soils							
CY1	4.7076	4.5934	0.1141	0.1456	0.7840	0.4382	1
CY2	4.3873	4.5934	-0.2061	0.1456	-1.4160	0.1654	4
CY3	4.6123	4.5934	0.0188	0.1456	0.1295	0.8977	3
CY4	4.6732	4.5934	0.0797	0.1456	0.5477	0.5872	2

GCA: general combining ability, SE: square error

Appendix 3.4 Mean grain yield (t ha^{-1}) estimates and specific combining ability effects for GY of the yellow maize F_1s under acid, non-acid and across acid and non-acid soil conditions

Line	Tester	Mean			SCA	SCA_SE_LxT	T_Value_SCA	Prob_T_SCA	SCA Rank
		LxT	Tester	Line					
A. Acid soils									
ZY1	CY1	4.860	4.197	4.046	0.645	0.401	1.608	0.109	2
ZY1	CY2	3.806	3.661	4.046	0.127	0.401	0.316	0.753	16
ZY1	CY3	4.232	4.171	4.046	0.044	0.401	0.109	0.913	19
ZY1	CY4	3.220	4.104	4.046	-0.902	0.401	-2.252	0.025	34
ZY2	CY1	4.341	4.197	4.560	-0.389	0.401	-0.972	0.332	31
ZY2	CY2	4.461	3.661	4.560	0.267	0.401	0.666	0.506	13
ZY2	CY3	5.046	4.171	4.560	0.343	0.401	0.855	0.393	7
ZY2	CY4	4.372	4.104	4.560	-0.266	0.401	-0.663	0.508	27
ZY3	CY1	4.860	4.197	4.653	0.037	0.401	0.091	0.927	20
ZY3	CY2	4.377	3.661	4.653	0.090	0.401	0.225	0.822	17
ZY3	CY3	4.649	4.171	4.653	-0.147	0.401	-0.367	0.714	23
ZY3	CY4	4.748	4.104	4.653	0.017	0.401	0.043	0.966	22
ZY4	CY1	4.182	4.197	3.698	0.314	0.401	0.784	0.434	9
ZY4	CY2	3.621	3.661	3.698	0.290	0.401	0.723	0.471	12
ZY4	CY3	2.668	4.171	3.698	-1.173	0.401	-2.926	0.004	35
ZY4	CY4	4.320	4.104	3.698	0.545	0.401	1.360	0.175	3
ZY5	CY1	3.533	4.197	3.709	-0.346	0.401	-0.863	0.389	28
ZY5	CY2	1.096	3.661	3.709	-2.247	0.401	-5.606	0.000	36
ZY5	CY3	4.165	4.171	3.709	0.313	0.401	0.782	0.435	10
ZY5	CY4	3.951	4.104	3.709	0.165	0.401	0.412	0.680	14
ZY6	CY1	4.013	4.197	4.056	-0.213	0.401	-0.532	0.596	25
ZY6	CY2	4.202	3.661	4.056	0.512	0.401	1.278	0.203	4
ZY6	CY3	4.490	4.171	4.056	0.291	0.401	0.726	0.469	11
ZY6	CY4	3.602	4.104	4.056	-0.531	0.401	-1.324	0.187	33
ZY7	CY1	4.746	4.197	4.121	0.456	0.401	1.137	0.257	5
ZY7	CY2	3.539	3.661	4.121	-0.215	0.401	-0.536	0.592	26
ZY7	CY3	3.809	4.171	4.121	-0.455	0.401	-1.134	0.258	32
ZY7	CY4	4.271	4.104	4.121	0.074	0.401	0.184	0.854	18
ZY8	CY1	4.414	4.197	3.929	0.315	0.401	0.787	0.432	8
ZY8	CY2	3.210	3.661	3.929	-0.352	0.401	-0.880	0.380	29
ZY8	CY3	-	4.171	3.929	-	0.401	-	-	37
ZY8	CY4	4.162	4.104	3.929	0.157	0.401	0.391	0.696	15
ZY9	CY1	3.154	4.197	3.145	-0.161	0.401	-0.403	0.688	24
ZY9	CY2	3.137	3.661	3.145	0.358	0.401	0.893	0.373	6
ZY9	CY3	-	4.171	3.145	-	0.401	-	-	38
ZY9	CY4	-	4.104	3.145	-	0.401	-	-	39
ZY10	CY1	3.951	4.197	3.760	0.022	0.401	0.054	0.957	21
ZY10	CY2	3.022	3.661	3.760	-0.372	0.401	-0.927	0.355	30
ZY10	CY3	4.705	4.171	3.760	0.802	0.401	2.001	0.047	1
ZY10	CY4	-	4.104	3.760	-	0.401	-	-	40

Appendix 3.4 (Continued) Mean grain yield (t ha^{-1}) estimates and specific combining ability effects for GY of the yellow maize F_1s under acid, non-acid and across acid and non-acid soil conditions

Line	Tester	Mean			SCA	T_Value_SCA	Prob_T_SCA	SCA Rank
		L x T	Tester	Line				
B. Non-acid soils								
ZY1	CY1	6.095	5.357	5.940	0.102	0.146	0.884	15
ZY1	CY2	5.859	5.273	5.940	-0.050	-0.072	0.943	21
ZY1	CY3	5.260	5.185	5.940	-0.561	-0.803	0.423	28
ZY1	CY4	6.548	5.380	5.940	0.532	0.761	0.448	8
ZY2	CY1	7.007	5.357	5.516	1.439	2.058	0.041	2
ZY2	CY2	5.474	5.273	5.516	-0.010	-0.015	0.988	18
ZY2	CY3	4.010	5.185	5.516	-1.387	-1.983	0.049	35
ZY2	CY4	5.572	5.380	5.516	-0.019	-0.028	0.978	20
ZY3	CY1	5.256	5.357	5.984	-0.781	-1.118	0.265	31
ZY3	CY2	6.531	5.273	5.984	0.579	0.828	0.409	7
ZY3	CY3	6.654	5.185	5.984	0.789	1.129	0.261	5
ZY3	CY4	5.496	5.380	5.984	-0.564	-0.806	0.421	29
ZY4	CY1	5.042	5.357	4.535	0.455	0.650	0.516	9
ZY4	CY2	4.858	5.273	4.535	0.355	0.508	0.612	10
ZY4	CY3	3.410	5.185	4.535	-1.006	-1.438	0.152	33
ZY4	CY4	4.829	5.380	4.535	0.218	0.312	0.755	14
ZY5	CY1	4.250	5.357	5.030	-0.833	-1.192	0.235	32
ZY5	CY2	0.750	5.273	5.030	-4.249	-6.076	0.000	36
ZY5	CY3	5.217	5.185	5.030	0.306	0.438	0.662	12
ZY5	CY4	6.158	5.380	5.030	1.053	1.506	0.134	4
ZY6	CY1	4.742	5.357	4.691	-0.002	-0.002	0.998	16
ZY6	CY2	4.572	5.273	4.691	-0.087	-0.124	0.901	22
ZY6	CY3	7.860	5.185	4.691	3.289	4.703	0.000	1
ZY6	CY4	3.724	5.380	4.691	-1.042	-1.491	0.138	34
ZY7	CY1	5.931	5.357	5.109	0.769	1.099	0.273	6
ZY7	CY2	4.865	5.273	5.109	-0.213	-0.305	0.761	24
ZY7	CY3	5.212	5.185	5.109	0.222	0.318	0.751	13
ZY7	CY4	4.430	5.380	5.109	-0.755	-1.080	0.282	30
ZY8	CY1	5.851	5.357	6.021	-0.223	-0.319	0.750	25
ZY8	CY2	6.303	5.273	6.021	0.313	0.448	0.655	11
ZY8	CY3	-	5.185	6.021	-	-	-	37
ZY8	CY4	5.867	5.380	6.021	-0.230	-0.329	0.743	26
ZY9	CY1	4.226	5.357	4.181	-0.008	-0.011	0.991	17
ZY9	CY2	4.135	5.273	4.181	-0.014	-0.020	0.984	19
ZY9	CY3	-	5.185	4.181	-	-	-	38
ZY9	CY4	-	5.380	4.181	-	-	-	39
ZY10	CY1	5.285	5.357	5.607	-0.375	-0.536	0.593	27
ZY10	CY2	5.421	5.273	5.607	-0.154	-0.220	0.826	23
ZY10	CY3	6.540	5.185	5.607	1.053	1.506	0.134	3
ZY10	CY4	-	5.380	5.607	-	-	-	40

Line	Tester	Mean			SCA	T_Value_SCA	Prob_T_SCA	SCA Rank
		L x T	Tester	Line				
C. Across acid & non-acid soils								
ZY1	CY1	5.409	4.708	4.912	0.383	0.946	0.345	7
ZY1	CY2	4.718	4.387	4.912	0.013	0.031	0.975	18
ZY1	CY3	4.716	4.612	4.912	-0.215	-0.530	0.596	27
ZY1	CY4	4.786	4.673	4.912	-0.205	-0.507	0.612	26
ZY2	CY1	5.596	4.708	4.991	0.491	1.211	0.227	5
ZY2	CY2	4.911	4.387	4.991	0.126	0.312	0.755	15
ZY2	CY3	4.586	4.612	4.991	-0.424	-1.047	0.296	32
ZY2	CY4	4.905	4.673	4.991	-0.166	-0.409	0.683	24
ZY3	CY1	5.046	4.708	5.253	-0.321	-0.793	0.428	31
ZY3	CY2	5.335	4.387	5.253	0.288	0.710	0.478	11
ZY3	CY3	5.540	4.612	5.253	0.268	0.663	0.508	12
ZY3	CY4	5.080	4.673	5.253	-0.253	-0.624	0.533	29
ZY4	CY1	4.564	4.708	4.070	0.380	0.939	0.348	8
ZY4	CY2	4.171	4.387	4.070	0.307	0.759	0.448	10
ZY4	CY3	2.998	4.612	4.070	-1.091	-2.693	0.007	35
ZY4	CY4	4.546	4.673	4.070	0.396	0.979	0.328	6
ZY5	CY1	3.851	4.708	4.288	-0.551	-1.361	0.174	33
ZY5	CY2	0.981	4.387	4.288	-3.102	-7.658	0.000	36
ZY5	CY3	4.633	4.612	4.288	0.326	0.804	0.422	9
ZY5	CY4	4.932	4.673	4.288	0.564	1.393	0.165	4
ZY6	CY1	4.337	4.708	4.319	-0.096	-0.237	0.813	21
ZY6	CY2	4.367	4.387	4.319	0.254	0.627	0.531	13
ZY6	CY3	5.333	4.612	4.319	0.995	2.457	0.014	1
ZY6	CY4	3.654	4.673	4.319	-0.744	-1.837	0.067	34
ZY7	CY1	5.273	4.708	4.573	0.586	1.446	0.149	3
ZY7	CY2	4.202	4.387	4.573	-0.164	-0.406	0.685	23
ZY7	CY3	4.433	4.612	4.573	-0.159	-0.392	0.696	22
ZY7	CY4	4.342	4.673	4.573	-0.311	-0.767	0.444	30
ZY8	CY1	4.953	4.708	4.814	0.025	0.061	0.951	17
ZY8	CY2	4.585	4.387	4.814	-0.023	-0.057	0.954	19
ZY8	CY3	-	4.612	4.814	-	-	-	37
ZY8	CY4	4.920	4.673	4.814	0.026	0.065	0.949	16
ZY9	CY1	3.630	4.708	3.605	-0.089	-0.220	0.826	20
ZY9	CY2	3.581	4.387	3.605	0.181	0.448	0.655	14
ZY9	CY3	-	4.612	3.605	-	-	-	38
ZY9	CY4	-	4.673	3.605	-	-	-	39
ZY10	CY1	4.500	4.708	4.576	-0.190	-0.468	0.640	25
ZY10	CY2	4.151	4.387	4.576	-0.219	-0.540	0.590	28
ZY10	CY3	5.521	4.612	4.576	0.926	2.286	0.023	2
ZY10	CY4	-	4.673	4.576	-	-	-	40

L xT: line by tester, SCA: specific combining ability, SE: square error

Appendix 3.5 BLUPs and BLUEs for grain yield of 36 F_1s and six commercial check hybrids of yellow maize under acid, non-acid and across acid and non-acid soil conditions

Entry	Cross	Line	Tester	Acid		Non-acid		Across Acid & Non-acid	
				BLUP_GY	BLUE_GY	BLUP_GY	BLUE_GY	BLUP_GY	BLUE_GY
1	ZY5 x CY2	ZY5	CY2	3.793	2.557	4.832	-2.965	3.906	0.859
2	ZY7x CY2	ZY7	CY2	3.883	3.663	5.211	4.865	4.399	4.185
3	ZY8 x CY2	ZY8	CY2	3.641	3.216	5.646	6.303	4.602	4.585
4	ZY3 x CY2	ZY3	CY2	4.218	4.388	5.715	6.531	5.009	5.335
5	ZY4 x CY2	ZY4	CY2	3.839	3.622	5.209	4.858	4.376	4.171
6	ZY1 x CY2	ZY1	CY2	3.931	3.804	5.512	5.859	4.674	4.718
7	ZY2 x CY2	ZY2	CY2	4.246	4.457	5.395	5.474	4.779	4.911
8	ZY10 x CY2	ZY10	CY2	3.559	2.986	5.379	5.421	4.339	4.091
9	ZY6 x CY2	ZY6	CY2	4.121	4.201	5.122	4.572	4.483	4.367
10	ZY9 x CY2	ZY9	CY2	3.595	3.131	4.990	4.135	4.055	3.581
11	ZY5 x CY1	ZY5	CY1	3.794	3.530	5.024	4.25	4.203	3.851
12	ZY7 x CY1	ZY7	CY1	4.379	4.737	5.534	5.931	4.976	5.273
13	ZY8 x CY1	ZY8	CY1	4.223	4.413	5.454	5.704	4.805	4.973
14	ZY3 x CY1	ZY3	CY1	4.330	4.650	5.329	5.256	4.774	4.908
15	ZY4 x CY1	ZY4	CY1	4.119	4.188	5.264	5.042	4.590	4.564
16	ZY1 x CY1	ZY1	CY1	4.445	4.860	5.583	6.095	5.050	5.409
17	ZY2 x CY1	ZY2	CY1	4.090	4.139	5.860	7.007	5.058	5.445
18	ZY10 x CY1	ZY10	CY1	4.006	3.959	5.507	5.884	4.71	4.788
19	ZY6 x CY1	ZY6	CY1	4.037	4.022	5.174	4.742	4.467	4.337
20	ZY9 x CY1	ZY9	CY1	3.608	3.150	5.017	4.226	4.082	3.630
21	ZY5 x CY4	ZY5	CY4	3.993	3.943	5.602	6.158	4.790	4.932
22	ZY7 x CY4	ZY7	CY4	4.170	4.284	5.079	4.430	4.469	4.342
23	ZY8 x CY4	ZY8	CY4	4.109	4.169	5.514	5.867	4.784	4.920
24	ZY3 x CY4	ZY3	CY4	4.396	4.757	5.402	5.496	4.871	5.080
25	ZY4 x CY4	ZY4	CY4	4.180	4.320	5.200	4.829	4.580	4.546
26	ZY1 x CY4	ZY1	CY4	3.618	3.136	5.720	6.548	4.662	4.696
27	ZY2 x CY4	ZY2	CY4	4.204	4.371	5.425	5.572	4.776	4.905
28	ZY6 x CY4	ZY6	CY4	3.917	3.736	4.770	2.934	4.041	3.405
29	ZY5 x CY3	ZY5	CY3	4.097	4.159	5.317	5.217	4.628	4.633
30	ZY7 x CY3	ZY7	CY3	3.934	3.811	5.316	5.212	4.519	4.433
31	ZY3 x CY3	ZY3	CY3	4.344	4.650	5.753	6.654	5.121	5.540
32	ZY4 x CY3	ZY4	CY3	3.370	2.664	4.77	3.410	3.738	2.998
33	ZY1 x CY3	ZY1	CY3	4.043	4.044	5.33	5.260	4.607	4.598
34	ZY2 x CY3	ZY2	CY3	4.539	5.051	4.952	4.010	4.602	4.586
35	ZY10 x CY3	ZY10	CY3	3.964	3.784	5.246	4.756	4.46	4.193
36	ZY6 x CY3	ZY6	CY3	4.002	3.918	5.254	4.146	4.498	4.234
37	Check1	Check1	Check1	4.160	4.277	5.424	5.569	4.746	4.85
38	Check2	Check2	Check2	4.107	4.186	5.68	6.414	4.928	5.185
39	Check3	Check3	Check3	3.634	3.199	5.868	7.153	4.77	4.899
40	Check4	Check4	Check4	4.104	4.180	5.317	5.216	4.630	4.637
41	Check5	Check5	Check5	4.925	5.847	5.788	6.770	5.515	6.263
42	Check6	Check6	Check6	4.280	4.535	5.677	6.403	5.030	5.373

GY: grain yield, BLUP: best linear unbiased predicts, BLUE: best linear unbiased estimates

Appendix 4.1 The 47 line x tester white kernel F_1s evaluated together with eight commercial check hybrids under acid and non-acid soil conditions, during the 2015-2016 cropping seasons in Angola and Zimbabwe

Entry	Hybrid name	Crosses	Entry	Hybrid name	Crosses
1	CH142471	ZW7 x CW1	29	CH142499	ZW8 x CW4
2	CH142472	ZW5 x CW1	30	CH142500	ZW3 x CW4
3	CH142473	ZW4 x CW1	31	CH142501	ZW6 x CW4
4	CH142474	ZW4 x CW8	32	CH142502	ZW7 x CW5
5	CH142475	ZW1 x CW2	33	CH142503	ZW5 x CW5
6	CH142476	ZW2 x CW1	34	CH142504	ZW4 x CW5
7	CH142477	ZW8 x CW2	35	CH142505	ZW1 x CW5
8	CH142478	ZW3 x CW1	36	CH142506	ZW2 x CW5
9	CH142479	ZW6 x CW1	37	CH142507	ZW8 x CW5
10	CH142480	ZW5 x CW3	38	CH142508	ZW3 x CW5
11	CH142481	ZW1 x CW3	39	CH142509	ZW6 x CW5
12	CH142482	ZW2 x CW3	40	CH142510	ZW7 x CW8
13	CH142483	ZW8 x CW3	41	CH142511	ZW5 x CW8
14	CH142484	ZW3 x CW3	42	CH142474	ZW4 x CW8
15	CH142485	ZW6 x CW3	43	CH142512	ZW1 x CW8
16	CH142486	ZW7 x CW7	44	CH142513	ZW2 x CW8
17	CH142487	ZW5 x CW6	45	CH142514	ZW8 x CW8
18	CH142488	ZW4 x CW7	46	CH142515	ZW3 x CW8
19	CH142489	ZW1 x CW7	47	CH142516	ZW6 x CW8
20	CH142490	ZW2 x CW7	48	Check1	Check1
21	CH142491	ZW8 x CW7	49	Check2	Check2
22	CH142492	ZW3 x CW6	50	Check3	Check3
23	CH142493	ZW6 x CW7	51	Check4	Check4
24	CH142494	ZW7 x CW4	52	Check5	Check5
25	CH142495	ZW5 x CW4	53	Check6	Check6
26	CH142496	ZW4 x CW4	54	Check7	Check7
27	CH142497	ZW1 x CW4	55	Check8	Check8
28	CH142498	ZW2 x CW4			

Appendix 4.2 Mean grain yield (t ha^{-1}) estimates and general combining ability effects for white maize lines under acid, non-acid and across acid and non-acid soil conditions

Line	Mean	GCA_	T_value_ GCA_line	Prob_t_ GCA_line	Rank
A. Acid soils					
ZW1	4.141	0.421	1.781	0.0813	2
ZW2	3.189	-0.531	-2.243	0.0295	8
ZW3	3.496	-0.224	-0.946	0.3490	7
ZW4	3.709	-0.011	-0.048	0.9623	4
ZW5	3.791	0.071	0.299	0.7659	3
ZW6	4.298	0.578	2.444	0.0183	1
ZW7	3.588	-0.132	-0.557	0.5798	6
ZW8	3.625	-0.095	-0.400	0.6912	5
B. Non-acid soils					
ZW1	4.946	0.280	0.762	0.4534	2
ZW2	4.473	-0.193	-0.524	0.6054	6
ZW3	4.536	-0.130	-0.353	0.7275	5
ZW4	4.190	-0.475	-1.293	0.2084	8
ZW5	4.921	0.256	0.695	0.4936	3
ZW6	4.541	-0.125	-0.339	0.7376	4
ZW7	4.346	-0.319	-0.868	0.3942	7
ZW8	5.156	0.490	1.333	0.1951	1
C. Across acid & non-acid soils					
ZW1	4.391	0.382	1.540	0.1279	1
ZW2	3.613	-0.396	-1.598	0.1143	8
ZW3	3.816	-0.193	-0.778	0.4392	7
ZW4	3.856	-0.154	-0.619	0.5379	5
ZW5	4.139	0.130	0.523	0.6029	3
ZW6	4.352	0.343	1.384	0.1707	2
ZW7	3.832	-0.177	-0.713	0.4781	6
ZW8	4.116	0.107	0.432	0.6668	4

GCA: general combining ability

Appendix 4.3 Mean grain yield (t ha-1) estimates and general combining ability effects for white maize testers under acid, non-acid and across acid and non-acid soil conditions

Tester	Mean	GCA	T_value_GCA	Prob_t_GCA	Rank
A. Acid soils					
CW1	4.048	0.328	1.574	0.1221	2
CW2	4.066	0.346	1.658	0.1038	1
CW3	3.986	0.266	1.275	0.2085	3
CW4	3.984	0.263	1.264	0.2122	4
CW5	3.309	-0.411	-1.973	0.0543	8
CW6	3.936	0.215	1.034	0.3063	5
CW7	3.861	0.141	0.678	0.5013	6
CW8	3.315	-0.405	-1.943	0.0579	7
B. Non-acid soils					
CW1	5.364	0.698	3.080	0.0051	2
CW2	5.856	1.190	5.248	0.0000	1
CW3	4.324	-0.342	-1.508	0.1447	7
CW4	5.237	0.571	2.518	0.0189	3
CW5	4.427	-0.239	-1.053	0.3029	6
CW6	5.027	0.362	1.595	0.1238	4
CW7	4.606	-0.059	-0.262	0.7955	5
CW8	4.081	-0.585	-2.578	0.0165	8
C. Across acid & non-acid soils					
CW1	4.414	0.404	2.030	0.0460	2
CW2	4.662	0.653	3.279	0.0016	1
CW3	4.088	0.079	0.395	0.6940	5
CW4	4.335	0.326	1.637	0.1060	3
CW5	3.687	-0.322	-1.617	0.1104	7
CW6	4.286	0.277	1.392	0.1682	4
CW7	4.082	0.073	0.364	0.7166	6
CW8	3.551	-0.458	-2.300	0.0243	8

GCA: general combining ability

Appendix 4.4 Mean grain yield (t ha-1) estimates and specific combining ability effects for GY of the white maize F_1s under acid, non-acid and across acid and non-acid soil conditions

Line	Tester	Mean			SCA_ LxT	SCA_SE LxT	T_Value LxT	Prob_T LxT	SCA_LxT RANK
		LxT	Tester	Line					
A. Acid soils									
ZW1	CW1	-	4.048	4.141	-	0.423	-	-	47
ZW1	CW2	4.924	4.066	4.141	0.437	0.423	1.034	0.302	11
ZW1	CW3	4.708	3.986	4.141	0.301	0.423	0.711	0.477	16
ZW1	CW4	4.423	3.984	4.141	0.018	0.423	0.044	0.965	26
ZW1	CW5	3.103	3.309	4.141	-0.627	0.423	-1.483	0.139	43
ZW1	CW6	-	3.936	4.141	-	0.423	-	-	48
ZW1	CW7	3.476	3.861	4.141	-0.806	0.423	-1.906	0.057	45
ZW1	CW8	4.664	3.315	4.141	0.927	0.423	2.193	0.029	1
ZW2	CW1	4.296	4.048	3.189	0.779	0.423	1.842	0.066	4
ZW2	CW2	-	4.066	3.189	-	0.423	-	-	49
ZW2	CW3	3.195	3.986	3.189	-0.260	0.423	-0.615	0.539	32
ZW2	CW4	3.161	3.984	3.189	-0.292	0.423	-0.689	0.491	34
ZW2	CW5	3.209	3.309	3.189	0.431	0.423	1.018	0.309	12
ZW2	CW6	-	3.936	3.189	-	0.423	-	-	50
ZW2	CW7	3.585	3.861	3.189	0.255	0.423	0.602	0.548	18
ZW2	CW8	2.429	3.315	3.189	-0.355	0.423	-0.840	0.402	36
ZW3	CW1	3.872	4.048	3.496	0.048	0.423	0.113	0.910	25
ZW3	CW2	-	4.066	3.496	-	0.423	-	-	51
ZW3	CW3	3.467	3.986	3.496	-0.295	0.423	-0.698	0.485	35
ZW3	CW4	4.447	3.984	3.496	0.687	0.423	1.624	0.105	6
ZW3	CW5	2.703	3.309	3.496	-0.382	0.423	-0.904	0.367	37
ZW3	CW6	4.135	3.936	3.496	0.423	0.423	1.000	0.318	13
ZW3	CW7	-	3.861	3.496	-	0.423	-	-	52
ZW3	CW8	2.829	3.315	3.496	-0.263	0.423	-0.621	0.535	33
ZW4	CW1	4.952	4.048	3.709	0.915	0.423	2.164	0.031	2
ZW4	CW2	-	4.066	3.709	-	0.423	-	-	53
ZW4	CW3	-	3.986	3.709	-	0.423	-	-	54
ZW4	CW4	3.865	3.984	3.709	-0.107	0.423	-0.253	0.800	27
ZW4	CW5	3.368	3.309	3.709	0.070	0.423	0.167	0.868	24
ZW4	CW6	-	3.936	3.709	-	0.423	-	-	55
ZW4	CW7	4.447	3.861	3.709	0.597	0.423	1.412	0.159	8
ZW4	CW8	3.162	3.315	3.709	-0.142	0.423	-0.335	0.738	28
ZW5	CW1	3.550	4.048	3.791	-0.569	0.423	-1.344	0.180	41
ZW5	CW2	-	4.066	3.791	-	0.423	-	-	57
ZW5	CW3	4.366	3.986	3.791	0.310	0.423	0.733	0.464	14
ZW5	CW4	4.231	3.984	3.791	0.177	0.423	0.418	0.676	22
ZW5	CW5	3.208	3.309	3.791	-0.172	0.423	-0.407	0.684	29
ZW5	CW6	3.791	3.936	3.791	-0.216	0.423	-0.510	0.611	30
ZW5	CW7	-	3.861	3.791	-	0.423	-	-	56
ZW5	CW8	3.614	3.315	3.791	0.228	0.423	0.539	0.590	20
ZW6	CW1	5.459	4.048	4.298	0.833	0.423	1.969	0.050	3

Appendix 4.4 (Continued) Mean grain yield (t ha^{-1}) estimates and specific combining ability effects for GY of the white maize F_1s under acid, non-acid and across acid and non-acid soil conditions

ZW6	CW2	-	4.066	4.298	-	0.423	-	-	58
ZW6	CW3	4.014	3.986	4.298	-0.550	0.423	-1.301	0.194	40
ZW6	CW4	5.285	3.984	4.298	0.723	0.423	1.709	0.088	5
ZW6	CW5	4.029	3.309	4.298	0.142	0.423	0.335	0.738	23
ZW6	CW6	-	3.936	4.298	-	0.423	-	-	59
ZW6	CW7	4.744	3.861	4.298	0.305	0.423	0.721	0.471	15
ZW6	CW8	2.859	3.315	4.298	-1.034	0.423	-2.445	0.015	46
ZW7	CW1	3.481	4.048	3.588	-0.435	0.423	-1.028	0.304	38
ZW7	CW2	-	4.066	3.588	-	0.423	-	-	62
ZW7	CW3	-	3.986	3.588	-	0.423	-	-	60
ZW7	CW4	3.354	3.984	3.588	-0.498	0.423	-1.176	0.240	39
ZW7	CW5	3.354	3.309	3.588	0.177	0.423	0.419	0.676	21
ZW7	CW6	-	3.936	3.588	-	0.423	-	-	61
ZW7	CW7	3.976	3.861	3.588	0.247	0.423	0.584	0.559	19
ZW7	CW8	3.792	3.315	3.588	0.609	0.423	1.439	0.151	7
ZW8	CW1	-	4.048	3.625	-	0.423	-	-	64
ZW8	CW2	3.350	4.066	3.625	-0.621	0.423	-1.469	0.143	42
ZW8	CW3	4.408	3.986	3.625	0.517	0.423	1.222	0.223	10
ZW8	CW4	3.631	3.984	3.625	-0.258	0.423	-0.610	0.543	31
ZW8	CW5	3.483	3.309	3.625	0.268	0.423	0.635	0.526	17
ZW8	CW6	-	3.936	3.625	-	0.423	-	-	63
ZW8	CW7	3.134	3.861	3.625	-0.633	0.423	-1.496	0.135	44
ZW8	CW8	3.747	3.315	3.625	0.527	0.423	1.245	0.214	9
B. Non-acid soils									
ZW1	CW1	-	5.364	4.946	-	1.022	-	-	46
ZW1	CW2	5.665	5.856	4.946	-0.471	1.022	-0.461	0.646	30
ZW1	CW3	5.181	4.324	4.946	0.577	1.022	0.564	0.573	13
ZW1	CW4	2.509	5.237	4.946	-3.008	1.022	-2.943	0.004	45
ZW1	CW5	5.038	4.427	4.946	0.331	1.022	0.324	0.746	18
ZW1	CW6	-	5.027	4.946	-	1.022	-	-	47
ZW1	CW7	5.249	4.606	4.946	0.363	1.022	0.355	0.723	17
ZW1	CW8	5.993	4.081	4.946	1.632	1.022	1.597	0.112	4
ZW2	CW1	6.039	5.364	4.473	0.868	1.022	0.849	0.397	10
ZW2	CW2	-	5.856	4.473	-	1.022	-	-	48
ZW2	CW3	4.634	4.324	4.473	0.503	1.022	0.493	0.623	15
ZW2	CW4	4.998	5.237	4.473	-0.046	1.022	-0.045	0.964	23
ZW2	CW5	3.835	4.427	4.473	-0.400	1.022	-0.391	0.696	28
ZW2	CW6	-	5.027	4.473	-	1.022	-	-	49
ZW2	CW7	3.116	4.606	4.473	-1.298	1.022	-1.270	0.206	40
ZW2	CW8	4.799	4.081	4.473	0.911	1.022	0.891	0.374	8
ZW3	CW1	5.291	5.364	4.536	0.057	1.022	0.055	0.956	22
ZW3	CW2	-	5.856	4.536	-	1.022	-	-	50
ZW3	CW3	3.750	4.324	4.536	-0.444	1.022	-0.434	0.665	29
ZW3	CW4	17.006	5.237	4.536	11.899	1.022	11.642	0.000	1
ZW3	CW5	3.569	4.427	4.536	-0.728	1.022	-0.712	0.477	34

Appendix 4.4 (Continued) Mean grain yield (t ha^{-1}) estimates and specific combining ability effects for GY of the white maize F_1s under acid, non-acid and across acid and non-acid soil conditions

B. Non-acid soils									
ZW3	CW6	5.416	5.027	4.536	0.518	1.022	0.507	0.613	14
ZW3	CW7	-	4.606	4.536	-	1.022	-	-	51
ZW3	CW8	2.535	4.081	4.536	-1.416	1.022	-1.386	0.168	41
ZW4	CW1	5.173	5.364	4.190	0.284	1.022	0.278	0.781	19
ZW4	CW2	-	5.856	4.190	-	1.022	-	-	52
ZW4	CW3	-	4.324	4.190	-	1.022	-	-	53
ZW4	CW4	13.668	5.237	4.190	8.907	1.022	8.715	0.000	2
ZW4	CW5	2.869	4.427	4.190	-1.083	1.022	-1.059	0.291	38
ZW4	CW6	-	5.027	4.190	-	1.022	-	-	54
ZW4	CW7	3.907	4.606	4.190	-0.224	1.022	-0.219	0.827	24
ZW4	CW8	4.097	4.081	4.190	0.492	1.022	0.481	0.631	16
ZW5	CW1	5.780	5.364	4.921	0.161	1.022	0.157	0.875	20
ZW5	CW2	-	5.856	4.921	-	1.022	-	-	56
ZW5	CW3	4.235	4.324	4.921	-0.344	1.022	-0.336	0.737	26
ZW5	CW4	4.761	5.237	4.921	-0.731	1.022	-0.715	0.476	35
ZW5	CW5	6.218	4.427	4.921	1.536	1.022	1.503	0.135	5
ZW5	CW6	4.716	5.027	4.921	-0.566	1.022	-0.554	0.580	33
ZW5	CW7	-	4.606	4.921	-	1.022	-	-	55
ZW5	CW8	3.588	4.081	4.921	-0.749	1.022	-0.733	0.465	36
ZW6	CW1	-	5.364	4.541	-	1.022	-	-	57
ZW6	CW2	-	5.856	4.541	-	1.022	-	-	58
ZW6	CW3	4.866	4.324	4.541	0.667	1.022	0.653	0.515	12
ZW6	CW4	6.164	5.237	4.541	1.052	1.022	1.029	0.305	6
ZW6	CW5	5.182	4.427	4.541	0.880	1.022	0.861	0.390	9
ZW6	CW6	-	5.027	4.541	-	1.022	-	-	59
ZW6	CW7	2.545	4.606	4.541	-1.936	1.022	-1.894	0.060	44
ZW6	CW8	2.340	4.081	4.541	-1.616	1.022	-1.581	0.115	43
ZW7	CW1	4.668	5.364	4.346	-0.376	1.022	-0.368	0.713	27
ZW7	CW2	-	5.856	4.346	-	1.022	-	-	62
ZW7	CW3	-	4.324	4.346	-	1.022	-	-	60
ZW7	CW4	4.112	5.237	4.346	-0.805	1.022	-0.788	0.432	37
ZW7	CW5	5.156	4.427	4.346	1.048	1.022	1.025	0.307	7
ZW7	CW6	-	5.027	4.346	-	1.022	-	-	61
ZW7	CW7	4.415	4.606	4.346	0.128	1.022	0.125	0.900	21
ZW7	CW8	3.252	4.081	4.346	-0.510	1.022	-0.499	0.618	31
ZW8	CW1	-	5.364	5.156	-	1.022	-	-	64
ZW8	CW2	6.015	5.856	5.156	-0.331	1.022	-0.324	0.746	25
ZW8	CW3	3.669	4.324	5.156	-1.144	1.022	-1.120	0.264	39
ZW8	CW4	5.216	5.237	5.156	-0.510	1.022	-0.499	0.618	32
ZW8	CW5	3.372	4.427	5.156	-1.545	1.022	-1.511	0.132	42
ZW8	CW6	-	5.027	5.156	-	1.022	-	-	63
ZW8	CW7	6.773	4.606	5.156	1.676	1.022	1.640	0.103	3
ZW8	CW8	5.344	4.081	5.156	0.773	1.022	0.756	0.450	11

Appendix 4.4 (Continued) Mean grain yield (t ha^{-1}) estimates and specific combining ability effects for GY of the white maize F_1s under acid, non-acid and across acid and non-acid soil conditions

C. Acid-non-acid soils									
ZW1	CW1	-	4.414	4.391	-	0.394	-	-	47
ZW1	CW2	5.171	4.662	4.391	0.127	0.394	0.322	0.748	19
ZW1	CW3	4.866	4.088	4.391	0.396	0.394	1.003	0.316	11
ZW1	CW4	3.945	4.335	4.391	-0.773	0.394	-1.959	0.051	45
ZW1	CW5	3.786	3.687	4.391	-0.283	0.394	-0.718	0.473	33
ZW1	CW6	-	4.286	4.391	-	0.394	-	-	48
ZW1	CW7	3.998	4.082	4.391	-0.466	0.394	-1.181	0.238	40
ZW1	CW8	5.063	3.551	4.391	1.130	0.394	2.865	0.004	2
ZW2	CW1	5.043	4.414	3.613	1.026	0.394	2.602	0.010	4
ZW2	CW2	-	4.662	3.613	-	0.394	-	-	49
ZW2	CW3	3.618	4.088	3.613	-0.073	0.394	-0.185	0.853	27
ZW2	CW4	3.773	4.335	3.613	-0.165	0.394	-0.419	0.675	29
ZW2	CW5	3.430	3.687	3.613	0.139	0.394	0.353	0.724	18
ZW2	CW6	-	4.286	3.613	-	0.394	-	-	50
ZW2	CW7	3.447	4.082	3.613	-0.238	0.394	-0.604	0.546	31
ZW2	CW8	3.219	3.551	3.613	0.065	0.394	0.165	0.869	23
ZW3	CW1	4.345	4.414	3.816	0.124	0.394	0.316	0.752	20
ZW3	CW2	-	4.662	3.816	-	0.394	-	-	51
ZW3	CW3	3.561	4.088	3.816	-0.334	0.394	-0.846	0.398	34
ZW3	CW4	5.842	4.335	3.816	1.700	0.394	4.309	0.000	1
ZW3	CW5	2.992	3.687	3.816	-0.503	0.394	-1.274	0.203	41
ZW3	CW6	4.562	4.286	3.816	0.468	0.394	1.187	0.236	9
ZW3	CW7	-	4.082	3.816	-	0.394	-	-	52
ZW3	CW8	2.737	3.551	3.816	-0.621	0.394	-1.574	0.116	44
ZW4	CW1	4.984	4.414	3.856	0.724	0.394	1.835	0.067	6
ZW4	CW2	-	4.662	3.856	-	0.394	-	-	53
ZW4	CW3	-	4.088	3.856	-	0.394	-	-	54
ZW4	CW4	5.266	4.335	3.856	1.084	0.394	2.748	0.006	3
ZW4	CW5	3.181	3.687	3.856	-0.353	0.394	-0.894	0.372	38
ZW4	CW6	-	4.286	3.856	-	0.394	-	-	55
ZW4	CW7	4.278	4.082	3.856	0.350	0.394	0.888	0.375	14
ZW4	CW8	3.474	3.551	3.856	0.077	0.394	0.194	0.846	22
ZW5	CW1	4.206	4.414	4.139	-0.337	0.394	-0.855	0.393	36
ZW5	CW2	-	4.662	4.139	-	0.394	-	-	57
ZW5	CW3	4.328	4.088	4.139	0.110	0.394	0.280	0.780	21
ZW5	CW4	4.408	4.335	4.139	-0.057	0.394	-0.145	0.885	26
ZW5	CW5	4.211	3.687	4.139	0.395	0.394	1.001	0.317	12
ZW5	CW6	4.080	4.286	4.139	-0.336	0.394	-0.852	0.395	35
ZW5	CW7	-	4.082	4.139	-	0.394	-	-	56
ZW5	CW8	3.607	3.551	4.139	-0.074	0.394	-0.187	0.852	28
ZW6	CW1	5.459	4.414	4.352	0.703	0.394	1.781	0.075	7
ZW6	CW2	-	4.662	4.352	-	0.394	-	-	58
ZW6	CW3	4.241	4.088	4.352	-0.190	0.394	-0.481	0.630	30
ZW6	CW4	5.460	4.335	4.352	0.782	0.394	1.982	0.048	5

Appendix 4.4 (Continued) Mean grain yield (t ha^{-1}) estimates and specific combining ability effects for GY of the white maize F_1s under acid, non-acid and across acid and non-acid soil conditions

C. Acid-non-acid soils									
ZW6	CW5	4.413	3.687	4.352	0.383	0.394	0.971	0.332	13
ZW6	CW6	-	4.286	4.352	-	0.394	-	-	59
ZW6	CW7	4.378	4.082	4.352	-0.047	0.394	-0.119	0.905	25
ZW6	CW8	2.765	3.551	4.352	-1.129	0.394	-2.863	0.004	46
ZW7	CW1	3.830	4.414	3.832	-0.406	0.394	-1.030	0.303	39
ZW7	CW2	-	4.662	3.832	-	0.394	-	-	62
ZW7	CW3	-	4.088	3.832	-	0.394	-	-	60
ZW7	CW4	3.607	4.335	3.832	-0.552	0.394	-1.398	0.163	43
ZW7	CW5	3.955	3.687	3.832	0.445	0.394	1.127	0.260	10
ZW7	CW6	-	4.286	3.832	-	0.394	-	-	61
ZW7	CW7	4.123	4.082	3.832	0.218	0.394	0.553	0.581	16
ZW7	CW8	3.623	3.551	3.832	0.249	0.394	0.632	0.528	15
ZW8	CW1	-	4.414	4.116	-	0.394	-	-	64
ZW8	CW2	4.238	4.662	4.116	-0.531	0.394	-1.347	0.178	42
ZW8	CW3	4.191	4.088	4.116	-0.004	0.394	-0.011	0.991	24
ZW8	CW4	4.160	4.335	4.116	-0.283	0.394	-0.717	0.474	32
ZW8	CW5	3.450	3.687	4.116	-0.344	0.394	-0.872	0.384	37
ZW8	CW6	-	4.286	4.116	-	0.394	-	-	63
ZW8	CW7	4.347	4.082	4.116	0.158	0.394	0.400	0.689	17
ZW8	CW8	4.280	3.551	4.116	0.621	0.394	1.576	0.116	8

L x T: line by tester, SCA: specific combining ability, SE: square error

Appendix 4.5 BLUEs and BLUPs for grain yield of 47 F_1s and 8 commercial checks hybrids under acid, non-acid and across acid and non-acid soil conditions

Entry	Cross	Line	Tester	Acid		Non-acid		Across Acid & Non-acid	
				BLUP_GY	BLUE_ GY	BLUP_GY	BLUE _GY	BLUP_G Y	BLUE_G Y
1	ZW7 x CW1	ZW7	CW1	3.406	2.988	5.057	5.689	3.999	3.936
2	ZW5 x CW1	ZW5	CW1	3.519	3.42	5.285	6.880	4.249	4.571
3	ZW4 x CW1	ZW4	CW1	3.529	3.372	4.685	0.422	3.812	3.234
4	ZW4 x CW8	ZW4	CW8	3.561	3.543	4.685	3.794	3.850	3.613
5	ZW1 x CW2	ZW1	CW2	3.841	4.315	4.991	5.330	4.295	4.662
6	ZW2 x CW1	ZW2	CW1	3.264	2.022	4.757	3.578	3.631	2.528
7	ZW8 x CW2	ZW8	CW2	3.45	3.194	5.138	6.032	4.081	4.137
8	ZW3 x CW1	ZW3	CW1	3.638	3.756	4.945	4.790	4.082	4.146
9	ZW6 x CW1	ZW6	CW1	3.744	4.295	.	.	4.179	4.731
10	ZW5 x CW3	ZW5	CW3	3.865	4.433	4.957	5.332	4.290	4.699
11	ZW1 x CW3	ZW1	CW3	3.808	4.269	4.808	4.203	4.139	4.307
12	ZW2 x CW3	ZW2	CW3	3.403	3.056	5.132	6.311	4.053	4.090
13	ZW8 x CW3	ZW8	CW3	3.835	4.326	4.814	4.184	4.158	4.352
14	ZW3 x CW3	ZW3	CW3	3.543	3.497	4.698	3.913	3.850	3.615
15	ZW6 x CW3	ZW6	CW3	3.649	3.794	5.081	6.058	4.218	4.502
16	ZW7 x CW7	ZW7	ZW7	3.523	3.398	4.794	4.154	3.895	3.688
17	ZW5 x CW6	ZW5	CW6	3.618	3.676	5.072	5.802	4.176	4.391
18	ZW4 x CW7	ZW4	CW7	3.816	4.328	4.857	4.762	4.161	4.362
19	ZW1 x CW7	ZW1	CW7	3.5	3.355	4.877	4.576	3.935	3.784
20	ZW2 x CW7	ZW2	CW7	3.474	3.276	4.783	4.248	3.856	3.615
21	ZW8 x CW7	ZW8	CW7	3.456	3.237	5.29	6.809	4.200	4.472
22	ZW3 x CW6	ZW3	CW6	3.51	3.339	4.873	4.627	3.946	3.774
23	ZW6 x CW7	ZW6	CW7	3.788	4.161	4.934	5.283	4.224	4.563
24	ZW7 x CW4	ZW7	CW4	3.544	3.481	4.745	4.146	3.878	3.663
25	ZW5 x CW4	ZW5	CW4	3.751	4.041	4.905	4.779	4.167	4.351
26	ZW4 x CW4	ZW4	CW4	3.44	3.085	5.132	9.351	4.071	4.210
27	ZW1 x CW4	ZW1	CW4	3.869	4.493	4.907	4.863	4.265	4.675
28	ZW2 x CW4	ZW2	CW4	3.299	2.769	4.911	4.837	3.799	3.473
29	ZW8 x CW4	ZW8	CW4	3.681	3.885	4.996	5.387	4.167	4.367
30	ZW3 x CW4	ZW3	CW4	3.653	3.8	5.304	12.685	4.375	5.115
31	ZW6 x CW4	ZW6	CW4	3.871	4.571	4.872	4.426	4.241	4.679
32	ZW7 x CW5	ZW7	CW5	3.445	3.216	4.969	5.134	3.964	3.894
33	ZW5 x CW5	ZW5	CW5	3.499	3.349	5.16	6.002	4.132	4.278
34	ZW4 x CW5	ZW4	CW5	3.61	3.679	4.541	3.289	3.783	3.414
35	ZW1 x CW5	ZW1	CW5	3.348	2.903	4.904	5.003	3.833	3.582
36	ZW2 x CW5	ZW2	CW5	3.482	3.262	4.727	3.980	3.823	3.502
37	ZW8 x CW5	ZW8	CW5	3.455	3.202	4.789	4.161	3.838	3.554
38	ZW3 x CW5	ZW3	CW5	3.304	2.856	4.639	3.670	3.619	3.111
39	ZW6 x CW5	ZW6	CW5	3.759	4.072	4.989	5.265	4.224	4.475
40	ZW7 x CW8	ZW7	CW8	3.674	3.886	4.777	4.386	4.008	4.011
41	ZW5 x CW8	ZW5	CW8	3.588	3.63	4.812	4.183	3.964	3.891
42	ZW4 x CW8	ZW4	CW8	3.328	2.861	4.802	4.239	3.749	3.355

Appendix 4.5 (Continued) BLUEs and BLUPs for grain yield of 47 F_1s and 8 commercial check hybrids under acid, non-acid and across acid and non-acid soil conditions

43	ZW1 x CW8	ZW1	CW8	3.798	4.336	5.154	7.094	4.402	5.126
44	ZW2 x CW8	ZW2	CW8	3.149	2.394	4.919	5.009	3.692	3.240
45	ZW8 x CW8	ZW8	CW8	3.642	3.784	4.977	5.130	4.112	4.224
46	ZW3 x CW8	ZW3	CW8	3.321	2.853	4.622	3.192	3.614	3.025
47	ZW6 x CW8	ZW6	CW8	3.302	2.698	4.584	1.730	3.558	2.665
48	Check1	Check1	Check1	3.7	3.953	4.951	5.235	4.144	4.322
49	Check2	Check2	Check2	3.898	4.495	5.046	6.242	4.397	5.016
50	Check3	Check3	Check3	3.447	3.189	4.745	4.351	3.807	3.494
51	Check4	Check4	Check4	3.595	3.632	5.156	6.226	4.203	4.447
52	Check5	Check5	Check5	3.906	4.537	5.145	6.125	4.451	5.071
53	Check6	Check6	Check6	3.63	3.726	4.951	4.909	4.087	4.147
54	Check7	Check7	Check7	3.431	3.165	4.96	5.241	3.946	3.834
55	Check8	Check8	Check8	3.701	3.921	4.777	4.114	4.019	4.000

BLUP: Best linear unbiased predicts, BLUE: Best linear unbias estimates, GY: grain yield