

**Genetic analysis of maize hybrids derived from temperate by
tropical germplasm under low and high plant population density
stress**

by

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GENERAL ABSTRACT

Maize is a major staple food crop in Sub-Saharan Africa and it plays a vital role in the livelihoods of small-scale and resource-limited farmers. The demand for maize is high and is also expected to increase due to the increasing population. Grain yield per unit area can be increased by increasing the plant population density. In this regard, the new improved maize varieties should be richly endowed with high and enhanced frequency of genes that confers high yield under varying plant population density stress conditions. The objective of this study was to conduct a genetic analysis of maize hybrids derived from temperate by tropical germplasm under low and high plant population density stress in order to identify hybrids that combine high yield, earliness and tolerance to high plant population density stress as well as the breeding strategy for these essential traits. New maize inbred lines derived from tropical by temperate populations were selected based on observation trials for yield potential and prolificacy to ensure adaptation. These were used to generate hybrids using two different testers with different genetic attributes. The hybrids were planted in four environments; Ukulinga1 (Env-1), Cedara (Env-2), Dundee (Env-4) and Ukulinga 2 (Env-3) in two replications. One of these environments (Ukulinga 2), had a high plant population density. Data was collected on various agronomic traits that include grain yield, plant height, ear height, days to anthesis, ear position, number of ears per plant, anthesis-silking interval, grain moisture content, root and stem lodging, number of tassel branches, number of leaves above the cob, days to cob dryness and number of plants per row. Analysis of variance for single sites showed that hybrids were significantly different on the traits studied, and across environments (low and high plant population densities). This enabled the genotype plus genotype by environment biplots to be used in identifying varieties suitable for given environments as well as stable and high yielding varieties. The line by tester analysis of variance showed that the general combining ability effects of the lines were significant ($P < 0.05$) and that narrow sense heritability was low for grain yield but higher for other traits. The results of this study identified hybrids (and their inbred lines) that performed better under high plant population density stress and the traits associated with high yield under high and low plant population densities across different genetic backgrounds. Superior, stable and high yielding hybrids were selected and hybrids 15XH214, 15XH215 and 15XH121 were the most adaptable genotypes across environments, out-competing the highest yielding commercial hybrids such as PAN6Q345BC and BG5285 under high stress conditions. With regards to the

genetic gain, the study revealed 16.70 % and 22.70 % genetic gain of grain yield under both Tester 9 (Testers A) and DTAB32 (Tester B), respectively, which was displayed by the high-yielding experimental hybrids. The studies also revealed high genetic variability of traits among hybrids, which can be exploited to obtain further breeding gains. The high genetic gains and stress tolerance indices of these hybrids over the checks were related to resistance to stem lodging and increased ears per plant. Most of these hybrids were derived from the tester DTAB32 which is associated with a huge contribution to stress resistance, including lodging. Based on the combining ability analysis, inbred lines with resistance to stem lodging and high ear prolificacy were identified as, 15XH214 and 15XH215 under tester B and 15XH121 under tester A. In producing better hybrids, such inbred lines were complimented by Tester DTAB32 that has been shown to have resistance to lodging and other abiotic stresses. The identification of the best genotypes based on the increase of plant population density stress tolerance was achieved through the selection of the hybrids which possessed good standability, yield stability and high grain yielding ability. The genetic coefficient of variation (GCV) and narrow sense heritability values estimated were moderate for all traits but low for grain yield thus calling for a need to identify the traits which could be targeted for improving the grain yield of the hybrids based on indirect selection of traits highly correlated with grain yield, easy to measure and have higher heritability. Generally, the results of this study identified inbred lines with good general combining ability (GCA). This shows the possibility of developing desirable cross combinations and synthetic varieties through crossing of inbred lines with desirable traits of interest. Furthermore, promising cross combinations identified in this study could be used for future breeding work as well as for direct release after confirming the stability of their performances observed in this study. Hence, the information on combining ability from this study may be useful for researchers to develop high yielding varieties of maize under high and low plant population densities as well as assisting in defining genetic advance; which will enable effective and efficient selection of the germplasm lines to produce new maize hybrids. From the study it was revealed that ears per plant and stem lodging were highly correlated with grain yield and had high positive direct effects on grain yield under high plant population density. These traits did not only have high correlations with grain yield, but also had high narrow sense heritabilities as well and were easy to select for, thus making them ideal candidates for indirect selection for improved grain yield under high plant population density stress. This study concluded that high plant population density reduces ears per plant and increases stem lodging which result

in reduced grain yield. Development of ideal breeding strategies that can improve grain yield under high plant population density is desired. Advance testing of these maize hybrids in more seasons could enhance good and desired breeding productivity with reference to cultivar stability and adaptation across environments. This suggested that this selected hybrids exhibits progressive stability in different environments, which is a desirable attribute for the smallholder farming conditions, where management conditions are variable. These hybrids have the potential to respond positively to improved environmental conditions, since they were able to obtain high yields under high plant population density. Therefore, they can be recommended for advancement in the following season. Further tests on these experimental hybrids for commercial use could be done to enable their release given the need for increased maize production and productivity in South Africa, to prevent recurrent food shortages that result food insecurity.

DECLARATION

I, NDOU Vuledzani Nico, certify that this is my original work and it contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by any other person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of KwaZulu-Natal and where applicable, any partner institution responsible for the joint-award of this degree. I also declare that;

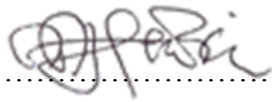
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As the candidate's supervisors, we agree to the submission of this thesis



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.....Date.....**28-09-2016**.....

Dr Pauline Chivenge (Co-Supervisor)

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LIST OF ACRONYMS

AD: Anthesis date

ANOVA: Analysis of variance

ASI: Anthesis-silking interval

CED: Cedara Agricultural research station

CIMMYT: International Maize and Wheat Improvement Center

CV: Coefficient of variation

DAFF: Department of Agriculture, Forestry and Fisheries

EH: Ear height

EPO: Ear position

EPP: Number of ears per plant

FAO: Food and Agriculture Organization of the United Nations

FAOSTAT: Food and Agriculture Organization Statistics

G x E: Genotype by environment interaction

GCA: General combining ability

GGE: Genotype plus genotype by environment interaction

GYG: Grain yield

IITA: International Institute of Tropical Agriculture

KZNDARD: KwaZulu-Natal Department of Agriculture & Rural Development

L x T: Line by tester

LSD: Least significant difference

MOI: Grain moisture

MT: Metric tonnes

PH: Plant height

RL: Root lodging

SCA: Specific combining ability

SL: Stem lodging

SSA: Sub-Saharan Africa

STI: Stress tolerance index

TL: Total plant lodging

UK1; Ukulinga research station 1

UK2: Ukulinga research station 2

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CHAPTER 1

Introduction

1.1. Background of maize and its significance

Maize (*Zea mays* L.) is the most important grain crop in South Africa, being both the major feed grain and the staple food for the majority of the South African population (FAO, 2013) and has the highest production and consumption among other cereal crops (ACB, 2007). Maize is the third most important source of calories for humankind after rice and wheat in the world (Bänziger *et al.*, 2006) and it is the second largest crop produced in South Africa after sugar cane (DAFF, 2014). Breeding for yield potential and abiotic stress tolerance in maize germplasm in Sub-Saharan Africa (SSA) is essential to achieve future food security, because future food security is compromised by the lack of maize cultivars that are resistant to abiotic stresses such as high plant population density stress. Recently, maize has gained additional interest as a renewable energy source as a result of its high biomass production potential (FAO, 2015). Breeders maintain maize at high genetic diversity to allow production under different climatic conditions across the globe. Maize is considered a model crop for genetic investigations because of its high degree of genetic diversity (Ackerson, 1983; Austin *et al.*, 2001; Zhang *et al.*, 2010) and ability of scientists to manipulate its genomic sequence via insertions, deletions, or recombination events (Agrama and Moussa, 1996; Xu *et al.*, 2009; Yan *et al.*, 2011).

One strategy for enhancing productivity in maize is through manipulation of plant population density. However, high plant population density is a worldwide phenomenon and can be a major production constraint that reduces crop yields, because different hybrids show different levels of tolerance to plant population density stress. The extent of climate change over the next 20 years and its impact are difficult to predict but it is essential to put research in place now that will be needed in the longer term (Hellin *et al.*, 2012).

1.2. Constraints to maize production

Maize production constraints include both biotic and abiotic factors. The main biotic factors are pests and diseases. The most common abiotic factors are drought, extreme temperatures, low soil fertility, high soil aluminium (soil acidity), flooding, salinity, and high plant population density (Austin and Lee, 1998; Schlenker and Lobell, 2010). Abiotic stress is a common phenomenon in the tropics thus contributing to yield losses in crop production. Moisture stress is one of the most common limitations of crop production in developing countries, and global warming is predicted to further aggravate abiotic stress impact on crops (FAO, 2012). This major limitation is caused by irregular rainfall distribution and this is exacerbated by the low water holding capacity of the soils (Jeffery *et al.*, 2011). More recently, global warming may be worsening this situation in most agricultural regions (FAO, 2013; Schlenker and Lobell, 2010). Indeed, plants show a wide range of adaptations, at different levels, to high and low plant population densities. At the same time, maize is grown without irrigation as a result of the high cost of installation of irrigation facilities, in which some of the resource-poor small-scale farmers cannot afford (Springer *et al.*, 2009). Global climate change is now generally considered to be underway (Chapman and Edmeades, 1999, Brown, 2010; Schlenker and Lobell 2010), and is expected to result in a long-term trend towards higher temperatures, greater evapotranspiration, and an increased incidence of drought in specific regions.

The yield of maize in South Africa is very low as compared to other maize producing countries globally. While maize yields have steadily increased in over 70 % of maize growing areas, in SSA maize yields remain the lowest in the world with the average production of about 65 million tonnes as compared to about 785 million tonnes in the world and have stagnated since the early 1990s (FAO, 2014; IITA, 2015; Ray *et al.*, 2012). In South Africa the average maize production is about 7.4 million tonnes (DAFF, 2015). One of the most important factors is adoption of sub-optimal plant population per hectare and maize hybrids differ in their response to plant population density (Xue *et al.*, 2002). As maize does not have tillering capacity to adjust to variation in plant stand, optimum plant population density for grain production is important (Barbieri *et al.*, 2000). Agronomic practices such as maintaining optimum plant population are

known to affect the crop environment, which influences the yield and yield components (Ray *et al.*, 2012). Optimum plant population levels should be maintained to exploit maximum natural resources, such as nutrients, sunlight, and soil moisture to ensure satisfactory yield. Moreover, application of optimum plant population density in maize production helps proper utilization of solar radiation (Austin and Lee, 1998). When plant population density is too high, it encourages inter-plant competition for resources (Edwards *et al.*, 2005). This will further affect the crop net photosynthesis process due to less light penetration in the crop canopy as well as increase in the competition for available nutrients, which in turn will affect grain yield.

If plant population density is below optimum, production will be low while weed infestation will also be greater (Allard, 1999). Photosynthetic efficiency and growth in maize are strongly related to the effect of canopy architecture on the vertical distribution of light within the canopy (Austin and Lee, 1998). Increasing plant density is one of the ways of increasing the capture of solar radiation within the canopy (Shahram *et al.*, 2012). However, the efficiency of the conversion of intercepted solar radiation into maize yield decreases with a plant population density that is too high because of mutual shading in the plants (Zhang *et al.*, 2006). Ganjali and Majidi (2000) and Cho *et al.* (2004) also reported that plant height increases with the increased plant population density due to competition for light interception. In addition, a plant population density resulting in interplant competition affects vegetative and reproductive growth (Zhang *et al.*, 2006). Many studies have been conducted with the aim of determining the optimum plant density for maize (FAOSTAT, 2010). Unfortunately, there is no single recommendation for all conditions, because the optimum plant density varies depending on environmental factors, such as soil fertility and moisture supply, genotype factors (Gonzalo *et al.*, 2006), planting date, planting pattern and plant population. The differential responses to plant density in maize cultivars have been reported by Xue *et al.* (2002). Generally, maize yield decreases with increasing plant population density whereas, the yield per unit area increases (FAO, 2013). Xue *et al.* (2002) suggested that the best way to affect future gains in yielding ability may be to make further improvements in tolerance to high plant population densities, in combination with improvements in potential yield per plant under low stress environments. Seyyed *et al.* (2014) emphasized the importance of low stress conditions such as very low plant population density to avoid competition among plants in

optimizing the effectiveness of selection for improved potential yield per plant, tolerance to stresses and responsiveness to inputs.

1.3. Problem statement and justification

Maize is a major staple food crop grown in diverse agro-ecological zones and farming systems, and consumed by people with varying food preferences and socio-economic backgrounds in sub-Saharan Africa (SSA) (Smale *et al.*, 2011). The central role of maize as a staple food in SSA is comparable to that of rice or wheat in Asia, with consumption rates being highest in eastern and southern Africa (ESA) (FAOSTAT, 2010). Low maize yields due to the impacts of plant population density on maize production highlight the need to improve maize hybrids for lodging resistance in order to increase plants per unit area in Southern Africa. Maize is essential for food security in South Africa. Biotic and abiotic stresses are the major constraints to maize production causing low yields in SSA. Among abiotic factors, plant population density, whether operating directly on the plant or indirectly on biotic factors associated with plant density, is one of the most important factors in determining grain yield and other important agronomic attributes of a crop (Wende, 2013; Meyer, 1970).

The maize plant is less capable of adjustment to a poor stand than other members of the grass family. Modern maize varieties do not tiller much, even at low plant population densities, and very often produce only one ear per plant. Therefore, maize does not have the flexibility of most crop species, which can increase leaf area and number of reproductive units by branching at low crop densities (Gardner and Eberhart, 1966). Tolerance to higher planting densities has contributed to yield increase in temperate germplasm in addition to large genetic gains in yield potential and biotic and abiotic stress tolerance. Furthermore, over the past 30 years, it is a noticeable trend that growing seasons are becoming shorter associated with climate change (FAO, 2013). It has been difficult for breeders to identify new varieties which combine high yield, early maturity and tolerance to high and low plant population densities. This has been attributed to the fact that high yield, early maturity and tolerance to high and low plant population densities are negatively correlated traits as stated by Agrama and Moussa (1996). Therefore, this prompts for an investigation to find germplasm between the tropical and

temperate maize which combine high yield, early maturity and low and high plant population density stress tolerance. Most importantly, germplasm which will give high yields under both stress and favourable conditions are required so that farmers cannot get a yield penalty when they grow a low and high plant population density stress tolerant variety. This can be achieved by doing a genetic diversity analysis to determine high grain yield under both conditions (low and high plant population density stresses).

1.4. Research objectives

To conduct a genetic analysis of maize hybrids derived from temperate by tropical germplasm under low and high plant population density stress in order to identify hybrids that combine high yield, earliness and tolerance to high plant population density stress as well as the breeding strategy for these essential traits.

1.4.1. Specific objectives

The following specific objectives were pursued in the study:

To determine the:

1. Stability and genetic gains of new hybrids from temperate by tropical germplasm under low and high plant population density stress;
2. Combining ability between the new lines derived from temperate by tropical germplasm under low and high population density stress; and
3. Contribution of secondary traits to grain yield under low and high plant population density stress.

1.4.2. Research questions

The following research questions were pursued in the study:

1. What is the extent of stability and genetic gain that has been realised by breeding new hybrids from the temperate by tropical maize germplasm populations under low and high plant population density stress?

2. Are there inbred lines and hybrids from the temperate and tropical maize germplasm with general and specific combining ability for yield and allied traits under low and high plant population density stress?
3. Are there secondary traits that are highly correlated with grain yield under low and high plant population density stress among hybrids from the temperate by tropical maize germplasm?

1.4.3. Research hypotheses

The following research hypotheses were pursued in the study:

1. Some hybrids from the temperate and tropical maize germplasm have greater stability and yield gains under low and high plant population density stress;
2. Some inbred lines and hybrids from the temperate and tropical maize germplasm have desirable general and specific combining ability for yield and allied traits under low and high plant population density stress; and
3. There are secondary traits that are highly correlated with grain yield under low and high plant population density stress among hybrids from the temperate by tropical maize germplasm.

1.5. Thesis outline

The thesis chapters are presented in the following order:

Chapter 1: General Introduction

This chapter provides the study background and outlines the scope, aim and objectives, problem statement, significance of the study and outline of the thesis.

Chapter 2: Literature Review

This chapter presents the theoretical background of the study by reviewing literature pertaining to the importance of maize in Sub-Saharan Africa and the effect of high and low plant population density stresses on maize and its tolerance.

Chapter 3: Materials and Methods

This chapter outlines the design and field experiments of this study as well as pollinations, field data collection and capturing methods and data analysis approaches used.

Chapter 4: Results

This chapter covers the breeding gains realised under high and low density stress and the combining ability of the lines derived from temperate x tropical germplasm under high and low density stress. The correlations of secondary traits to grain yield are also presented.

Chapter 5: General Discussion

The results of the study are discussed in this chapter, and it also provides a general discussion of the findings in relation to the findings provided by the research that informs the study.

Chapter 6: Conclusion, Implications and Recommendations

This chapter draws the conclusions that were revealed from the study and summarizes the key findings of the research chapters and presents the overall conclusions and recommendations for future breeding programs and research.

CHAPTER 2

Literature Review

2.1. Introduction

This chapter reviews the literature on the significance of maize, emphasizing on the adaptation of maize and responses to varying plant population densities as well as the factors that affect optimum plant population density. It focusses more on the effects of dense stands on ear development and discussing important changes in plant traits that have increased the tolerance of modern hybrids to high plant population density stress as well as the literature on maize germplasm backgrounds such as tropical and temperate maize. It also covers the importance on genotype by environment interaction and stability analysis, genetic gain and therefore combining ability as well as the correlations between the secondary traits and grain yield in maize breeding programmes. Lastly, conclusions are drawn in relation to objectives of the research, and the identified knowledge gaps are highlighted.

2.2. Significance of maize

Maize (*Zea mays* L.) is currently being cultivated on nearly over 100 million hectares in 125 developing countries and is among the three most widely grown cereal crops worldwide (FAO, 2013) with a world production of 981 million tons of grain in 2014 (FAO, 2015). Rosegrant *et al.* (2009) predicted that by 2050, maize production and demand in developing countries is expected to increase dramatically. Nevertheless, maize yields in many developing countries are severely limited by an array of abiotic and biotic stress factors. The diversity of several important crops, including maize, spread across the world is threatened by rapid urbanization and habitat erosion as well as by the unpredictable and extreme climatic events, including increasing frequency of drought, heat and flooding (FAO, 2013). Production may therefore, not be able to meet the demands without strong policy and technological interventions (Shiferaw *et al.*, 2011).

According to Cairns *et al.* (2012), uncontrolled area expansion cannot be a solution for boosting maize production, as this could potentially threaten the fragile natural resources, including

forests and hill slopes in the developing world. Another important challenge that threatens the long-term growth of production of maize is the changing global climate. Lobell *et al.* (2008) also stated that climate change scenarios such as rainfall distribution, increased variability in precipitation and rising temperatures shows that agricultural production especially maize will largely be negatively affected and will impede the ability of many regions to achieve the necessary yield and gains for future food security (Müller *et al.*, 2011; Adamgbe and Ujoh, 2013). Concerted and intensive efforts are required to develop climate change resilient maize cultivars while accelerating the yield growth. Without that, the outcome will be hunger and food insecurity for millions of consumers of maize, particularly those living in developing countries (Ray *et al.*, 2012). Maize has enormous genetic diversity that offers incredible opportunities for genetic enhancement despite the challenges mentioned above.

2.3. Importance of maize production in Southern Africa

Maize is the primary staple food in many developing countries, particularly in Africa, and is also used for livestock feed (ACB, 2007). It is a versatile crop with wider genetic variability and able to grow successfully throughout the world covering tropical, subtropical and temperate agro-climatic conditions (FAOSTAT, 2010). Maize acreage and production has an increasing tendency with the introduction of hybrids due to its high yield potential (FAO, 2013) as it has a great utility in the agro-industry. Literature revealed that maize has exceptionally higher grain protein content than food rice in South African (DAFF, 2014). Although, maize is grown throughout the world, there are large differences in production per country (Table 2.1). Based on area and production, maize is the 3rd most important cereal crop after wheat and rice in the world (FAO, 2015). Successful maize production depends on the correct application of production inputs that will sustain the environment as well as agricultural production. These inputs are, *inter alia*, adapted cultivars and better crop management options such as optimum plant population, improved soil tillage, proper fertilisation and better management options for weeds, insects and diseases.

Table 2.1. Country, maize production, metric tonnes (MT) and share of SSA (%), population and per capita consumption of maize in SSA

Rank	Country	Production (MT)	Production share of SSA (%)	Population	Per capita consumption (kg)
1	South Africa	11 830 000	22.64	52 980 000	229
2	Tanzania	5 104 248	8.66	49 250 000	86
3	Malawi	3 618 699	7.93	16 360 000	195
4	Ethiopia	3 615 898	7.82	101 810 009	94
5	Kenya	2 919 931	6.99	47 260 744	171
6	Zambia	2 852 687	4.69	14 540 000	78
7	Mozambique	1 177 390	2.8	25 830 000	52
8	Uganda	1 169 019	2.73	40 322 768	55
9	Zimbabwe	1 000 000	2.38	14 150 000	125
10	Angola	454 343	1.21	21 470 000	33

Source: FAO, 2013

2.4. Maize production constraints in Southern Africa

Among the abiotic factors limiting maize production in SSA, population density stress, water limitation and harsh climatic conditions contribute to poor production of maize and yield loss (Adeniyani, 2014; FAO, 2013). Currently, high plant population density stress is one of the worldwide problems that cause reduction in maize yield (FAOSTAT, 2010). As a result, there is a need to develop stress tolerant maize hybrids as a result of challenges posed by increasing climate change, and increasing costs of water, nutrients and land (Bodnar, 2010). Increasing demands and decline in global maize supplies have weakened market volatility and somehow resulted in increased global maize prices (Shiferaw *et al.*, 2011). Climatic variability and change, and the consequent rise in abiotic stresses such as high plant population density stress and biotic stresses such as pathogenic diseases, further exacerbate the problem (Shiferaw *et al.*, 2011).

However, there are many techniques accessible today to achieve a better understanding of the multifarious network of plant responses to high population density stress as well as how to manoeuvre these responses. Maize grain yield is more affected by variations in plant density than other members of the grass family due to its low tillering ability, its monoecious floral organisation and the presence of short flowering period. Population density associated with plant density, whether operating directly on the plant or indirectly on biotic factors, is one of the most important factors in determining grain yield and other important agronomic attributes of a crop (Meyer, 1970).

Table 2.2. Production of maize in different African regions and the importance of maize in sub-Saharan Africa.

Region	Maize Production area (M ha)	Maize yields (t/ha)	Maize consumption (kg/capita/year)	% Calories and protein
Western Africa	8.34	1.41	27.9	9.43
Central Africa	2.36	1.7	17.86	7.7
Eastern Africa	8.33	2.49	30.33	13.44
Southern Africa	7.93	1.29	79.6	31.13
Sub-Saharan Africa	26.97	1.71	39.07	15.17

(Data from FAO, 2014)

In large parts of SSA, maize is the principal staple crop, covering a total of approximately 27 M ha (Table 2.2). However, maize production remains low when compared to the high maize producing countries in the world. Maize accounts for about 30 % of the total area under cereal production in SSA, 19 % in West Africa, 61 % in Central Africa, 29 % in Eastern Africa and 65 % in Southern Africa (FAOSTAT, 2010). In Southern Africa maize is particularly important, accounting for over 30 % of the total calories and protein consumed (FAOSTAT, 2010). Despite the importance of maize in SSA, yields remain low (Shiferaw *et al.*, 2011). While maize yields in the top five maize producing countries in the world (USA, China, Brazil, Mexico and Indonesia) have increased three-fold since 1961 (from 1.84 t/ha to 6.10 t/ha) (FAO, 2014), maize yields in SSA have stagnated at less than 2 t/ha, for example less than 1.5 t/ha in Western and Southern

Africa. In SSA maize is predominantly grown in smallholder farming systems under rainfed conditions with limited inputs.

2.4.1. Effects of high plant population density stress on maize

A high plant population density may result in overgrown plants (Carvalho *et al.*, 2010) and subsequent plant lodging, whereas a low plant population may favour weed infestation, late flowering and wide stems, which impair mechanical harvesting (Lopes *et al.*, 2008; Severino *et al.*, 2012). Light interception by plants strongly influences the crop yield when other environmental factors are favourable, and it is modified by the plant spatial distribution in a given area (Severino *et al.*, 2012). High plant population density results in inter-plant competition and affects vegetative and reproductive growth (Tetio-Kagho and Gardner, 1988) and as a result of increased inter-plant competition, benefits of higher planting densities might therefore not be the same as in temperate germplasm (Hammer *et al.*, 2009) due to high variability of stress factors found in the tropical areas. Increases in maize yield over the past few decades have been associated with breeding for tolerance to progressively higher plant densities. Since high plant density exacerbates interplant competition, it has been suggested that improved resource capture through delayed senescence might be advantageous in such situations (Rossini *et al.*, 2011).

An increase in either the number of maize plants per unit area or the number and size of weeds within a maize stand will enhance the competition among plants for resources within the maize canopy (Tollenaar and Wu, 1999). High plant population density increases stalk breakage, root lodging, barrenness and results in smaller ears and reduced harvest index (Tollenaar and Lee, 2011). Stalk breakage and ear falling increase because crowded maize plants have smaller diameter stems and shanks due to mutual shading (Troyer, 1996). Breeding for tolerance to high plant population density raises a number of issues. For example, grain yield per unit area of new hybrids depend highly on plant population density, with smaller and more variable ranges of optimum plant population densities than older genotypes (Fasoula and Fasoula, 2002; Tokatlidis *et al.*, 2005). This may result in yield penalties in sites where occasional stress makes it difficult

to predict optimum plant population density (Duvick, 2005a; Tokatlidis *et al.*, 2011). Furthermore, at high interplant competition levels, stand variability increases because dominant plants show luxury consumption of nutrients to the detriment of weaker plants (Tollenaar and Wu, 1999; Tokatlidis *et al.*, 2005; Rossini *et al.*, 2011). Whether the trend for higher plant population density continues in the future or not, improved understanding of morpho-physiological traits related to high plant population density stress tolerance could help in breeding efforts to enhance grain yield (Kheibari *et al.*, 2012). The increase in plant population density decreases the amount of resources available per plant (Abuzar *et al.*, 2011; Tollenaar and Lee, 2002). During the reproductive stage, high plant population density stress reduces kernel number per plant as kernel number fixation is related to plant growth rate around silking stage (Bänziger *et al.*, 2006; Lashkari *et al.*, 2011).

Unlike other stresses, most of the densely planted maize, many, if not all plants, may be barren but remain green and vigorous in appearance (Sarjamei *et al.*, 2014). High plant population density also causes increased plant and ear heights, fewer ears per plant, decreased ear length and diameter, less kernel depth, and later flowering, with silk emergence delayed more than pollen shed (El-Lakany and Russell, 1971). However, Tetio-Kagho and Gardner (1988) revealed that plant height increases to a maximum and then decreases (parabolically) with increasing plant population density that probably associates with limitation of assimilate and perhaps minerals and water. The reports by Severino *et al.* (2012) and Soratto *et al.* (2012) indicated that increasing plant population density increases leaf area index and vegetative dry matter yield but tiller number decreased linearly with increasing plant population density to no tillers at about 3.5 plants m⁻². However, a hybrid with tillers and prolificacy at low density was less affected (Andrade *et al.*, 1993; Andrade *et al.*, 2002; Rahmani *et al.*, 2015). Intolerant genotypes to abiotic stresses usually have higher grain yields and larger ears than tolerant hybrids at low populations, whereas the opposite is true at high plant population density (Otegui, 1997; İlker *et al.*, 2011). Similarly, anthesis-silking interval (ASI) increased much more with density than days to anthesis (Edmeades *et al.*, 1999; Sharma *et al.*, 2010) but tolerant genotypes possess shorter ASI and increased ears per plant (EPP) than intolerant genotypes (Buren *et al.*, 1974). Drought tolerant genotypes also exhibit reduced ASI under drought conditions but limited information is

available about their performance in ASI and other traits under high plant population density stress.

Xue *et al.* (2002) asserted that one of the most important factors is that non-application of optimal maize plant population per hectare and maize hybrids differ in their response to plant population density. Therefore, it is important to note that as maize does not have tillering capacity to adjust to variation in plant stand, optimum plant population density is important for maize grain production (Brekke *et al.*, 2011). An agronomic training, such as maintaining optimum plant population density is known to affect the crop environment, which influences the yield and yield components. Consequently, optimum plant population levels should be maintained to exploit maximum natural resources, such as nutrient, sunlight, soil moisture and to ensure satisfactory yield. To increase grain yield, maize should be planted at proper plant population density (Cairns *et al.*, 2012). As a result, the crop net photosynthesis process will be affected due to less light penetration in the crop canopy as well as an increase in the competition for available nutrients which in turn will affect grain yield (Edwards, 2011). Furthermore, application of optimum plant density in maize production helps for the proper utilization of solar radiation.

According to Vega *et al.* (2001), although maize yield is considerably affected by a number of biotic and abiotic factors; variations in plant population density is the most important factor that affects maize grain yield than any other member of the grass family. As highlighted by Luque *et al.* (2006) maize differs in its responses to plant population density. Liu *et al.* (2004) and Rossini *et al.* (2011) further explained this statement by stating that maize yield differs significantly under varying plant density levels due to differences in genetic potential. In another study, Munamava *et al.* (2006) reported that correspondingly, maize also responds differently in quality parameters like crude starch, protein and oil contents in grains. Consequently, plant population affects most growth parameters of maize even under optimal growth conditions and therefore, it is considered as a major factor determining the degree of competition between plants (Sangakkara *et al.*, 2004; Soratto *et al.*, 2012). The studies outlined by Luque *et al.* (2006) and Ali *et al.* (2003) also revealed that grain yield per plant decreases in response to decreasing light and other environmental resources available to each plant. Stand density affects plant architecture, alters growth and developmental patterns and influences carbohydrate production

(Seyyed *et al.*, 2014). At low plant population densities, many modern maize varieties do not tiller and quite often produce only one ear per plant (Soratto *et al.*, 2012). The use of high plant population density, on the other hand, increases inter-plant competition for light, water, nutrients and other resources necessary for plant growth (Tollenaar and Lee, 2011). This may be detrimental to final yield as it stimulates apical dominance, induces barrenness, and ultimately decreases the number of ears produced per plant and kernels set per ear (Sangoi *et al.*, 2002; Valadabadi and Farahani, 2010). At the individual plant level, grain yield is typically reduced with increasing planting density as a result of reduced light penetration into the canopy and increased competition for soil resources (Lambert and Johnson 1978; Mickelson *et al.*, 2002; Ku *et al.*, 2010).

At higher plant population densities, where shading effects are significant, increased light penetration into the canopy becomes an important factor. The photosynthetic capacity of a canopy is directly related to the total amount of leaf area exposed to sunlight, thus, the greater the amount of light penetration into a canopy, the greater the photosynthetic capacity (Brekke *et al.*, 2011; Edwards, 2011). Hesketh and Musgrave (1962) and Mock and Pearce (1975) revealed that near maximum photosynthetic rates are attainable even when leaves are exposed to less than 100% of maximum available sunlight. Mock and Pearce (1975) further elaborated that leaf exposure to a light intensity of 50 % was sufficient enough to produce a photosynthetic rate of 80% by comparison to leaves exposed to the maximum available sunlight intensity. However, the efficiency of the conversion of intercepted solar radiation into maize yield decreases with a high plant population density because of mutual shading in the plants (Zhang *et al.*, 2006). In addition, a plant population density resulting in interplant competition affects vegetative and reproductive growth (Zhang *et al.*, 2006).

Many studies have been conducted with the aim of determining the optimum plant density for maize. Unfortunately, there is no single recommendation for all conditions, because the optimum plant density varies depending on environmental factors, such as soil fertility and moisture supply and phenotypic factors such as planting date, planting pattern and harvest time (Gonzalo *et al.*, 2006; Yan *et al.*, 2011). Xue *et al.* (2002) identified differential responses to plant population density in maize cultivars. Then it was stated that generally, the yield of a single

maize plant decreases with increasing plant population density while the yield per unit area increases. The best way to effect future gains in yielding ability may be to make further improvements in tolerance to high plant population densities, in combination with improvements in potential yield per plant under low stress environments (Yan *et al.*, 2011). Furthermore, Xue *et al.* (2002) emphasized the importance of low stress conditions such as low plant population density, so that competition among plants is avoided in optimizing the effectiveness of selection for improved potential yield per plant, tolerance to stresses and responsiveness to inputs. Since the 1930s, the average maize grain yield per unit area has increased significantly due to the adaptability of maize plants to higher planting densities (Duvick, 2005b).

The increase in maize productivity has been associated with changes in shoot morphology that permit more light penetration into the canopy (Brekke *et al.*, 2011; Edwards, 2011). At higher densities, horizontally oriented leaves with a larger surface area and a higher position in the canopy, intercept more sunlight than is needed to achieve sufficient photosynthetic rates while restricting light penetration to the lower portion of the canopy (Mock and Pearce, 1975; Brekke *et al.*, 2011). Thus, at higher densities, leaves with an upright angle and a smaller surface area, higher up in the canopy, allows for more efficient light interception and penetration that consequently results in higher photosynthetic rates specifically at leaves located in the lower portion of the canopy (Brekke *et al.*, 2011). In a simulation study conducted by Hammer *et al.* (2009), it was concluded that the presence of vertically oriented maize leaves, within the upper portion of the canopy, resulted in a reduction of the canopy light extinction coefficient, increased light penetration to the lower portion of the canopy, and more uniform photosynthetic rates within the canopy.

Duncan (1984) stated that at higher plant densities, shading of underlying leaves by large maize tassels can decrease light penetration within the canopy, therefore, resulting in reduced photosynthetic rates of lower leaves. Duncan *et al.* (1967) also revealed that at lower densities, tassel shading effects are negligible; however, at higher plant densities, the tassel shading effects become significant (Edwards, 2011). At a planting density of 98,000 plants per ha, 19.4% reduction in photosynthetic rates associated with tassel shading effects was estimated on underlying leaves (Duncan *et al.* 1967; Yan *et al.*, 2011). In addition, it was displayed that

through measuring differences in shadow sizes associated with tassels of varying dimensions, that larger tassels intercept more light than smaller tassels.

2.4.2. Maize response to narrow rows and increased plant population

Van Roekel and Coulter (2011) revealed that, over a certain period of time, maize hybrids have been bred for increased tolerance to the stresses associated with high plant populations. Much emphasis has been placed on long-term research and the impact of stress tolerance on maize at varying plant populations. Taking the crop management tools into consideration, hybrids introduced in the 1990s tolerate high plant populations much better than genotypes used in the past (Almeida and Sangoi, 1996; Almedia *et al.*, 2000). Particular hybrid yields were examined from eras of release ranging from the 1930s to the 2000s by Hammer *et al.* (2009). The authors concluded that much of the yield increase associated with newer hybrids was due to increased stress tolerance, which allowed growers to adopt higher plant population densities and thus obtain higher yields.

Hammer *et al.* (2009) studied grain yield of maize hybrids released in the past 70 years and found in several years that at the low density of 10 000 plants per hectare, grain yield increased at a rate of 0.01 Mg per hectare per year. However, at the high density of 79 000 plants per hectare grain yield increased at a rate of 0.11 Mg per hectare per year. Tollenaar (1989) noted that hybrids developed in recent years are able to withstand higher plant population levels than older hybrids. Widdicombe and Thelen (2002) detected that plant population had a significant effect on grain yield, moisture, test weight, and stalk lodging. Interestingly, Sangoi *et al.* (2002) observed that the highest plant population in the study (90 000 plants per hectare) resulted in the highest grain yield at three locations evaluated in Indiana. Cardwell *et al.* (1982) reported inconsistent optimal plant population levels ranging from 86 000 to 101 000 plants per hectare for maize grain yield across three Minnesota locations.

Average row spacing declined from 107 cm (1930s standard) to 102 cm in the 1950s, to 96 cm a decade later, and to 90 cm in 1979 (Cardwell, 1982). Rossman and Cook (1966) summarized 10 studies in which reducing row widths from over 100 to less than 60 cm generally increased

yields from 3 to 20% (Yan *et al.*, 2011). When reduced from what is referred to as a wide row (76 cm) down to a width as narrow as 38 cm, narrow rows resulted in a range of responses from no yield advantage (Johnson *et al.*, 1998; Farnham, 2001; Zamir *et al.*, 2011) to a 7% increase in yield (Porter *et al.*, 1997). According to Farnham (2001), narrow rows spacing showed a 6.2% advantage in the northern U.S. Corn Belt and diminished as the trials moved south where wide rows spacing showed a 4.1% advantage. According to Karlen *et al.* (1987) and Ray *et al.* (2012) the narrow row spacing system, including the twin row configuration (46 and 20 cm) increases yield, because in theory, at comparable populations, the narrower row decreases intra-row plant competition for water, nutrients, and light. El-Abady (2015) observed that maize grown in an equidistant plant-spacing pattern (38 cm) often yields more grain per unit area of land than maize grown in conventional plant spacing patterns (76 cm) rows. In conjunction with those results, Kratochvil and Taylor (2005) and Van Roekel and Coulter (2011) found no increase in maize grain yield with twin-row spacing in the Delmarva region. Fulton (1970) reported a significant plant population by row spacing (50 cm) interaction in only one of four experimental years in Canada. This interaction indicated that the effect of narrow row spacing was greater at high plant populations (54 000 plants per hectare) than at low plant populations (40 000 plants per hectare) provided that adequate moisture was available.

Rossman and Cook, (1966) acknowledged that a higher plant population was found to have a greater effect on yield than row width or planting pattern. Sangoi *et al.* (2002) and Rossini *et al.* (2011) considered this an important feature because the greater benefits of reducing maize row width occurs at high plant populations. Although the altering of row spacing and plant population is not a new management approach, there are some drawbacks that have prevented the spread and adoption of the approach besides the mixed results of grain yield that have occurred throughout current research (Zamir *et al.*, 2011). According to Hallman and Lowenberg-DeBoer (1999), widespread adoption of narrow row maize has been limited due to risk and lack of profitability which has been affected by harvest equipment availability, increased production costs related to insect management, and poor equipment resale. As more and more research has occurred on this subject and in time, manufacturers are ready to deliver equipment for narrow row production, as long as it proves to be cost-effective and profitable to maize growers (Sangoi *et al.*, 2002).

2.5. Maize response to high population density stress

2.5.1. Maize adaptation to high plant population density stress

Plants respond to their changing environment in a complex, integrated way that allows them to react to the specific set of conditions and constraints present at a given time (Brekke, 2011). Therefore, the genetic control of tolerance to abiotic stresses is not only very complex, but also highly influenced by other environmental factors and by the developmental stage of the plant. Plant population density tolerance in plants is defined as the extent to which the crop maintains yield per unit area as plant population density increases beyond standard levels (Rossini *et al.*, 2011). Genetic contributions to gains in field maize productivity over the last 80 years have been driven largely by improvements in stress tolerance in modern hybrids (Duvick, 2005b; Tokatlidis and Koutroubas, 2004; Tollenaar and Wu, 1999).

Maize grain yield per unit area has increased exponentially and significantly since the early 1930s, however, grain yield per plant has experienced an almost negligible increase (Duvick, 2005a; Brekke, 2011). Previous research, conducted on maize hybrids from the central Iowa region, revealed that yield potential per plant has remained stagnant over the years (Duvick, 2005a). When the hybrids from the central Iowa region were grown at a very low density of about 10,000 plants per hectare and on a relatively stress free environment, yield per plant remained almost unchanged (Duvick *et al.*, 2004; Duvick, 2005b). Thus, the exponential and continuous gains in maize grain yield observed over the years can be attributed to the adaptability of maize to higher planting densities rather than an increased production of grain on a per plant basis (Duvick, 2005a).

Ray *et al.* (2012) revealed that maize does not have the flexibility of most crop species, which can increase leaf area and number of reproductive units by branching at low crop densities. The use of high populations, on the other hand, may be detrimental to final yield by stimulating apical dominance and inducing barrenness. As the number of plants in a planting pattern

increase, distance between plants decrease and competition among individuals increase (Duncan, 1984).

2.5.2. Maize tolerance to high plant population density stress

Many researchers pointed out that maize hybrids grain yield improvement in North America and Europe has been related to an increased tolerance of high plant population density (Duvick, 1984; Tollenaar *et al.*, 1989; Troyer, 1996). In addition, Tollenaar and Lee (2002) reported that more recently developed hybrids were less influenced by weed interference than the older hybrids in Ontario (Canada). Other researchers also suggested that progress to increase yields at high plant population densities is likely to be achieved as maize breeders continue to develop and evaluate materials at higher plant population densities (Seyyed *et al.*, 2014). With regard to the production of maize hybrid seed, the yield of inbred lines is often a limiting factor. Therefore, it seemed appropriate to study the feasibility of increasing the productivity of inbred lines through the use of high plant population densities. In general, it is important to determine the genotypes that are tolerant to high plant population density.

The tolerance of maize grain yields to abiotic stresses such as exposure to high plant population density is largely determined by events that occur at or shortly after flowering (Lafitte *et al.*, 1997). A shortened ASI is indicative of a high relative flow of assimilate to developing ears during early reproductive development under conditions of stress (Edmeades *et al.*, 1999). High plant population density tolerant genotypes possess shorter ASI than intolerant genotypes (Duvick, 2004). Benjamin (2007) also reported that selection under high plant population density stress might improve general stress tolerance as well as specific stress tolerance. Their report showed that high plant population density is particularly useful in amplifying selection for drought and low nitrogen tolerance. Several commercial maize breeders in North America improved drought resistance by screening under high plant population density (Benjamin, 2007).

High plant population density plantings are valuable when selecting for reduced barrenness and lodging as well as shorter ASI (Russel, 1991). Reduction in tassel size also tends to reduce barrenness and increase maize grain yields at high plant population densities (Duvick, 2004).

Correspondingly, Buren *et al.* (1974) described that reduced ASI, ear prolificacy, reduced tassel size, and efficient production of grain per unit leaf area would characterize plant population density tolerant genotypes. On the other hand, optimum plant population density for yield increased when recurrent selection for reduced plant height was carried out on tropical maize population, Tuxpeño Crema (Johnson *et al.*, 1998). According to these researchers, selection for reduced plant height on this population has reduced the incidence of plant lodging and barrenness.

2.6. Past yield gain under high population density

Duvick (2005a) indicated that since the 1950s, the average maize grain yield per unit area has increased exponentially without ceasing if not disturbed by the environmental conditions. The increased adaptability and tolerance of maize genotypes to higher planting densities has been associated with this trend (Cardwell, 1982; Russell, 1991; Duvick 2005b). Cardwell (1982) also estimated that 21% of the observed maize grain yield gain in newer hybrids is associated with increased planting densities. This data was derived from a study which was conducted in Minnesota and compared a sample of sequentially released hybrids representative of the time period 1930-1970. Hammer *et al.* (2009) reported that hybrids representative of the 1960s achieved maximum grain yield at approximately 30, 000 plants per hectare while hybrids representative of the year 2000 achieved maximum grain yield at or in excess of 80,000 plants per hectare. Furthermore, in a similar study conducted by Tollenaar (1989), it was revealed that at a density of 40, 000 plants per hectare, modern hybrids yielded 25% more than the oldest hybrid. Similarly, at a density of 130, 000 plants per hectare, modern hybrids yielded 190% more than the oldest hybrid. Currently, it has been reported that densities as high as 90, 000 plants per hectare were still below the potential maximum yield densities (Widdicombe and Thelen, 2002; Brekke, 2011).

2.7. Tropical and temperate germplasm

Most commercial maize varieties grown around the world are derived from the cross of two or more inbred lines such as tropical by temperate lines. FAO (2012) reported that top crosses of derivatives of tropical hybrids were sometimes competitive with commercial hybrids. Similar results were also reported by Goodman (2005) in the U.S. Cargill and Northrup King provided top cross seed of all recently-released North Carolina (NC) lines crossed with LH132, a short-statured, stiff-stalk-synthetic line, and LH150, a tall, southern, non-stiff-stalk-synthetic line. At the time, the yield trials were conducted, all NC lines from NC250 to NC300 that represent all NC line released from 1980 to the early 1990s, were tested in such single-crosses (Holley and Goodman, 1988; Duvick, 2005a). Subsequently, these crosses resulted in high yielding and competed with the known commercial hybrids.

Tropical germplasm, also known as exotic germplasm, is suggested as a source to widen the existing genetic diversity of U.S. maize breeding programs (Goodman, 2005). Non-adaptation to temperate regions and poor standability has been the major problems for the widespread utilization of tropical germplasm for breeding in the USA. In spite of several reports involving both private and public research programs, very few tropical germplasm has achieved the farmers' needs in Mexico (Hellin *et al.*, 2014). Goodman (2005) estimated that the percentage of exotic germplasm including both temperate and tropical in the U.S. hybrid maize market is about 2.9%, however, tropical germplasm constituted only one-tenth of the total exotic germplasm used (Chukan, 2012). Most of these lines *per se* reported to have undesirable agronomic characteristics such as weak roots, susceptibility to smut and barrenness when grown in temperate regions (Hellin *et al.*, 2013). The lack of convincing yield trial data for public tropical line testcrosses has been the other major limitation to their use in temperate hybrid development programs. Thus, agronomic evaluation of temperate and tropical inbred line crosses could provide useful information to combine these two sources for the genetic improvement of hybrid maize for high density stress option.

2.8. Combining ability

The combining ability (CA) of inbred lines determines their potential value in the development of hybrid or synthetic varieties with enhanced yield and stress tolerance. Crosses between inbred lines from different heterotic groups result in higher hybrid vigour than crosses within the same heterotic group. Furthermore, the nature of gene action affects expression of both quantitative and qualitative traits of economic importance (Dehghanpour and Ehdaie, 2013). Sprague and Tatum (1942) defined the concept of combining ability as the genotypes ability to transmit superior performance to its crosses and thus producing superior hybrids. This concept of combining ability was defined on the basis of general combining ability (GCA) and specific combining ability (SCA). Combining ability studies have been conducted in many crops indicating that it is a crucial tool in plant breeding (Sofi and Rather, 2006). For example, combining ability studies have been conducted in crops such as wheat (Bao *et al.*, 2009; Khaled *et al.*, 2013), sunflower (Deglene *et al.*, 2013), sorghum (Makanda *et al.*, 2010), maize (Qu *et al.*, 2012; Dehghanpour and Ehdaie, 2013), cotton (Hinze *et al.*, 2011), and chickpea (Bicer and Sakar, 2008). Interesting combining ability analyses were recently performed in watermelon (Bahari *et al.*, 2012) and oil palm (Noh *et al.*, 2012).

General combining ability (GCA) is the average performance of a line in a series of hybrid combinations and it is directly related to the breeding value of a parent and is associated with additive genetic effects (Kambe Gowda *et al.*, 2013). In contrast, specific combining ability (SCA) is the relative performance of a hybrid, which is associated with non-additive gene action predominantly contributed by dominance or epistasis (Falconer, 1951). Half-sib (hybrids with one common parent) families are used to estimate GCA. Therefore, the average performance of all F₁ crosses resulting from a particular line when randomly crossed with a series of lines in a population is the estimate of GCA and is expressed as a deviation from the population mean. Best parental lines to be used in inbred line development are selected based on GCA. The presence of GCA is an indication of additive genetic variance thus; GCA is correlated with narrow sense heritability (Amiruzzaman *et al.*, 2013).

General combining ability estimates can be positive, negative or zero. A zero or close to zero GCA indicates that the mean of a line is not different from the average mean of all crosses. Whereas, a positive or negative GCA estimate suggest that the performance of a line is better or poorer than the other lines, thus parents that would result in superior higher yielding hybrids are selected based on favourable GCA estimates (Griffing, 1956; Vencovsky, 1969).

Specific combining ability denotes the performance of a line in specific combinations and is expressed as a deviation of a cross between two inbred lines from the estimated value of the average general combining ability of its two parents. The presence of SCA indicates non-additive effects. Specific combining ability is estimated from full-sib families and is positively correlated with heterosis, for example, high SCA values in hybrid combinations is an indication of high heterosis, thus where there are no SCA estimates, heterosis can be used to select for superior crosses (Machado *et al.*, 2009). High SCA values (negative or positive) indicate superior crosses and the presence of variability among crosses. Superior crosses or hybrids are therefore selected based on the favourable SCA effects (Machado *et al.*, 2009; Pswarayi and Vivek, 2008).

2.8.1. Significance of combining ability studies

Different methods have been used to evaluate relative importance of GCA and SCA in plant breeding. The first step is to check whether or not both GCA and SCA are significant. If both the GCA and SCA values are not significant, epistatic gene effects may play a remarkable role in determining these characters (Fehr, 1993). The ratio of combining ability variance components (predictability ratio) determines the type of gene action involved in the expression of traits and allows inferences about optimum allocation of resources in hybrid breeding and development.

For effective improvement of breeding lines and hybrid development, information on combining ability among germplasm to be used is very important (Vasal, 1998; Beck *et al.*, 2000). The GCA effects have been widely used in maize breeding programmes in inbred line selection for hybrid development, to estimate heterosis, to identify heterotic patterns and heterotic groups and to understand the nature of gene action involved in the expression of quantitative traits

(Amiruzzaman *et al.*, 2010; Galal and Mahgoub, 2011; Machikowa *et al.*, 2011; Bidhendi *et al.*, 2012). Combining ability information also helps breeders to identify good combiners that can be used in crosses to accumulate superior genes and to exploit maximum heterosis (Amiruzzaman *et al.*, 2010).

In general, a significant GCA and SCA indicate the predominance of both additive and non-additive gene effect for the traits, respectively (Fan *et al.*, 2010; Badu-Apraku *et al.*, 2011; Kambe-Gouda *et al.*, 2013). A significant GCA and SCA has been reported for grain yield and other yield related traits in maize (Muraya *et al.*, 2006; Aliu *et al.*, 2008; Fan *et al.*, 2010; Khalil *et al.*, 2010; Kambe-Gouda *et al.*, 2013). Fan *et al.* (2010) suggested that when parental lines have a significant positive and high GCA effects, the selection of those lines for inbred development will result in superior high yielding hybrids.

The importance of combining ability in applied genetics including plant and animal breeding cannot be overemphasized. The GCA concept has been effectively used in crop and livestock breeding for more than 70 years (Sprague and Tatum 1942; Shikano *et al.*, 2000; Aliu, 2006; Adebambo, 2011; Wang *et al.* 2014). GCA is an effective tool used in selection of parents based on performance of their progenies, usually the F₁ but it has also been used in F₂ and later generations. A low GCA value, positive or negative, shows that the mean of a parent in crossing with the other does not vary largely from the general mean of the crosses. In contrast, a high GCA value shows that the parental mean is superior or inferior to the general mean. This indicates a potent evidence of desirable gene flow from parents to offspring at high intensity and represents information regarding the concentration of predominantly additive genes (Franco *et al.*, 2001). A high GCA estimate indicates higher heritability and less environmental effects. It may also result in less gene interactions and higher achievement in selection (Topal *et al.*, 2004; Chigeza *et al.*, 2014). One of the main features of the elite parent with high GCA effect is its large adaptability. A parent good in *per se* performance may not necessarily produce better hybrids when used in hybridization (Allard, 1971; Tyagi and Lal, 2005; Shukla and Pandey, 2008). Concurrently, it also indicated that one parent of the worst combination could make the best combination if the other parent was selected properly (Bao *et al.*, 2009).

In GCA determination, SCA usually acts as a masking effect. By using genetically broad testers or increasing number of testers, SCA impact can be decreased (Hallauer and Miranda, 1998). Parental choice only on the basis of SCA effect has limited value in breeding programs. Therefore, SCA effect should be used in combination with a high performance *per se* hybrid, favourable SCA estimates, and involving at least one parent with high GCA (Franco *et al.*, 2001; Marilia *et al.*, 2001; Joshi *et al.*, 2002; Kenga *et al.*, 2004; Makanda *et al.*, 2010). Observations of performance of different cross patterns on the basis of SCA have been used to make inferences on gene action at play. High SCA effects resulting from crosses where both parents are good general combiners (good GCA \times good GCA) may be ascribed to additive \times additive gene action (Verma and Srivastava 2004; Dey *et al.*, 2014). The high SCA effects derived from crosses including good \times poor general combiner parents (Verma and Srivastava 2004; Dey *et al.*, 2014) may be attributed to favourable additive effects of the good general combiner parent and epistatic effects of poor general combiner, which fulfils the favourable plant attribute. High SCA effects manifested by low \times low crosses (Verma and Srivastava 2004; Dey *et al.*, 2014) may be due to dominance \times dominance type of non-allelic interaction producing over dominance thus being non-fixable (Wassimi *et al.*, 1986). Predominance of non-additive effects has been also reported for inheritance of pod yield and related traits in other crops such as groundnut under salinity stress in which there were cross combinations with high SCA effects arising from parents with high and low GCA, and another set of crosses with high SCA effects arising from both parents with good GCA effects (Azad *et al.*, 2012).

2.8.2. Techniques for estimation of combining ability

With progress in biometrical genetics, several techniques are suggested for the estimation of combining ability. These include top cross suggested by Davis (1927) and developed by Jenkins and Brunaon (1932), poly cross technique proposed by Tysdal *et al.* (1942), diallel cross analysis by Griffing (1956), line \times tester analysis by Kempthorne (1957), partial diallel cross by Kempthorne and Curnow (1961), North Carolina design by Comstock *et al.* (1949), and triallel cross by Rawlings and Cockerham (1962) are used to estimate combining ability.

2.9. Heterosis and combining ability in maize germplasm under high plant population density

Heterosis and combining ability are prerequisites for developing a good economically viable hybrid maize variety (Ruswandi *et al.*, 2015). Information on the heterotic patterns and combining ability among maize germplasm is essential in maximizing the effectiveness of hybrid development (Beck *et al.*, 2000; Abdel-Moneam *et al.*, 2014). In maize, considerable percentage of heterosis for yield and combining ability were studied (Roy *et al.*, 1998; Rokadia and Kaushik, 2005; Rovaris *et al.*, 2014). Combining ability analysis is one of the most powerful tools in identifying the best combiners that may be used in crosses either to exploit heterosis or to accumulate productive genes. It also helps to understand the genetic architecture of various characters that enable the breeder to design effective breeding plans for future improvement of the existing materials.

Heterosis has been extensively studied in maize because of various factors, these include large expression for grain yield, intensive exploitation in hybrid breeding of maize, and the favourable biological prerequisites such as large multiplication coefficient and ease of both self- and controlled cross-fertilization (Kamara *et al.*, 2014). Although many hypotheses have been suggested to explain heterosis, its genetical, physiological, and biochemical bases still remain largely unexplained. Maize heterosis is a major factor of yield in all breeding categories except in line breeding (Schnell, 1982; Mosa, 2010). To systematically exploit heterosis in hybrid breeding, the concept of heterotic groups and patterns was suggested (Roy *et al.*, 1998; El-Hosary and El-Gammaal, 2013). Melchinger and Gumber (1998) defined a heterotic group as a group of related or unrelated genotypes from the same or different populations, which display similar combining ability response when crossed with genotypes from other genetically distinct germplasm groups. By comparison, the term heterotic pattern refers to a specific pair of two heterotic groups, which express high heterosis and consequently high hybrid performance in their cross. The concept of heterotic patterns includes the subdivision of the germplasm available in a hybrid breeding program in at least two divergent populations, which will be improved with inter-population selection methods. Heterotic patterns have a strong impact in crop improvement because they predetermine to a large extent the type of germplasm used in a hybrid breeding program over a long period of time (Melchinger and Gumber, 1998).

Heterosis is not only dependent on the parent combinations but also on the effect of environmental conditions and species as well as the trait under consideration (Chapman *et al.*, 2000). Young and Virmani (1990) also reported that the extent of heterosis in rice was higher in a stress environment than in a favourable environment. For temperate maize, Duvick (2004) also pointed out that yield gains in hybrids always were accompanied by improvement in tolerance to biotic and abiotic stresses, and that improvement occurred in parental inbreds as well as in their hybrid progeny. Similarly, for tropical maize, Betran *et al.* (2003b) stated extremely high expression of heterosis under stress, especially under high plant population density stress because of the poor performance of inbred lines under these conditions. The superior performance of inbreds under high plant density was also observed as superior performance under high plant population densities of hybrids derived from such lines (Russel, 1991; Troyer, 1996; Abdel-Moneam *et al.*, 2014). It is generally considered that inbred lines with superior yields under drought and low N will result in superior hybrids under these stresses, even though their correlations are relatively weak (Vasal, 1998). Since selection for tolerance to mid-season drought appears to increase grain yield across a range of nitrogen stress (Bänziger *et al.*, 1999; Abdel-Moneam *et al.*, 2014), tolerance to other abiotic stresses is also expected. However, there is a lack of information about the magnitude of heterosis in hybrids developed from drought tolerant lines when tested under high plant population density conditions and in different environments (Kamara *et al.*, 2014).

The main objective of maize breeders, according to Russel (1991), is the development of lines whose hybrid combinations present superior performance. However, the superiority of a cultivar in a particular environment may not be verified in another (Allard, 1971; Cruz *et al.*, 2004). Phenotypic appearances are the result of the action of the underlying genetic factors and the environmental factors (Kamara *et al.*, 2014). Hence, when different environments are considered, an additional effect apart from the genetic and environmental effects is detected that is caused by their interaction. The genotype x environment interaction has been divided into simple and complex interactions. The simple interaction is caused by differences of variability among the genotypes in the environments in which the superior performances of genotypes are measured. In this type of interaction the highest yielding genotype is the one that will be recommended. The second interaction is caused by the lack of repeatability of selection performance of the

genotypes. It is important to know the type of the interaction involved, so as measures can be taken to minimize and/or exploit its effects (Gauch, 2013; Shukla and Pandey, 2008).

2.10. Testers

A tester, as defined by many researchers, is a common parent that is crossed with several inbred lines to develop a desired hybrid. Successful maize breeding depends on the choice of testers for selection of potential lines for hybridization. Maize breeders have to identify an ideal or suitable tester for hybrid development and evaluation of inbred lines. The definition or choice of an ideal tester depends upon the breeder's objectives and characteristics of the proposed breeding program (Hallauer *et al.*, 2010). Seemingly in coining a definition for a tester, researchers have been influenced by their quest to find the best or most convenient tester for use in hybrid programs. Smith (2006) and Hallauer and Miranda (1998) asserted that a line or a population with low frequency of favourable alleles in testcrosses can be employed as a tester to find lines with large frequency of favourable alleles. Such testers would be crucial when dominance gene action for the traits of interest is envisaged. Castellanos and Cordova (1998) and Pswarayi and Vivek (2008) pointed out that a suitable tester is one which combines the following attributes: reveals large variation between testcrosses, has desirable combining ability, has high and significant correlation with average of the testers used, and has acceptable *per se* performance. This definition is partly consistent with Russell (1991) who asserted that an ideal tester shows large genetic differences between testcrosses.

There are several features of a convenient and a good tester which have been proposed; these suitable tester features are suggested by several researchers in the following manner; a tester that properly discriminates among lines in crosses and correctly classifies the relative performances of the tested lines (Li *et al.*, 2007). A good and a convenient tester should have satisfactory agronomic traits and should desirable estimates of GCA, large variation among testcrosses and acceptable performance *per se* (Oliveira *et al.*, 2011). An ideal tester should be the most discriminating (discriminate differences among lines) or the largest vector of all testers and should be the most representative of testers (Badu-Apraku *et al.*, 2011). A good tester displays

the expression of greater genetic diversity among progenies or testcrosses (Castellanos *et al.*, 1998). A good tester should be a good pollen donor to ease crossing with lines under evaluation, it should also be superior in agronomic traits such as resistance to root and stalk lodging (Li *et al.*, 2007).

2.10.1. Summary of the major characteristics of a tester

Mumtaz *et al.* (2015) proposed four major characteristics of a suitable good tester for a breeding programme and presented them as; (i), broad genetic base, which allows for greater genetic diversity to be expressed in hybrids or test crosses as well as a broad genetic base that is one containing heterozygous cultivars and crosses, (ii) wide adaptability, the crosses between inbred lines and testers are generated in different environments, thus to be able to test for an inbred line's combining ability, a tester should display a good performance under diverse environmental conditions. Days to maturation are more important because germplasm may be evaluated in environments with shorter days to maturation (Li *et al.*, 2011), (iii) Low yield potential, the line's ability to express its superiority is the primary aim in a testcross; therefore the tester should not perform above the line so that the yield potential of a line is not masked by the higher yielding tester, (iv) Low performance of other traits; compared to a line under evaluation, a tester should display poor performance on the important traits under selection or traits that a line possesses. Therefore, a homozygous recessive line or a line with low allelic frequency is ideal. For example, if a tester with low frequency or no favorable alleles is used, the lines displaying high frequency of favorable alleles can be easily identified (Castellanos *et al.*, 1998).

2.10.2. Significance of testers in breeding

The testers are used to classify lines into heterotic groups and to study the combining ability and to identify heterotic pattern in maize populations as well as to identify superior germplasm in accordance with breeding objectives in a hybrid-oriented program. The testers also help in selecting and eliminating lines showing a GCA below average (Castellanos *et al.*, 1998; Oliveira *et al.*, 2011). Pswarayi and Vivek (2008) identified a suitable tester from their choice of potential

testers based on three characteristics; display of high desirable GCA effects, classification of lines into heterotic groups, and *per se* grain yield.

2.11. Line by tester mating scheme

Line by tester mating scheme is an efficient procedure because it allows for inclusion of a large number of lines and provides reliable information on the general combining ability (GCA) and specific combining ability (SCA) effects of parents and their hybrid combinations, genetic components and gene action governing quantitative traits (Sofi and Rather, 2006; Iqbal *et al.*, 2007). The line by tester method proposed by Kempthorne (1957) can accommodate large numbers of genotypes and is therefore suitable for testing early generation inbred lines to produce desirable hybrid combinations. This method can also provide information about the efficacy of lines for use as parents in a hybridization programmes (Dabholkar, 1992). The line \times tester method is the most widely used mating design in hybrid programs. Line \times tester analysis, which involves lines and testers, is an extension of the analysis of two factor factorial experiment introduced by Fisher (1926). All 'l' lines are crossed to each of the 't' testers and thus line \times tester (l \times t) full-sib progenies are produced. The developed progenies together with or without parents, that is, lines and testers, are examined in a replicated trial by a suitable field design (Comstock *et al.*, 1949; Singh and Chaudhary 1985; Tyagi and Lal, 2005).

All relevant inbred lines are mated to the testers and single crosses are evaluated to provide information about GCA effects of the lines and testers, and SCA effects due to line by tester interaction effects (Fan *et al.*, 2010). Mid-parent and high-parent heterosis can be calculated from the means of lines and testers (Hallauer and Miranda, 1998). In this mating design, testers need to be selected; however, the selection of testers has been controversial for many years. Some authors defended the use of high performance testers while others defended the use of low performance testers. There are also studies that did not find any correlation between performances of testers with ranking of inbred lines in relation to their GCA (Sharma *et al.*, 1967). In general, the selection of a tester is based on (i) the genetic base of the tester (broad or narrow based); (ii) low performance or susceptibility of the tester to the major traits under

investigation, and (iii) heterotic background of the testers (Fan *et al.*, 2010). Use of a broad-based population as a tester was suggested by several studies; especially at early generation stage of lines and aiming to generate improved synthetics (Narro *et al.*, 2003). The narrow-based testers such as inbred lines and single crosses are considered the best alternative in a hybrid oriented breeding programme that aims at generating superior single cross, three-way and double cross hybrids (Castellanos *et al.*, 1998). However, Russell (1991) considered an ideal tester as the one showing maximum genetic variability among the lines in the study. Use of many testers was considered as an advantage in genetic studies oriented for heterotic grouping of lines based on their heterosis, SCA and GCA effects, mainly when the lines under study were exotic (Fan *et al.*, 2010).

2.12. Stress tolerance indices

To improve maize yield and stability in stressful environments, there is a necessity to identify selection indices that are able to distinguish high yielding maize hybrids in these situations because selection of different entries under a wide range of environments is important in a breeding program. Fernandez (1992) classified plants according to their performance in stress and non-stress environments into four groups: (A) Genotypes producing high yield under both stress and non-stress environments, (B) genotypes with high yield under non-stress environments, (C) genotypes with high yield under stress environments, and (D) genotypes with poor performance under both stress and non-stress environments. Moghaddam and Hadi-Zadeh (2002) found that stress tolerant index (STI) was more useful in order to select favourable maize hybrids under stress and non-stress conditions. Rosielle and Hamblin (1981) suggested stress tolerance index and defined it as the difference between the production obtained in conditions without stress (Y_p) and stress (Y_s), and productivity (MP), which they defined as the average of Y_p and Y_s .

Three breeding approaches for abiotic stress tolerance have evolved. The first one is to breed for high yield under optimum condition. As the maximum genetic potential of yield is expected to be realized under optimum conditions and a high positive correlation exists between performance in

optimum and stress conditions, a genotype superior under optimum level will also yield relatively well under stress condition (Tollenaar and Lee, 2002). However, the presence of genotype x environment interaction may restrict the high-yielding genotype to perform well under stress condition. Thus, as a second approach, breeding under stress condition has been suggested. The problem in this approach is that the intensity of stress is highly variable from year to year and as a consequence the efficiency of selection for stress tolerance is reduced. The simultaneous selection in non-stress environment for yield and in stress condition for stability may be done as an alternative approach to achieve the desired goal of evolving stress-resistant genotype with high yield. Due to the spatial and temporal variability in population density within most agricultural systems, a stable cultivar must possess stress tolerance.

2.13. Genetic correlation between tolerance to low and high population density stress

The recurrent expression of drought stress and high population density are important factors limiting maize production in Southern Africa, because as the number of plants in a planting pattern increases, distance between plants decreases and competition for water and nutrients among individuals increases. Maize yield improvement has been strongly associated with improvements in stress tolerance, particularly to increased interplant competition in SSA and in the U.S. As a result, modern hybrids are able to produce kernels at high plant population densities. Identification of the genetic factors responsible for density response in maize requires direct testing of interactions between genetic effects and density as well as evaluation of that response in multiple traits.

Genetic variation for yield potential in tropical maize populations appears to be controlled by many genetic factors, each with relatively small effects (Setter *et al.*, 2001). Therefore, the effectiveness of the quantitative trait loci (QTL) mapping and marker-assisted selection approaches for yield potential in maize is questionable (Holland, 2004). However, it should be possible to separate maize responses to specific biotic and abiotic stresses into less complex component traits. These component traits may be controlled by smaller sets of genes, making them more amenable to QTL mapping and marker-assisted selection (Ribaut *et al.*, 2001;

Tuberosa and Salvi, 2006). This makes stress resistance traits such as tolerance to interplant competition, pests, and drought, along with enhancement of yield stability across environments and production systems a primary objective for plant breeders.

2.14. Genetic gain

Knowledge of the magnitude of genetic variability, heritability and genetic gains in selection of desirable characters could assist the plant breeder in ascertaining criteria to be used for the breeding programmes. Genetic improvements, resulting in the increased adaptation of newer hybrids to higher plant population densities, are associated with 50-60% of yield gains per unit area (Duvick, 2005a). Knowledge of heritability influences the choice of selection procedures used in plant breeding to decide which selection methods would be most useful to improve the character, to predict gain from selection and to determine the relative importance of genetic effects (Tollenaar and Lee, 2011). A successful plant breeding program is directly related to the superiority of the new cultivars. Studies have shown that the average annual maize culture gain is around 2 %. Cardwell (1982) showed that the annual maize yield increase in Minnesota was 85 kg/ha, with 43 % of this increase due to the introduction of new cultivars. Studies done by Castleberry *et al.* (1984) show that genetic gains are different across contrasting environments and that genetic gains are higher in environments that do not cause any type of stress. Thus, in order to improve plant breeding efficiency under stress conditions, parental selection must be based on results obtained in that specific environment.

2.15. Path coefficient and correlation analysis

The analysis of path coefficients has been made to identify the important yield attributes by estimating the direct effects of the contributing characters to grain yield and separating the direct from the indirect effects through other related characters by partitioning the correlation coefficient and finding out the relative importance of different characters as selection criteria. Knowledge of the association of yield components and their traits as well as association between the yield components themselves, can improve selection efficiency (Raghu *et al.*, 2011). Path

coefficient analysis is a statistical method capable of partitioning correlations into direct and indirect effects, as well as distinguishing between correlation and causation. Path coefficient estimates are useful in understanding the contribution and roles played by different plant traits in establishing growth pattern and behaviour of crop cultivars in a particular environment (Carpici and Celik, 2010). Path coefficient analysis enables breeders to test theoretical hypotheses about the cause and effect, without employing variables. It is an important tool when dealing with quantitative traits such as grain yield (Acquaah, 2007; Hepziba *et al.*, 2013).

Correlation refers to the association of variables that exhibit some related trends of change (Mohanani, 2010). The correlation of characters can either be negative or positive (Mohanani, 2010). The coefficient of correlation signifies the intensity of correlation between cause and effect (Sharma, 2006). Correlation can be phenotypic as well as genotypic, which expresses the degree to which two characteristics are genetically associated (Yousuf and Saleem, 2001). Both genotypic and phenotypic correlation can be used as the basis of indirect selection (Yousuf and Saleem, 2001).

Breeding for direct increase in maize grain yield is complicated due to the fact that maize grain yield is the end-product of interactions among contributing traits to maize grain yield (Raghu *et al.*, 2011). An alteration in a particular trait results in changes in another trait as explained by Ahmad and Saleem (2003). In order to improve gains from selection, it is desirable to have positive significant correlations between yield and agronomic characteristics that contribute towards higher yield. Ear mass and grain yield are highly and positively correlated (El-Shouny *et al.*, 2005), implying that selecting for heavier maize cobs will contribute toward higher grain yield. El-Shouny *et al.* (2005) indicated that primary selection for traits which are positively correlated with yield, such as plant and ear height, ear length and girth, contribute to high single plant yield potential in maize. However, contradicting findings have been reported by other previous investigators (Kumar *et al.*, 2011; Jayakumar *et al.*, 2007). These differences in results obtained by several researchers can be explained by the use of different populations.

Yusuf (2010) observed that several secondary traits, such as number of leaves per plant with plant height, days to silking with tasselling, and plant height with ear height, were positively

correlated and that these pairs of correlated traits could be simultaneously selected for. A positive correlation between silking and tasselling enables efficient breeding for earlymaturing maize varieties. A high and positive correlation between 100 kernel mass and number of kernels per row was reported in eleven maize hybrids (Zarei *et al.*, 2012). This positive correlation is welcome, as these two traits contribute toward grain yield. Improving both traits at the same time will thus have a positive effect on grain yield. Total number of kernels and ear mass were significantly correlated (Bello *et al.*, 2012), indicating that ear mass could be improved by selecting for many rows. Several studies conducted on maize have reported that plant and ear height were positively correlated (El-Shouny *et al.*, 2005; Bello *et al.*, 2012; Rafiq *et al.*, 2010). This facilitates synchronised breeding for a desired plant stature. Lodging can be caused by many factors in grain crops, such as rice, wheat and maize. Previous studies by Esechie *et al.* (2004), Tripathi *et al.* (2004), Mobasser *et al.* (2009) and Xiang *et al.* (2010) focused mainly on differences in lodging-related traits in varieties (e.g. rice, maize, and wheat), including correlations between lodging resistance and plant height, stem diameter and plant population, as well as those between cultivation conditions and yield or lodging resistance. The risk of lodging increases at high planting density and when lodging (root or stem) appeared, the normal canopy structure can be altered with the photosynthetic capability and dry matter production dropped (Hitaka and Kobayashi, 1961). However, In wheat it has been reported that lodging is the most limiting factor in attaining higher wheat yields (Ransom, 2005) and Kelbert *et al.* (2004) also stated that lodging can cause grain yield losses up to 40 % if happens during the 10 days after heading. Previously, it was suggest by Rawson and Macpherson (2000) that lodging is induced as a result of inadequate standing power of the crop and adverse weather conditions, such as rain, strong winds. Rajcan and Swanton (2001) asserted that stalk diameter is associated with plant population density because as the plant population increased, stalk diameter declined by 0.07 mm per thousand plants and it was due to the main effects of year and target population and the interaction of year by row configuration and. Stalk lodging is correlated to crop management factors such as plant population and hybrid characteristics such as plant and ear height and leaf area index (Rajcan and Swanton, 2001), and stalk diameter which causes stem lodging and results in reduced grain yield (Moentono *et al.*, 1984). Similarly, Sibale *et al.* (1992), Pedersen and Lauer (2002) and Stanger and Lauer (2006) reported that increasing target plant population increased stalk lodging which results in grain yield reduction.

2.16. Summary

Maize grain yield advance depends upon enhanced tolerance to improved stand density (Duvick, 2005a), which reduced the number of infertile plants and increased the number of harvestable kernels (Tollenaar, 1989) that results in high grain yield. Tolerance to a diversity of environmental stresses has played a key role in genetic improvement, as evidenced by maize hybrid 'era' studies (Edmeades *et al.*, 2004). Such studies display that yield potential per plant has remained unchanged for decades while yield potential per unit area has increased as a function of both higher population density and year of hybrid introduction (Duvick and Smith, 2004; Russell, 1991). Adaptation to continual increases in plant population density not only explains much of the relationship between population density and historic U.S. field maize yields, but also opens debate about how to improve future maize grain yields (Duvick, 2005a). High plant population densities used in current maize production promote a high level of intra-specific competition, which causes an early increase in interplant variability within the plant stand. This variability holds during the critical period for kernel set and affects biomass partitioning to the ear (Maddonni and Otegui, 2004; Pagano and Maddonni, 2007; Lobell *et al.*, 2008).

Generally, this review revealed that there is very little available information on maize studies for tolerance to high plant population density stress conducted in SSA as well as in Southern Africa compared to European and American countries. Genetic information attained from outside the sub-continent might not have direct application, because the agricultural systems and agricultural environmental conditions are quite diverse in the different regions. An enormous gap still exists between grain yield potential and the actual yield, indicating the existence of opportunities for grain yield improvement. Improvement in yielding ability of temperate maize was associated with increasing stress tolerance, especially under high plant population density. Consequently, it can be suggested that breeding for baseline tolerance to high plant population density stress through combining ability would contribute towards reducing the yield gap in Southern African environments.

Based on the literature provided, it is evident that for high yields to be achieved, there is a need to grow superior varieties which exhibit high tolerance to high plant population density stress. Superior hybrids are developed from inbred lines with favourable traits that are genetically inherited. A line by tester mating design is commonly used to identify and select the inbred lines which possess high combining ability and yield stability across conditions. A successful cultivar needs to possess high and stable grain yield potential over a wide range of environmental conditions (Eberhart and Russel, 1969; Wricke and Weber, 1986; Becker and Leon, 1988; Fasoula and Fasoula, 2002). Elementary causes for the differences between maize genotypes in their grain yield stability is a wide occurrence of genotype by environment interaction. The literature also provided the information about the amount of genetic advances which is achievable largely by genotype by environment interactions which provide both opportunities and challenges to breeding. However, the knowledge of genotype by environment interactions can help to reduce the cost of extensive genotype evaluation by eliminating unnecessary testing sites and by fine-tuning breeding programs. The presence of genotype by environment interaction in any genetic study simply leads to overestimation of genetical and statistical parameters (Sharma, 2006). Genetic correlation in particular determines the degree of association between traits and how they may enhance selection. It is beneficial to use indirect selection for the traits than using the direct selection for the same trait if indirect selection gives greater response and it is suggested that indirect selection would be effective if heritability of the secondary trait is greater than that of the primary trait and genetic correlation between them is significant (Falconer, 1951).

This literature review identified the gaps that need to be filled by the objectives of this study, the relationship between yield and secondary traits that varies under low and high plant population densities and across the testers. Therefore there is need to evaluate the local population under local environments. Likewise, genetic gains are also variable under different environments. The combining ability of the inbred lines with different testers under high and low plant population densities were identified and the traits which would result in the highest yield improvement under high and low plant population density together with the traits which were successfully introgressed from temperate by tropical germplasm lines selected.

CHAPTER 3

Materials and Method

3.1. Introduction

This chapter presents research methods that were employed in the study. The chapter outlines the study area, research design and experimental management aspects such as methods of planting and pollinations as well as data collection and methods of data analysis. The details of the materials used and methodology adopted for the collection of various types of data from the experiments conducted are given under this chapter.

3.2. Germplasm

In this study, inbred lines were derived from F₂-crosses between tropical and temperate lines. The USA temperate lines contributed genes for early physiological maturity and good standing ability (stiff stalk source), while the tropical germplasm lines provided water stress tolerance. Self-pollination was applied to advance the materials with concomitant pedigree selection for good agronomic traits and seed parent characteristics. This was achieved in a shuttle programme involving winter nurseries at the Makhathini Agriculture Research Station (27°23'15.04"S and 32°09'31.01"E) and Ukulinga Research Farm (29°39'57.41"S and 30°24'21.34"E) in South Africa (Appendix A and Appendix B), from 2011 to 2013. The seed from the F₆ generation of each family was bulked and used for the current study. Seed of the two tester inbred lines DTAB32 and Tester 9 were bulked at both stations. The DTAB32 was derived from a subtropical synthetic population which is adapted to South African conditions. It is a white grain inbred line which has high level of ear prolificacy and medium maturing period. It also has good standing ability and adaptation to abiotic stress environments, including drought. On the other hand, the Tester 9 was derived from a synthetic temperate maize population. The Tester 9 lacks drought tolerance, but it is a very early maturing maize inbred line which is prone to root lodging. It has white grain, produces single ears and has high yield potential under non-stress conditions.

Testcross hybrids were generated at the Makhathini Research Station, in South Africa, during the 2014 winter (May-October) season under irrigation. The experimental materials consisted of 100 test inbred lines which were crossed to two testers (DTAB32 and Tester 9). The 100 inbred lines were crossed with the two testers based on the line x tester mating scheme (Kempthorne, 1957) to generate 200 F₁ testcross hybrids. Both tester inbred lines and test inbred lines were used interchangeable as both male and female donors for pollen during pollination. However, at harvest the seed from reciprocal crosses was combined to obtain sufficient seed for planting in trials. For the study, the 93 testcrosses of Tester 9 which had sufficient seed for planting in trials were designated 15XH45 to 15XH135. The other 93 testcrosses of DTAB32 were designated 15XH136 to 15XH228. Two standard commercial maize hybrids, PAN6Q-345CB and BG5285, which are widely grown in South Africa, were included as the commercial controls. In addition five promising experimental hybrids which had been tested extensively for the three previous years (11C1774, 11C1579, 11C2245, 11C1483 and 10HDTX11) in the East and Western South Africa were included as additional control hybrids to obtain the desired 100 entries for the study based on each tester. The list of the hybrids which were evaluated in the study is presented in Appendix A and Appendix B.

3.3. Site and test environment description

The hybrids were evaluated across three sites in KwaZulu-Natal province of South Africa, during the 2014/15 summer cropping season. The sites used were Ukulinga Research Farm (UKZN), Dundee Research Station (28° 10' 13.1219" S and 30° 31' 45.2365" E) and Cedara Research Station (29° 32' 38.1624" S and 30° 15' 59.8536" E). The geographical description for the three sites is presented in Table 3.1. Four test environments, which were designated as Env-1 to Env-4, were created for the study by varying the population density of the hybrids at Ukulinga Farm, resulting in two testing environments at that station (Table 3.1 and Table 3.2). The two test environments at Ukulinga Farm were designated Ukulinga 1 and Ukulinga 2 experiments. The experiments at Ukulinga 1 and Ukulinga 2 were planted on the 26th of November 2014 and the 5th of December, 2014, respectively. Only one test environment was created at Dundee and Cedara Agricultural Research Stations. At Dundee Agricultural Research Station, the experiment was planted on the 27th of November, 2014. At Cedara Agricultural Research Station, the experiment was planted on 09th of December, 2014 depending on the effective rains received.

Table 3.1. Geographical coordinates and environmental conditions for the study sites

Test environment (Env)	Location	Plant density	Latitude	Longitude	Altitude (m.a.s.l)	Total season rainfall (mm)	Temperature range (°C)
Env-1	Ukulinga 1	37,037	29.67S	30.41E	809	676.17	13.65 – 24.83
Env-2	Cedara	44,444	29.76S	30.26E	1068	696.96	9.85 – 24.41
Env-3	Ukulinga 2	74,074	29.67S	30.41E	809	676.17	13.65 – 24.83
Env-4	Dundee	74,074	28.13S	30.31E	1219	782.80	9.70 – 24.10

The climate conditions of Ukulinga Research Farm are characterized by low and erratic rainfall with unimodal pattern of precipitation. The soil in the testing field of Ukulinga Research Farm is sandy clay-loam, fertile and friable with good water drainage (Cambisol). It is composed of 35% sand, 44% silt, 21% clay, 7.4 pH, 1.2% organic matter, 10.32 ppm available phosphorous (P), and cation exchange capacity (CEC) of 22.34 (meq/100 g). However it is susceptible to cracking and crusting under flooding. Cedara Research Station is characterised by sandy clay soils which are reasonably fertile and well drained. Chances of flooding were very low due to a good slope and ground cover. The fields at Ukulinga 1 and 2 and Dundee planting fields were ploughed and disced before planting although minimum tillage was done at Cedara. The Cedara field had high organic matter from the stover of preceding maize crop. The ground cover also provided mulch and helped in moisture conservation.

3.4. Experimental design and management

The testcrosses were organised into two trials based on the tester, hence two field trials were conducted at each of the three different locations and test environments at Ukulinga Farm, during the 2014/15 summer season in KwaZulu natal, South Africa. The 100 entries in two replicates for the Tester 9 (Tester A) and DTAB32 (Tester B) testcrosses and seven control hybrids were laid out as 10 x 10 simple lattice design at all sites and test environments. Plot sizes at each site had single rows of 5m long but the spacing varied as follows: 0.9 m inter-row spacing and 0.3 m intra-row spacing at Dundee and Ukulinga 1 and 2, and 0.75 m inter-row and 0.3 m intra-row at Cedara. The plots were 17 planting stations per row resulting in 34 plants before thinning at all sites and test environments. This is because two seeds were

planted per station by hand and later thinned down to one at 21 days after planting to give the desired plant population of 44,444 and 37,037 plants per hectare, at Cedara and Ukulinga 1, respectively. The second planting was not thinned at Ukulinga 2 and Dundee research station resulting in a population density of 74,074 plants per hectare. This was considered to be high plant population density because the average planting density for the area is 37,000 to 45,000 plants per hectare. In the fields where thinning was done, the first and the last stations in the rows were not thinned to minimise the competition advantages along the edges. The experiments at Cedara and Dundee had two border rows planted at either side of the field, while at Ukulinga 1 and Ukulinga 2 there was one border row on both sides.

Experimental management including fertilizer, chemical and herbicide application and weed control followed standard practice for maize trials. The experiments were conducted under rain fed conditions at all sites. The total amount of the monthly rainfall for the growing season and the temperature range data is shown in Table 3.1. Fertilizer was applied as basal at planting in the form of compound (NPK) 2:3:4 at 250 kg ha⁻¹ (56 kg ha⁻¹ of N, 83 kg ha⁻¹ of P and 111 kg ha⁻¹ of K). Nitrogen fertilizer was applied at four weeks after crop emergence in the form of LAN (Lime Ammonium Nitrate, 28% N) at the rate of 250 kg ha⁻¹. The herbicides, Gramoxone, Dual, Basagran, and 2,4-D were applied to control weeds. This was augmented by hand weeding to keep the fields relatively clean of weeds throughout the season. Insecticide granules were applied in the maize leaf whorls for stalk borer control. An insecticide, Karate, was applied to control cutworms at planting and seedling emergence.

Table 3.2. Summary description of trial management in all four experimental environments

Test Environment (Env)	Planting date	Row spacing (inter x intra) (m)	Plant Population Density	Water Source
Ukulinga Research Farm 1 (Env-1)	26 Nov 2014	0.9 x 0.3	37,037	Rainfed
Cedara Agriculture Research Station (Env-2)	09 Dec 2014	0.75 x 0.3	44,444	Rainfed
Ukulinga Research Farm 2 (Env-3)	05 Dec 2014	0.9 x 0.3	74,074	Rainfed
Dundee Agriculture Research Station (Env-4)	27 Nov 2014	0.9 x 0.3	74,074	Rainfed, but was irrigated in the first week after planting

Env = Environment

3.5. Data collection

Data for maize traits was collected following the standard protocols which are used at International Maize and Wheat Improvement Center (CIMMYT) (Magorokosho *et al.*, 2009). Data recorded on yield components included grain yield (t/ha), plant height (cm), ear height (cm), ear position, anthesis date, silking date, root lodging (%), stem lodging (%), total plant lodging (%), grain moisture content (%), anthesis-silking interval (ASI) (days), number of tassel branches, number of leaves above the cob and ear prolificacy (EPP) (number of ears per plant). The number of ears per plant (EPP) was then computed as the proportion of the total number of ears at harvest divided by the total number of plants harvested. Grain yield (GYG) (t/ha) was measured as grain mass per plot adjusted to 12.5% grain moisture content at harvest. Grain yield was estimated using the measured field weight as cob weight per plot adjusted to 12.5 % grain moisture content and 80 % shelling percentage using the following formula: $GYG = \text{Field weight (kg)} * 10\,000 \text{ m}^2 * (100 - \text{MOI}) * \text{Shelling \%} / 1000 \text{ (kg)} *$

Plot area (m²) * (100 – 12.5) %, Where: GYG = Calculated grain yield per ha, MOI = measured grain moisture content at harvest, Shelling % = Assumed to be 80% for all genotypes. Plant height (PH) (cm) was measured as the distance from the base of plant to the insertion point of the top tassel. It was measured when all the plants had flowered, since plants reach their maximum height at flowering. Ear height (EH) (cm) was measured as height from ground level up to the base of the upper most ear. Ear position (EPO) was measured as the ratio of ear height to plant height. Small values indicate low ear position and large values indicate high ear position. Anthesis-silking interval (ASI) was determined by finding the difference between the number of days after planting when 50% of the plants shed pollen (anthesis date, AD) and the number of days after planting when 50% of the plants show silks (silking date, SD). Grain moisture content (MOI) was measured as percentage water content of grain measured at harvest using the Moisture meter (Eaton, Model 500). Root lodging (RL) was measured as a percentage of plants that showed lodging by being inclined 45°. Stem lodging (SL) was measured as a percentage of plants that were broken below the ear. Total plant lodging (TL) was measured as the percentage mean value of the root and stem lodging. Number of tassel branches (NTB) was measured by counting the number of the main tassel branches. Number of leaves above the cob (NLAC) was measured by counting all the main leaves above the cob. DCD = was determined as the number of days when 50% of the ears in a plot dries, calculated from day of planting to drying. Due to logistical and management reasons, only number of plants (NP), number of ears per plot, grain moisture content and grain yield was measured at Dundee agricultural research station while all other grain yield related traits were measured and collected in the other three study sites.

3.6. Data analysis

3.6.1. Single site and across site analysis of variance

Data were subjected to single site and across site analysis of variance (ANOVA) using the GenStat version 17 VSN international, 2015. The mathematical models for single site ANOVA was:

$$Y_{ij(k)} = \mu_i + r_j + b_k(r_j) + e_{ij(k)}$$

Where, Y_{ijk} is the yield of the i^{th} hybrid evaluated in the k^{th} block nested with the j^{th} replication, h_i is the effect of the i^{th} hybrid, r_j is the effect of the j^{th} replication, $b_k(r_j)$ is the effect of the k^{th} block nested with the j^{th} replication and $e_{ij(k)}$ is the random error.

The across site ANOVA model was;

$$Y_{ijk(l)} = h_i + s_j + r_k + h_i s_j + s_j(r_k) + s_j r_k(b_l) + e_{ijk(l)}$$

Where, $Y_{ijk(l)}$ is the yield of the i^{th} hybrid evaluated in the l^{th} block nested with the k^{th} replication of the j^{th} environment, h_i is the effect of the i^{th} hybrid, s_j is the effect of the j^{th} environment, $h_i s_j$ is the interaction between i^{th} hybrid and the j^{th} environment, $s_j(r_k)$ is the effect of the k^{th} replication nested within the j^{th} environment, $s_j r_k(b_l)$ is the effect of the l^{th} block nested within the k^{th} replication which is also nested within the j^{th} environment and $e_{ijk(l)}$ is the random error.

3.6.2 Frequency distribution

The frequency distribution bar graphs were generated using GenStat software version 17 on selected traits that include grain yield (GYG), root lodging (RL), stem lodging (SL), total plant lodging (TL), plant height (PH), ears per plant (EPP), days to anthesis (AD), and grain moisture content (MOI).

3.6.3. Genotype x environment interaction

Since the genotype x environment was significant from the across environment ANOVA, the genotype plus the genotype by environment interaction (GGE) model was used to identify genotypes for specific environments and stable genotypes. In order to determine the number of principal components to retain during GGE biplot analyses, a postdictive evaluation was done for model fitting using Gollob's (1968) F-test (Zobel *et al.*, 1988; Dias and Krzanowski 2003; Gauch, 2013). Gollob's (1968) F-test (Zobel *et al.*, 1988; Gauch 2013) showed that the two principal components of the biplot were significant and thus a GGE-2 biplot analysis (Yan and Tinker, 2006) was conducted using Genstat Software version 17. The GGE biplots were constructed using least squares (adjusted) means for each trait from each environment.

The GGE biplot model used (Yan, 2002) was $Y_{ij} - \mu - \beta_j = \lambda_1 \xi_{i1} \eta_{j1} + \lambda_2 \xi_{i2} \eta_{j2} + \varepsilon_{ij}$, where Y_{ij} is the mean of i^{th} genotype in the j^{th} environment, μ is the grand mean, β_j is the j^{th} environment main effect, and $\mu + \beta_j$ is the mean of all genotypes in the j^{th} environment. The terms λ_1 and λ_2 are the singular values for the first (PC1) and second (PC2) principal components, respectively; ξ_{i1} and ξ_{i2} are eigenvectors of the i^{th} genotype for PC1 and PC2, respectively. The components η_{j1} and η_{j2} are eigenvectors of the j^{th} environment for the principal components PC1 and PC2, respectively; and ε_{ij} is the residual associated with the i^{th} genotype in the j^{th} environment. The which-won-where scatter biplot (for mega-environment delineation) and the genotype comparison biplot (for comparing genotypes based on mean yield and stability) were generated using the appropriate singular value partition methods (Yan, 2002). In the scatter biplot, the polygon view displaying the which-won-where pattern was formed by connecting the genotype markers furthest away from the biplot origin such that the polygon contained all other genotypes (Yan, 2002). The polygon was then dissected by straight lines perpendicular to the polygon sides and running from the biplot origin. Visualization of the mean and stability of genotypes using a genotype comparison biplot was achieved by representing an average environment by an arrow. A line that passes through the biplot origin to the average environment (average genotype axis) was drawn followed by a perpendicular line that passes through the biplot origin.

3.6.4. Estimation of Stress tolerance index (STI)

Stress tolerance index (STI) was calculated based on formula suggested by Bouslama and Schapaugh (1984) by finding the quotient between the hybrid mean yield under stress condition and the mean yield under the optimal condition according to the formula:

$$STI = \frac{(Yp) * (Ys)}{Ypi}$$

Where,

STI = Stress tolerance index

Y_s = Mean of the hybrid under stress condition

Y_{pi} = Mean of the hybrids under optimal condition

3.6.5. Estimation of genetic gain

The realized genetic gain was calculated by finding the difference between the population mean and the mean of the selected hybrids according to the formula described by Nyquist (1991) as:

$$\Delta G = \mu_2 - \mu_1$$

Where μ_2 = mean of selected hybrids,

μ_1 = population mean.

The predicted genetic gain was estimated as described by (Nyquist, 1991) as:

$$\Delta G = R = i\sigma_p H^2$$

Where

ΔG is the genetic gain,

R is the response to selection, i is the selection intensity,

H^2 is the broad sense heritability and

σ_p is the phenotypic variance.

3.6.6. Combining ability and related genetic parameters

Line x tester analysis of variance was also performed using the GenStat software. Grain yield for each plot was adjusted to tonnes ha⁻¹ at 12.5% moisture content. The mathematical model of the line x tester across sites was expressed as:

$$Y_{ijkl} = \mu + s_i + l_j + t_k + lt_{jk} + sl_{ij} + st_{ik} + slt_{ijk} + e_{ijkl}$$

Where:

Y_{ijkl} is the l^{th} observation at the i^{th} site on the jk^{th} progeny.

μ is the general mean

s_i = site main effects

l_j is the effects of the j^{th} line, (GCA effects for line)

t_k is the effects t^{th} tester, (GCA effects for tester)

$(lt)_{jk}$ is the interaction effect of the cross between the j^{th} line and k^{th} tester (SCA effects)

sl_{ij} , st_{ik} and slt_{ijk} interaction of sites with the lines, testers and line x tester effects

and e_{ijkl} is the error term associated with each observation.

To estimate general combining ability (GCA) effects, their standard error and their mean square were estimated using the line x tester analysis using the following equations adapted from Shashidhara (2008):

$$GCA = \chi_i - \mu$$

Where:

GCA = general combining ability

χ_i = predicted mean of line or tester

μ = grand mean

Standard error for GCA effects were estimated following a methodology presented in Dabholkar (1992)

$$SE = \sqrt{\frac{MSE}{E * T}}$$

Where:

SE = standard error

MSE_l = mean square for Lines

T = number of testers

E = number of environments

$$GCA_l = \frac{y_l}{rl} - \mu$$

$$GCA_t = \frac{y_t}{rt} - \mu$$

Where;

GCA_l and GCA_t = the general combining ability effect of the l^{th} line and t^{th} tester, respectively.

yl and y_t = the grand total of the l^{th} line mated with all testers and the t^{th} tester mated with all lines, respectively

μ = the grand mean of all crosses in all sites

r = the number of replications

l^{th} = the number of lines

t^{th} = the number of testers

The variance components from the line x tester analysis of variance were used to estimate heritability estimates. Heritability (broad, H^2 and narrow, h^2) were calculated using the following formulas:

$$H^2 = \frac{\sigma_{GCA_l}^2 + \sigma_{GCA_t}^2 + \sigma_{SCA}^2}{\sigma_{Sl}^2 + \sigma_{St}^2 + \sigma_{Stl}^2 + \sigma_{tl}^2 + \sigma_t^2 + \sigma_l^2 + \sigma_e^2}$$

$$h^2 = \frac{\sigma_{GCA_l}^2 + \sigma_{GCA_t}^2}{\sigma_{Sl}^2 + \sigma_{St}^2 + \sigma_{Stl}^2 + \sigma_{tl}^2 + \sigma_t^2 + \sigma_l^2 + \sigma_e^2}$$

Where:

H^2 = Broad sense heritability

h^2 = Narrow sense heritability

$\sigma_{GCA_l}^2$ = Variance due to GCA of lines

$\sigma_{GCA_t}^2$ = Variance due to GCA of testers

σ^2_{SCA} = Variance due to SCA of lines x testers

The genotypic coefficient of variation (GCV) and phenotypic coefficient of variation (PCV) were calculated for all quantitative traits, according to Singh and Chaudhary (2004), using the following equations:

$$GCV (\%) = \frac{\sqrt{\sigma^2_g}}{\bar{x}} \times 100$$

$$PCV (\%) = \frac{\sqrt{\sigma^2_p}}{\bar{x}} \times 100$$

Where,

σ^2_g = genotypic variance,

σ^2_p = phenotypic variance and

\bar{x} = grand mean of the character.

3.6.7. Correlation and path coefficient analysis

Path coefficient analysis helps partitioning the correlation coefficient into its direct and indirect effects. This study was carried out to estimate the correlations and direct and indirect contributions of different traits to grain yield under low and high plant population density stress. The phenotypic correlations between secondary traits and grain yield were calculated using Genstat software as described by Snedecor and Cochran, (1981). The PATHSAS micros were used with the Statistical Analysis Software (SAS) version 9.3 for the phenotypic path analysis. Path analysis partitions correlation coefficients into direct and indirect effects using the method proposed by Wright (1934) and Dewey and Lu (1959).

3.7. Conclusion

This methodology chapter explained and presented all the methodology and materials employed in the study for developing the experimental plant material from line x tester mating design, crop management procedures, data collection and analysis required to achieve the research objectives. The findings from the study are reported in the next chapter.

CHAPTER 4

Results

4.1. Introduction

This chapter presents the results of this study and highlights the patterns observed. The results obtained from this study are presented in sections, namely; general analysis of variance and mean performance of hybrids for each site and each tester, frequency distribution comparison for the selected traits, genotype plus genotype by environment interaction, combined analysis of variance for all the entries for line by tester, correlation coefficient, and direct and indirect coefficients of path analysis to achieve the objectives of the study. Due to logistical and management challenges, only grain yield, ear prolificacy and grain moisture content were measured and collected at Dundee Research Station (Env-4). Therefore, the data is presented on a site by site basis for entries and across the sites for grain yield and grain moisture content at maturity.

4.2. General analysis of variance and mean performance

Analysis of variance (ANOVA) for grain yield and grain yield related components was done for each site and a combined ANOVA was computed across all sites using a GLM procedure, by considering environments and genotypes (lines, testers and hybrids) as fixed factors and replication and incomplete blocks as random factors. Across sites and within testers, analysis of variances and the mean tables for grain yield and yield related traits data for all the 100 entries is presented in Tables 4.1 to Table 4.12 and the analysis of variance showed different levels of significance for each trait associated with yield at $P \leq 0.05$, $P \leq 0.01$ and $P \leq 0.001$. The number of plants (NP) was used as the covariate in all the analysis.

There were significant differences ($P < 0.05$) among hybrids derived from tester A on all traits except for EPO, RL, SL and TL at Ukulinga 1 (Env-1) (Table 4.1). The top 10 and bottom 2 hybrids together with the mean performances for the control hybrids in terms of grain yield at Ukulinga 1 (Env-1) are presented in Table 4.2 and ranked from the top yielding as 15XH50, 15XH117, 15XH69, 15XH94, 15XH88, 15XH116, 15XH123, 15XH82, 15XH52 and 15XH99. However, these hybrids were not significantly different based on the 5% LSD.

Table 4.1. ANOVA table for 93 test cross experimental hybrids and seven standard commercial checks of maize germplasm developed from tester A under low plant population density at Ukulinga 1 (Env-1)

S.O.V	d.f.	GYG	PH	EH	AD	EPO	EPP	ASI	MOI	RL	SL	TL	NTB	NLAC	DCD
Rep	1	30.241	6891.4	9398.2	26.65	0.055	0.535	0.405	0.344	531.6	8.37	673.3	0.32	0.72	3.92
Rep.Blk	18	5.708	674.2	397.7	5.85	0.00271	0.056	0.98	3.82	3082.1	65.3	2974.4	10.14	1.083	11.2
NP	1	19.576	37.5	136	0.67	0.00183	0.424	0.0713	0.007	2494.4	98.2	1602.8	5.138	0.0291	0.736
Hybrids	99	4.009**	311.8***	219.6*	3.46***	0.00231	0.111***	0.88**	1.65**	901.3	53.2	909.3	5.132*	0.553*	5.9***
Error	80	2.25	137	152.5	1.265	0.00201	0.02457	0.4839	1.036	749.5	46.6	810.5	3.597	0.3652	2.094
Total	199	3.665	306	254.5	2.896	0.00248	0.07515	0.7244	1.584	1043.7	51.6	1058.7	4.944	0.5237	4.821
Av LSD		3.005	23.45	24.74	2.254	0.08994	0.3141	1.394	2.039	24.86	13.7	57.05	3.801	1.211	2.899
%cv		12.72	5.06	10.32	1.53	8.69	13.46	10.79	5.75	15.16	30.3	13.57	16.46	9.06	1.15
Se		1.5	11.7	12.35	1.125	0.04489	0.1567	0.6956	1.018	27.38	6.83	28.47	1.897	0.6043	1.447

S.O.V = Source of variation; d.f. = Degrees of freedom; GYG = Grain yield; PH = plant height; EH = Ear height; AD = Days to anthesis; EPO = Ear position; EPP = Number of ears per plant; MOI = grain moisture content; ASI = Anthesis-silking interval; RL = Root lodging; SL = Stem lodging; TL = Total lodging; NTB = Number of tassel branches; NLAC = Number of leaves above the cob, NP = Number of plant and DCD = Number of days to 50% cob dryness. *, **, *** significantly different at 0.05, 0.01 and 0.001 probability levels, respectively.

Table 4.2. Mean performance of 93 test cross experimental hybrids and seven standard commercial checks of maize germplasm developed from Tester A under low plant population density at Ukulinga 1 (Env-1).

HYBRIDS	GYG	PH	EH	AD	EPO	EPP	ASI	MOI	RL	SL	TL	NTB	NLAC	DCD	PopDen
Mean performance for the top 10 experimental hybrids															
15XH121	14.37	245.7	120.9	74.5	0.4919	1.035	0.557	19.33	40.78	0.437	41.21	12.01	8.002	132.1	37778
15XH117	14.31	235.2	122.9	76.02	0.5217	1.186	-0.727	18.24	18.15	5.93	24.08	10.02	7.01	125.7	33333
15XH69	14.29	241	132.5	75	0.5482	1.229	2.0032	18.6	11.96	0.025	11.98	14.5	7	128.5	38889
15XH94	14.21	229.5	120.8	75.51	0.5264	1.258	-0.889	19.16	80.25	0.848	81.1	11.51	6.004	132.3	36667
15XH88	14.09	214.2	108.6	73	0.5069	1.224	-0.051	18.07	14.57	2.554	17.12	11	6.498	124.9	40000
15XH116	13.87	256.5	148.2	72.99	0.5784	1.16	0.896	16.4	64.2	7.388	71.59	10.49	6.496	124.7	41111
15XH123	13.83	251.8	126.8	72.99	0.5036	1.392	-0.658	17.27	52.47	-1.211	51.26	9.49	7.494	124.6	42222
15XH82	13.74	228.2	123.9	75.5	0.5383	1.59	-0.943	17.13	43.23	3.378	46.6	8.51	6.002	125.1	37778
15XH52	13.65	259.9	144	77.51	0.5504	1.244	-0.782	17.01	37.35	1.672	39.02	15.52	7.008	125.6	34444
15XH99	13.54	223.3	114.3	73.04	0.5115	1.591	0.5413	17.93	41.55	4.143	45.69	8.55	7.019	126.4	27778
Mean performance for the control hybrids															
BG5285A	15.89	257	133.7	74.99	0.5205	2.13	-0.104	18.5	33.79	-0.799	32.99	12.49	7.496	131.7	41111
11C1774A	13.25	227	128.7	74.99	0.5663	1.665	-0.604	17.7	7.19	-0.799	6.39	10.99	5.996	124.7	41111
10HDTX11A	12.64	227.5	118	72.5	0.5176	1.709	0.003	19	41.13	0.025	41.15	12	6.5	132	38889
11C1483A	11.82	228.8	102.3	73.49	0.4419	1.734	-0.158	17.17	10.36	-1.211	9.15	13.49	5.994	124.6	42222
11C2245A	11.18	206	105	74.99	0.5094	1.646	-1.712	18.49	10.81	-1.623	9.19	9.48	6.492	124.5	43333
11C1579A	10.99	219.5	120.8	77.01	0.5503	1.432	-0.889	18.01	7.28	3.79	11.07	8.51	5.504	128.8	36667
PAN 6Q-345 CBA	10.72	228.8	120.8	73.49	0.5286	1.997	0.842	19.97	7.73	-1.211	6.52	14.99	5.994	124.6	42222
Mean of checks	12.36	227.8	118.47	74.49	0.52	1.76	-0.37	18.41	16.9	-0.26	16.64	11.71	6.28	127.3	40794
Mean performance for the least 2 experimental hybrids															
15XH122	8.68	219.7	124.4	73.52	0.5655	0.738	0.2723	17.09	45.27	2.084	47.35	14.02	6.51	125.7	33333
15XH118	7.14	215.7	115.4	72	0.535	1.004	0.057	17.83	63	0.437	63.43	14.51	7.502	125.1	37778
5% LSD	3.005	23.45	24.74	2.254	0.089	0.3141	1.394	2.039	54.86	13.68	57.05	3.801	1.211	2.899	7492
%cv	12.72	5.06	10.32	1.53	8.69	13.46	10.79	5.75	15.16	30.27	13.57	16.46	9.06	1.15	9.67

GYG = Grain yield (t/ha); PH = plant height (cm); EH = Ear height (cm); AD = Days to anthesis (Days); EPO = Ear position (EH/EP); EPP = Number of ear per plant; MOI = grain moisture content; ASI = Anthesis silking interval; RL = Root lodging (%); SL = Stem lodging (%); TL = Total lodging (%); NTB = Number of tassel branches; NLAC = Number of leaves above the cob and DCD = Number of days to 50% cob dryness.

Significant differences at $P < 0.05$ were observed among all traits except for PH, EPO, RL, SL and TL at Ukulinga 1 (Env-1) under Tester B (Table 4.3). The top 10 high yielding hybrids together with the mean performances for the control hybrids in terms of grain yield at Ukulinga 1 (Env-1) are ranked from the top yielding as 15XH172, 5XH215, 15XH213, 15XH187, 15XH214, 15XH212, 15XH156, 15XH174, 15XH138 and 15XH168 (Table 4.4). However, these hybrids were not significantly different based on the 5% LSD.

Table 4.3. ANOVA for the traits of 93 test cross experimental hybrids and seven standard commercial checks of maize germplasm developed from Tester B under low plant population density at Ukulinga 1. (Env-1)

S.O.V	d.f.	GYG	PH	EH	AD	EPO	EPP	ASI	MOI	RL	SL	TL	NTB	NLAC	DCD
Rep	1	25.18	1030.6	994.58	3.38	0.002	0.00042	0.02	19.78	167.18	70.87	20.35	4.205	0.72	3.92
Rep.Blk	18	2.65	500.4	462.82	4.39	0.006	0.059	2.49	2.68	154.93	6.375	166.71	4.76	1.51	13.72
NP	1	139.26	79	33.42	3.083	0.004	0.02664	0.019	1.531	155.78	7.792	233.26	0.9	0.1022	4.072
Hybrids	99	4.25***	228	151.03**	4.56***	0.003	0.082***	1.70**	1.79**	65.17	6.915	67.05	3.48*	0.87*	15.66***
Error	80	1.101	241.2	89.56	2.3	0.003	0.02148	1.051	0.919	51.86	6.748	60.79	2.394	0.611	6.291
Total	199	3.622	261.2	158.17	3.624	0.004	0.05514	1.495	1.611	68.91	7.125	74.15	3.153	0.8216	11.602
5% LSD		2.105	31.16	18.98	3.042	0.113	0.294	2.057	1.923	14.45	5.211	15.64	3.104	1.568	5.032
%cv		9.84	6.44	7.4	2.03	10.56	7.75	-17.94	5.62	11.26	24.28	14.45	12.08	13.14	1.95

S.O.V = Source of variation; d.f. = Degrees of freedom; GYG = Grain yield; PH = plant height; EH = Ear height; AD = Days to anthesis; EPO = Ear position; EPP = Number of ears per plant; MOI = grain moisture content; ASI = Anthesis-silking interval; RL = Root lodging; SL = Stem lodging; TL = Total lodging; NTB = Number of tassel branches; NLAC = Number of leaves above the cob, NP = Number of plant and DCD = Number of days to 50% cob dryness. *, **, *** significantly different at 0.05, 0.01 and 0.001 probability levels, respectively.

Table 4.4. Mean performances for the traits of the 93 test cross experimental hybrids and seven standard commercial checks of maize germplasm developed from tester B under low plant population density at Ukulinga 1 (Env-1).

HYBRIDS	GYG	PH	EH	AD	EPO	EPP	ASI	MOI	RL	SL	TL	NTB	NLAC	DCD	PopDen
Mean performance for the top 10 experimental hybrids															
15XH172	13.53	239.6	130.7	76.53	0.5446	2.053	-2.07	17.81	0.183	2.846	3.029	14.96	5.951	129.5	41111
15XH215	13.26	222.4	122.2	74.37	0.5516	1.966	-2.19	17.04	17.936	-0.304	17.632	11.16	5.718	129.6	34444
15XH213	13.24	231.3	121.9	74.45	0.5286	1.929	-1.88	17.42	17.331	2.823	20.155	13.06	6.085	129.6	37778
15XH187	13.23	247.9	143.7	76.48	0.5804	2.036	-3.94	17.48	2.628	-0.056	2.572	14.03	6.04	133	38889
15XH214	13.07	246.3	142.4	74.95	0.5798	1.951	-2.88	16.12	6.351	-0.118	6.233	13.56	6.085	129.6	37778
15XH212	12.68	240.2	124	75.56	0.5156	1.835	-3.13	18.47	13.96	0.13	14.09	11.93	6.406	132.9	42222
15XH156	12.64	253.5	135.5	77.5	0.5345	2.141	-1.51	17.95	8.35	0.006	8.356	13.5	5.496	129.5	40000
15XH174	12.64	244.1	123.2	74.03	0.504	2.239	-2.07	17.46	0.183	5.624	5.807	14.46	6.951	126	41111
15XH138	12.59	249.4	131.2	74.48	0.5282	1.807	-0.44	19.78	-0.149	-0.056	-0.205	11.53	7.04	133	38889
15XH168	12.52	238.5	117	76	0.4888	2.12	-1.51	16.55	0.017	2.638	2.654	11.5	6.496	126	40000
Mean performance for the control hybrids															
BG5285	13.05	246.7	125.5	75.56	0.5081	2.057	-2.63	16.22	19.238	0.13	19.368	12.93	6.406	129.4	42222
PAN 6Q-345 CB	11.44	227	110	76.5	0.4838	1.974	-1.01	16.4	2.794	0.006	2.801	12	6.996	129.5	40000
11C1483	10.7	233.7	134.7	74.42	0.5798	1.933	-1.32	17.66	-0.482	-0.18	-0.662	11.59	6.129	126.1	36667
11C1774	10.62	243	128	76	0.5258	1.586	-1.01	17.45	16.116	0.006	16.122	14.5	5.496	129.5	40000
10HDTX11	9.98	240.7	130	74.06	0.5396	1.838	-0.63	17.52	8.682	2.908	11.59	11.93	5.406	129.4	42222
11C1579	9.44	241.4	129.7	76.37	0.541	1.498	-1.19	17.99	2.757	-0.304	2.453	15.66	6.718	126.1	34444
11C2245	8.84	251.5	137.1	80.76	0.5525	1.314	-0.45	17.84	1.855	3.614	5.469	13.29	7.397	126.2	30000
Mean of checks	10.58	240.6	127.9	76.24	0.5329	1.743	-1.18	17.30	7.28	0.883	8.163	13.13	6.364	128.0	37936
Mean performance for the least 2 experimental hybrids															
15XH181	6.6	241.1	121.7	77.53	0.5054	1.945	-1.07	18.76	0.183	0.068	0.251	12.46	5.451	129.5	41111
15XH154	6.57	235.2	129.2	74.42	0.5495	1.92	-2.82	17.96	-0.482	-0.18	-0.662	14.59	5.129	126.1	36667
5% LSD	2.105	31.16	18.98	3.042	0.1126	0.294	2.057	1.923	14.45	5.211	15.64	3.104	1.568	5.032	5879
%cv	9.84	6.44	7.4	2.03	10.56	7.75	-17.9	5.62	16.26	24.28	14.45	12.08	13.14	1.95	7.41

GYG = Grain yield (t/ha); PH = plant height (cm); EH = Ear height (cm); AD = Days to anthesis (Days); EPO = Ear position (EH/EP); EPP = Number of ear per plant; MOI = grain moisture content; ASI = Anthesis silking interval; RL = Root lodging (%); SL = Stem lodging (%); TL = Total lodging (%); NTB = Number of tassel branches; NLAC = Number of leaves above the cob and DCD = Number of days to 50% cob dryness.

There were significant differences ($P < 0.05$) among hybrids derived from tester A on all traits except for PH, EH, MOI, EPO, NTB, NLAC and DCD at Ukulinga 2 (Env-3) (Table 4.5). The top 10 hybrids in terms of grain yield at Ukulinga 2 (Env-3) under tester A are ranked from the top yielding as 15XH92, 15XH45, 15XH80, 15XH87, 15XH81, 15XH119, 15XH122, 15XH94, 15XH124, 15XH71 and 15XH121 (Table 13). However, these hybrids were not significantly different based on the 5% LSD.

Table 4.5. ANOVA of 93 test cross experimental hybrids and seven standard commercial checks of maize germplasm developed from Tester A under high plant population density conditions at Ukulinga 2 (Env-3)

S.O.V	d.f.	GYG	PH	EH	AD	EPO	EPP	ASI	MOI	RL	SL	TL	NTB	NLAC	DCD
Rep	1	0.8301	278.2	103.8	7.73	0.01	0.0014	1.319	0.89	1102.9	10.8	895.7	0.92	0.156	15.13
Rep.Blk	18	1.3073	838.0	160.4	5.19	0.01	0.021	1.117	1.16	46.25	662	699.7	2.452	0.532	27.68
NP	1	82.0402	84.2	172.4	4.057	0.01	0.120	0.143	0.08	32.04	203.9	74.3	0.628	5.27	0.201
Hybrids	99	2.8***	246.0	150.1	5.6***	1.0E-4	0.03***	1.335**	1.24	44.1**	286.3***	368.1***	2.931	0.545	1.767
Error	80	0.8604	312.3	150.8	1.677	0.01	0.0069	0.695	0.96	24.8	108	113	2.49	0.673	2.088
Total	199	2.2737	325.6	151.2	4.001	0.01	0.02168	1.052	1.11	41.8	246.8	296.7	2.69	0.617	4.299
5% LSD		1.878	35.78	24.86	2.621	0.15	0.1688	1.688	1.98	10.08	21.04	21.52	3.199	1.661	2.925
%cv		9.341	7.43	9.74	1.76	14.19	7.72	-19.47	6.03	16.96	18.16	18.81	12.05	11.48	1.19

S.O.V = Source of variation; d.f. = Degrees of freedom; GYG = Grain yield; PH = plant height; EH = Ear height; AD = Days to anthesis; EPO = Ear position; EPP = Number of ears per plant; MOI = grain moisture content; ASI = Anthesis-silking interval; RL = Root lodging; SL = Stem lodging; TL = Total lodging; NTB = Number of tassel branches; NLAC = Number of leaves above the cob, NP = Number of plant and DCD = Number of days to 50% cob dryness. *, **, *** significantly different at 0.05, 0.01 and 0.001 probability levels, respectively.

Table 4.6. Mean performances of the 93 test cross experimental hybrids and seven standard commercial checks of maize germplasm for the traits developed from tester A under high population density at Ukulinga 2 (Env-3)

ENTRY	HYBRIDS	GYG	PH	EH	AD	EPO	EPP	ASI	MOI	RL	SL	TL	NTB	NLAC	DCD	PopDen
Mean performance for the top 10 experimental hybrids																
79	15XH121	12.91	225.6	125.8	75.33	0.5571	1.312	-0.987	15.87	5.341	4.69	10.03	14.67	6.454	120.5	66689
50	15XH92	11.97	233.5	128.3	75.09	0.5503	1.208	-1.0004	15.78	-0.009	1.57	1.56	14.55	6.481	122	62235
38	15XH80	11.81	248.9	124.3	75.13	0.4997	1.094	-0.9997	15.03	1.923	3.28	5.2	13.58	6.988	120.5	63371
45	15XH87	11.68	243.6	113.3	74.77	0.4643	0.985	-1.0681	17.21	20.412	1.52	21.93	12.83	7.204	122.2	39047
39	15XH81	11.67	186.1	123.2	72.83	0.7728	1.228	-1.0065	15.79	5.575	4.15	9.72	11.91	7.535	119	57858
77	15XH119	11.67	240.3	147	75.56	0.6138	1.079	-0.9727	16.57	6.624	3.98	10.6	11.83	5.913	123.4	71135
80	15XH122	11.66	248.1	136.1	74.27	0.5476	1.071	-0.4836	16.74	1.816	13.11	14.93	14.13	7.966	122	65625
52	15XH94	11.59	233.9	124	75.3	0.5323	1.035	-0.0127	16.71	10.24	4.94	15.18	12.6	7.447	120.5	65466
82	15XH124	11.55	238.9	144.6	74.12	0.6019	1.018	-0.9949	16.31	1.771	5.28	7.05	14.58	7.475	123	63289
29	15XH71	11.50	238	120.5	76.62	0.5069	1.046	-0.0129	16.44	8.966	11.36	20.32	14.8	7.552	122	54251
3	15XH45	11.47	251.5	130.2	74.53	0.5152	0.932	-1.0416	17.27	11.737	7.41	19.15	13.96	7.645	120.6	43182
Mean performance for the control hybrids																
100	BG5285	11.99	245.1	128.7	73.71	0.5291	1.142	-0.9746	16.2	3.369	-0.79	2.58	12.38	7.39	120.4	73355
99	PAN 6Q-345 CB	11.32	240.8	112.3	76.34	0.4661	1.422	-0.9566	15.7	2.174	-0.53	1.64	11.49	7.354	124.3	76641
98	10HDTX11	10.29	253	122.8	71.57	0.4861	1.138	-0.0043	16.13	8.895	4.92	13.82	13.05	6.994	122	62255
94	11C1774	9.87	234.7	111.5	74.44	0.4735	1.062	-0.482	16.5	6.744	2.62	9.36	12.73	7.437	122	68916
97	11C1483	8.89	224.1	136.3	73.46	0.6088	1.302	-2.0098	15.72	3.704	0.03	3.73	13.49	7.511	122	59891
95	11C1579	8.70	243.6	117.2	74.97	0.4806	1.013	-1.0015	15.76	1.844	9.27	11.11	12.48	7.008	122	60033
96	11C2245	7.63	240.9	131.5	77.14	0.5425	1.014	-1.0254	16.75	-0.276	3.15	2.87	13.82	6.55	128	54491
Mean performance for the least 2 experimental hybrids																
17	15XH59	7.56	227.8	126.1	71.48	0.5523	1.003	3.0285	14.63	5.694	59.34	65.03	12	6.006	119	61309
65	15XH107	7.54	236.6	123.4	70.87	0.5223	1.053	0.5132	15.22	10.149	51.8	61.94	14.21	7.941	120.5	67666
	5% LSD	1.88	35.78	24.86	2.621	0.153	0.1688	1.688	1.982	10.08	21.04	21.52	3.199	1.661	2.925	13963
	%cv	9.34	7.43	9.74	1.76	14.19	7.72	-19.47	6.03	16.96	14.16	18.81	12.05	11.48	1.19	11.53

GYG = Grain yield (t/ha); PH = plant height (cm); EH = Ear height (cm); AD = Days to anthesis (Days); EPO = Ear position (EH/EP); EPP = Number of ear per plant; MOI = grain moisture content; ASI = Anthesis silking interval; RL = Root lodging (%); SL = Stem lodging (%); TL = Total lodging (%); NTB = Number of tassel branches; NLAC = Number of leaves above the cob and DCD = Number of days to 50% cob dryness.

Significant differences at $P < 0.05$ existed among hybrids derived from tester B on all traits except for PH, EH, EPO, RL, NTB, NLAC and DCD at Ukulinga 2 (Env-3) (Table 4.7). The top 10 hybrids in terms of grain yield at Ukulinga 2 (Env-3) outperformed the commercial checks and were ranked from the top yielding as 15XH215, 15XH150, 15XH175, 15XH214, 15XH217, 15XH176, 15XH164, 15XH157, 15XH216, 15XH177 (Table 4.8). However, these hybrids were not significantly different based on the 5% LSD.

Table 4.7. Analysis of variance of 93 test cross experimental hybrids and seven standard commercial checks of maize germplasm developed from Tester B under high plant population density at Ukulinga 2 (Env-3)

S.O.V	d.f.	GYG	PH	EH	AD	EPO	EPP	ASI	MOI	RL	SL	TL	NTB	NLAC	DCD
Rep	1	34.15	393.3	1231.2	43.64	0.012	0.279	1.108	14.02	0.488	2555.65	2626.77	0.15	2.11	30.32
Rep.Blk	18	3.73	519	215.8	5.12	0.002	0.064	0.598	1.429	15.66	418.9	491.7	0.65	0.58	31.66
NP	1	52.47	42.9	0.1	4.78	0.0003	1.505	0.003	1.575	1.614	279.4	323.58	0.08	0.39	0.343
Hybrids	99	3.84***	128.4	162	8.61***	0.0024	0.05***	0.68*	1.78***	10.27	179.44***	194.56***	2.53	0.61	7.115
Error	80	1.14	152.2	164.1	1.92	0.0021	0.0141	0.462	0.8977	9.269	71.06	78.29	1.86	0.58	6.098
Total	199	3.14	174.2	172.3	5.76	0.0023	0.0464	0.585	1.4557	10.26	169.97	187.56	2.07	0.60	9.009
5% LSD		2.15	24.89	25.85	2.798	0.0921	0.2393	1.371	1.912	6.143	17.01	17.85	2.75	1.54	4.982
%cv		11.29	5.14	10.25	1.89	8.77	10.24	-14.38	6.03	16.9	16.43	10.21	10.2	13.6	1.95

S.O.V = Source of variation; d.f. = Degrees of freedom; GYG = Grain yield; PH = plant height; EH = Ear height; AD = Days to anthesis; EPO = Ear position; EPP = Number of ear per plant; MOI = grain moisture content; ASI = Anthesis silking interval; RL = Root lodging; SL = Stem lodging; TL = Total lodging; NTB = Number of tassel branches; NLAC = Number of leaves above the cob; DCD = Number of days to 50% cob dryness and NP = Number of plant. *, **, *** significantly different at 0.05, 0.01 and 0.001 probability levels, respectively.

Table 4.8. Mean performance of the 93 test cross experimental hybrids and seven standard commercial checks of maize germplasm for the traits developed from Tester B under high plant population density at Ukulinga 2 (Env-3)

ENTRY	HYBRIDS	GYG	PH	EH	AD	EPO	EPP	ASI	MOI	RL	SL	TL	NTB	NLAC	DCD	PopDen
Mean performance for the top ten experimental hybrids																
180	15XH215	12.99	238.9	122.8	73.88	0.515	1.249	-0.9647	17.17	6.247	-0.033	6.214	13.15	6.038	125.4	74523
115	15XH150	12.25	249.7	136.1	71.99	0.5448	1.048	0.4547	16.03	-0.09	0.516	0.426	14.94	5.442	125.6	69067
140	15XH175	11.84	227.3	130	73.33	0.5729	1.478	-0.9519	14.88	4.665	0.963	5.628	11.19	6.546	125.4	75627
179	15XH214	11.80	255.3	139.4	76.15	0.5454	1.217	-1.0408	15.22	6.578	10.453	17.031	13.31	4.954	128	65645
182	15XH217	11.73	222.5	113.9	72.78	0.5122	1.242	-0.9688	14.62	0.309	-0.578	-0.269	13.66	6.508	127	75702
141	15XH176	11.72	238.7	129.1	76.45	0.5439	1.31	-0.9827	15.9	1.604	2.597	4.201	13.08	5.514	125.5	72231
129	15XH164	11.66	238.7	140.3	77.52	0.5828	1.154	-0.0031	17.55	1.525	0.217	1.741	11.99	5.995	124	70031
122	15XH157	11.53	241	145.8	76.86	0.6021	1.439	-0.9613	15.61	0.209	1.486	1.695	14.63	5.531	125.5	74447
181	15XH216	11.35	242.3	125.1	74.74	0.5162	1.694	-1.0903	15.68	-0.566	3.931	3.366	14.61	5.401	129.5	60465
142	15XH177	11.16	256.1	131.5	74.29	0.5134	1.106	-0.9413	16.38	1.749	-0.933	0.816	14.24	6.562	125.4	76707
Mean performance for the control hybrids																
200	BG5285	10.82	239.7	125.4	72.87	0.5231	1.07	-0.9574	14.7	0.286	-0.856	-0.57	14.16	6.049	126.9	74502
199	PAN 6Q-345 CB	9.89	254.4	129.3	74.38	0.5081	1.214	-0.9658	16.32	3.433	11.902	15.335	12.65	6.037	123	74444
198	10HDTX11	9.59	248.6	125.5	71.4	0.5051	1.073	-0.4754	15.51	1.644	1.957	3.601	14.11	5.525	129.5	73411
194	11C1774	9.48	235.6	97.2	74.29	0.4125	0.919	-1.0774	15.89	-0.502	3.598	3.096	11.64	4.907	125.6	61133
196	11C2245	9.27	238.5	133.2	76.33	0.5571	0.931	-1.0933	16.33	5.493	5.849	11.343	11.58	6.411	122.1	60019
195	11C1579	8.77	232.5	122.7	74.65	0.528	0.896	-1.0461	14.01	1.74	3.891	5.631	12.26	5.444	132.1	64480
197	11C1483	7.58	233.5	105.8	73.1	0.4559	1.109	-1.0335	14.86	-0.212	1.51	1.298	13.85	4.959	125.6	66700
Mean performance for the least 2 experimental hybrids																
132	15XH167	6.05	245.6	127.3	70.63	0.5185	0.97	-1.026	14.29	1.633	21.685	23.318	11.88	4.965	125.6	67858
145	15XH180	4.89	234.9	123.9	77.94	0.5227	0.99	-0.4868	16.16	0.074	-0.673	-0.6	15.07	5.517	125.4	72231
	5% LSD	2.16	24.89	25.85	2.798	0.0921	0.2393	1.371	1.912	6.143	17.01	17.85	2.754	1.543	4.982	11497
	%cv	11.29	5.14	10.25	1.89	8.77	10.24	-14.38	6.03	16.95	16.43	10.21	10.23	13.56	1.95	8.19

GYG = Grain yield (t/ha); PH = plant height (cm); EH = Ear height (cm); AD = Days to anthesis (Days); EPO = Ear position (EH/EP); EPP = Number of ear per plant; MOI = grain moisture content; ASI = Anthesis silking interval; RL = Root lodging (%); SL = Stem lodging (%); TL = Total lodging (%); NTB = Number of tassel branches; NLAC = Number of leaves above the cob and DCD = Number of days to 50% cob dryness.

Among the rest of the studied selected traits derived from tester A, only GYG, EH, EPP, MOI, NTB and NLAC showed significant differences at $P < 0.05$ at CEDARA (Env-2) (Table 4.9). The top 10 hybrids in terms of grain yield at CEDARA (Env-2) were ranked from the top to bottom yielding as 15XH125, 15XH81, 15XH52, 15XH119, 15XH70, 15XH44, 15XH99, 15XH135, 15XH90 and 15XH121, these hybrids outperformed the commercial checks (Table 4.10). However, these hybrids were significantly differently based on the 5% LSD.

Table 4.9. Mean squares of the analyses of variance for grain yield and grain yield related traits of 93 test cross experimental hybrids and seven standard commercial checks of maize germplasm developed at CEDARA (Env-2) under Tester A.

S.O.V	d.f.	GYG	PH	EH	AD	EPO	EPP	ASI	MOI	RL	SL	TL	NTB	NLAC	DCD
Rep	1	4.95	411.8	414.7	5.78	0.0004	0.002	0.005	0.6384	60.08	1951.9	2696.9	17.41	0.72	12.5
Rep.Blk	18	4.23	907.3	413	1.84	0.0029	0.002	2.01	3.31	54.19	2776.5	2596.2	2.003	0.1489	7.027
NP	1	31.61	92.5	47.2	0.004	0.0001	0.011	2.23	2.3491	46.57	38.9	0.3	1.382	0.0313	8.188
Hybrids	99	2.67***	271.5	231.1*	0.793	0.0034	0.0004*	1.0153	1.94**	48.41	647.7	650.2	4.01*	0.46***	7.448
Error	80	0.73	176.2	147.7	0.8861	0.0026	0.00034	0.807	0.9993	38.34	462.4	475.9	2.667	0.2338	6.638
Total	199	2.19	290.5	214	0.9466	0.0030	0.00060	1.0221	1.6791	44.93	769.3	763.2	3.342	0.3417	7.113
5 % LSD		1.72	26.64	24.39	1.889	0.1015	0.03682	1.803	2.006	12.43	43.16	43.78	3.278	0.971	5.171
%cv		9.67	5.13	8.65	1.12	9.28	1.84	-12.17	6.3	18.39	16.51	13.27	14.43	8.06	1.91
Se		0.85	13.27	12.15	0.9414	0.05055	0.01835	0.8983	0.9997	6.192	21.5	21.81	1.633	0.4835	2.576

S.O.V = Source of variation; d.f. = Degrees of freedom; GYG = Grain yield; PH = plant height; EH = Ear height; AD = Days to anthesis; EPO = Ear position; EPP = Number of ear per plant; MOI = grain moisture content; ASI = Anthesis silking interval; RL = Root lodging; SL = Stem lodging; TL = Total lodging; NTB = Number of tassel branches; NLAC = Number of leaves above the cob; DCD = Number of days to 50% cob dryness and NP = Number of plant. *, **, *** significantly different at 0.05, 0.01 and 0.001 probability levels, respectively.

Table 4.10. Mean performance of 93 test cross experimental hybrids and seven standard commercial checks of maize germplasm developed from Tester A at CEDARA (Env-2)

ENTRY	HYBRIDS	GYG	PH	EH	AD	EPO	EPP	ASI	MOI	RL	SL	TL	NTB	NLAC	DCD	PopDen
Mean performance for the top ten experimental hybrids																
83	15XH125	11.487	270.2	153	85.16	0.5678	0.989	-2.03	16.05	6.741	33.74	40.48	12.82	6.1	135.6	36667
79	15XH121	11.278	277.5	154.7	84.39	0.5582	0.9825	-0.98	17	-0.33	68.28	67.95	10.12	5.932	134.6	43333
10	15XH52	11.12	294.9	171.1	83.98	0.5795	1.0013	-0.99	16.85	-0.05	70.7	70.64	13.52	5.488	137.9	41111
77	15XH119	10.943	261.4	137.1	83.98	0.5256	1.0013	0.503	16.7	5.204	67.63	72.83	11.52	4.988	132.9	41111
28	15XH70	10.868	268	154.3	85.11	0.5737	0.9921	-1.52	17.15	0.353	58.34	58.69	12.37	6.072	138.4	37778
2	15XH44	10.762	266.4	165.1	84.98	0.6223	1.0013	-2.497	17.15	2.572	41.17	43.74	9.02	5.988	132.9	41111
57	15XH99	10.529	263.5	137.8	85.61	0.5223	0.9921	-2.018	14.2	6.236	19.2	25.44	11.37	6.572	136.9	37778
93	15XH135	10.5	239.1	127.8	83.53	0.5343	0.9982	-0.004	15	0.078	34.21	34.29	12.47	6.016	136.6	40000
48	15XH90	10.474	261.2	147.8	83.3	0.5668	0.9267	-0.47	15.2	4.947	15.43	20.38	12.72	5.876	130.3	45556
79	15XH121	10.408	286.5	171.7	82.89	0.6	1.0075	-0.483	15.75	-0.334	70.52	70.19	12.12	5.432	136.1	43333
Mean performance for the control hybrids																
97	11C1483	10.655	257.5	132.7	84.39	0.5158	1.0075	-1.983	15.7	-0.334	6.44	6.11	9.62	5.932	132.6	43333
99	PAN 6Q-345 CB	10.359	205.5	132.7	84.89	0.6697	1.0075	-0.483	14.65	17.692	31.97	49.66	15.12	5.432	136.1	43333
100	BG5285	9.427	261.7	130.3	84.3	0.4988	1.0136	-1.47	16.2	4.947	45.74	50.69	13.22	6.376	130.3	45556
94	11C1774	8.909	261.1	144.3	84.53	0.551	0.9982	-1.504	17.3	2.71	10.22	12.93	10.97	5.516	133.1	40000
98	10HDTX11	7.538	248.6	142.8	85.53	0.5743	0.9982	-3.004	14.45	5.342	5.58	10.92	13.97	6.016	133.1	40000
95	11C1579	6.816	259.4	149	85.35	0.5749	0.9629	-0.98	16.45	6.671	50.84	57.52	9.67	5.404	133.9	44444
96	11C2245	6.456	267.2	140.4	85.94	0.526	1.0044	-2.49	16	-0.19	13.93	13.73	9.57	5.46	134.3	42222
Mean performance for the least 2 experimental hybrids																
71	15XH113	6.602	255.5	122	85.47	0.4755	0.9675	-2.07	14.54	1.453	9.69	11.15	10.47	6.297	136.2	28889
69	15XH111	4.817	238.9	113.3	84.84	0.4721	0.9767	-2.55	12.94	1.041	65.64	66.68	10.62	5.212	136.2	32222
	5 % LSD	1.715	26.64	24.39	1.889	0.1015	0.0368	1.803	2.006	12.43	43.16	43.78	3.278	0.971	5.171	7399
	%cv	9.67	5.13	8.65	1.12	9.28	1.84	-12.2	6.3	18.4	16.51	13.27	14.43	8.06	1.91	9.15

GYG = Grain yield (t/ha); PH = plant height (cm); EH = Ear height (cm); AD = Days to anthesis (Days); EPO = Ear position (EH/EP); EPP = Number of ear per plant; MOI = grain moisture content; ASI = Anthesis silking interval; RL = Root lodging (%); SL = Stem lodging (%); TL = Total lodging (%); NTB = Number of tassel branches; NLAC = Number of leaves above the cob and DCD = Number of days to 50% cob dryness.

There were significant differences ($P < 0.05$) among all traits in the studied hybrids derived from tester B except for AD, EPO, ASI, RL, SL, TL and DCD at CEDARA (Env-2) (Table 4.11). The top 10 hybrids in terms of grain yield at CEDARA (Env-2) outperformed the commercial checks and were ranked from the top to bottom yielding as 15XH214, 15XH155, 15XH145, 15XH168, 15XH158, 15XH156, 15XH186, 15XH172, 15XH218 and 15XH212 (Table 4.12). However, these hybrids were not significantly different based on the 5% LSD of 1.538 /t/ha.

Table 4.11. Mean squares of the analyses of variance for grain yield and grain yield related traits of 93 test cross experimental hybrids and seven standard commercial checks of maize germplasm evaluated at CEDARA (Env-2) under Tester B.

S.O.V	d.f.	GYG	PH	EH	AD	EPO	EPP	ASI	MOI	RL	SL	TL	NTB	NLAC	DCD
Rep	1	4.44	2422.1	1562.4	0.605	0.0027	0.01	15.21	2.0808	25.14	3458.6	2894	0.32	0.00001	0.245
Rep.Blk	18	5.27	741.7	344.4	1.138	0.0021	0.11	3.43	4.48	23.2	2280.3	2285.5	3.754	0.5156	9.878
NP	1	24.91	1.001	145.97	5.44	0.0017	0.26	6.645	0.2431	10.31	510.1	375.4	0.0001	0.001	2.309
Hybrids	99	3.84***	211.5***	192.3***	0.902	0.0014	0.08**	1.312	3.21***	21.84	409.8	423.6	6.62*	0.71**	8.26
Error	80	0.586	101.8	86.92	1.27	0.0011	0.037	1.994	0.8336	26.69	384.8	385.7	4.608	0.3887	9.058
Total	199	2.767	225.4	170.33	1.092	0.0014	0.06683	1.874	2.349	23.87	584.8	589	5.485	0.5572	8.657
5% LSD		1.538	20.27	18.73	2.264	0.0664	0.387	2.838	1.835	10.38	39.42	39.47	4.314	1.253	6.048
%cv		9	3.92	6.8	1.32	6.2	11.75	-12.13	6.07	31.28	16.82	13.71	17.38	10.68	2.25

S.O.V = Source of variation; d.f. = Degrees of freedom; GYG = Grain yield; PH = plant height; EH = Ear height; AD = Days to anthesis; EPO = Ear position; EPP = Number of ear per plant; MOI = grain moisture content; ASI = Anthesis silking interval; RL = Root lodging; SL = Stem lodging; TL = Total lodging; NTB = Number of tassel branches; NLAC = Number of leaves above the cob, NP = Number of plant and DCD = Number of days to 50% cob dryness. *, **, *** significantly different at 0.05, 0.01 and 0.001 probability levels, respectively.

Table 4.12. Mean performance for grain yield and yield related attributes (t/ha) of 93 test cross experimental hybrids and seven standard commercial checks of maize germplasm evaluated at CEDARA under Tester B

ENTRY	HYBRIDS	GYG	PH	EH	AD	EPO	EPP	ASI	MOI	RL	SL	TL	NTB	NLAC	DCD	PopDen
Mean performance for the top ten experimental hybrids																
179	15XH214	11.354	288.5	168.9	85.56	0.585	1.742	-0.5738	14.7	2.758	56.33	59.08	16.48	5.469	138	41111
120	15XH155	11.291	265.5	141.4	85.56	0.5323	2.01	-1.0738	16.7	-0.02	29.86	29.85	12.98	6.969	136.5	41111
110	15XH145	11.287	275	146.6	84.96	0.5332	1.688	-0.9444	16.29	2.647	64.41	67.06	15.01	6.023	134.5	40000
133	15XH168	11.167	259	139.9	86.06	0.542	1.821	-1.0738	16.15	-0.02	36.01	35.99	8.98	5.969	133	41111
123	15XH158	10.995	261.6	135.2	85.66	0.5168	1.843	-0.2032	16.31	-0.054	39.99	39.93	9.95	5.915	134.6	42222
121	15XH156	10.798	263.1	145.2	85.16	0.5522	1.949	-0.2032	16.26	-0.054	13.67	13.62	10.45	6.415	133.1	42222
151	15XH186	10.647	255.9	135.3	85.86	0.5281	1.656	-0.815	16.83	0.05	19.96	20.01	14.55	6.078	132.9	38889
137	15XH172	10.477	270.9	143.8	85.86	0.5313	1.831	-0.315	16.58	0.05	71.1	71.15	11.05	6.078	130.9	38889
180	15XH215	10.362	268.5	133.9	85.06	0.4986	1.637	-0.0738	15.2	-0.02	36.3	36.28	12.48	5.969	134.5	41111
177	15XH212	10.335	258	137.6	84.96	0.5335	1.858	-0.4444	16.54	0.015	48.62	48.64	13.51	5.023	136.5	40000
Mean performance for the control hybrids																
199	PAN 6Q-345 CB	9.767	270.1	147.7	85.16	0.5467	1.769	-0.2032	15.51	-0.054	46.62	46.57	13.95	4.915	135.1	42222
200	BG5285	9.071	269	134.1	85.46	0.4999	1.438	-1.4444	15.04	0.015	32.68	32.69	14.01	6.023	131	40000
194	11C1774	8.503	262.4	140.8	84.86	0.5368	1.178	-0.815	15.98	0.05	18.98	19.03	11.55	5.078	137.9	38889
197	11C1483	7.695	248.1	122.2	86.66	0.4912	1.659	-1.7032	14.56	-0.054	8.41	8.35	9.45	5.915	134.6	42222
196	11C2245	6.953	277.5	148.4	85.56	0.5354	1.389	-0.5738	16.4	-0.02	31.77	31.75	9.98	4.969	136.5	41111
195	11C1579	6.854	261.6	148.2	86.16	0.5669	1.264	-0.2032	14.71	-0.054	37.36	37.3	8.45	4.915	134.6	42222
198	10HDTX11	6.269	245.6	133.5	84.26	0.5429	1.504	0.4614	15.68	0.258	-2.43	-2.17	13.25	5.903	134.1	32222
Mean performance for the least 2 experimental hybrids																
131	15XH166	4.926	249.5	122.9	85.06	0.4925	1.542	0.4262	14.45	-0.02	47.12	47.1	10.48	6.469	133	41111
119	15XH154	4.003	223.7	105.3	85.86	0.4711	1.695	-0.9619	12.23	-0.124	27.36	27.23	7.88	5.306	134.7	44444
	5% LSD	1.538	20.27	18.73	2.264	0.06636	0.387	2.838	1.835	10.38	39.42	39.47	4.314	1.253	6.048	5366
	%cv	9	3.92	6.8	1.32	6.2	11.75	-12.13	6.07	31.28	16.82	13.71	17.38	10.68	2.25	6.66

GYG = Grain yield (t/ha); PH = plant height (cm); EH = Ear height (cm); AD = Days to anthesis (Days); EPO = Ear position (EH/EP); EPP = Number of ear per plant; MOI = grain moisture content; ASI = Anthesis silking interval; RL = Root lodging (%); SL = Stem lodging (%); TL = Total lodging (%); NTB = Number of tassel branches; NLAC = Number of leaves above the cob and DCD = Number of days to 50% cob dryness.

4.3. Summary of the ANOVAs

Across all testers and plant population densities, grain yield (GYG) and number of ears per plant (EPP) were significantly different at $P < 0.01$ and $P < 0.05$, while EPO was non-significant (Table 4.1 to Table 4.12). At low plant population density, RL, SL, TL, were non-significant across all testers (Tables 4.1, 4.3, 4.7 and 4.9) while at high plant population density, SL, and TL (Table 4.5 and Table 4.7) were highly significantly ($P < 0.001$) different, but root lodging was only significant ($P < 0.001$) under Tester A (Table 4.5). However, at low plant population density NTB, NLAC and DCD were significant at $P < 0.05$ (Tables 4.1, 4.3, 4.7 and 4.9) but all those traits were non-significant at high plant population density (Table 4.5). Interestingly, AD and ASI were significant at $P < 0.05$ at both low and high plant population densities across the two testers (Table 4.1 to Table 4.12). At high plant population under Tester A root lodging was highly significant at $P < 0.001$ while MOI was non-significant and the reverse was true for Tester B (Table 4.5 and Table 4.7). At low plant population density EH was significant at $P < 0.05$ for both testers while PH was not consistent under both testers and plant population densities. Significant differences ($P < 0.05$) were observed among environments, genotypes and environment by interaction and a similar pattern was found for tester A, Tester B and across testers.

4.4. Frequency distribution of hybrids for yield and selected yield related secondary traits

The data of the frequency of distribution for the selected yield traits from the studied experimental sites are shown in Figures 4.1 to 4.8. The frequency distribution table showed that grain yield was much higher under low plant population density but less so under high plant population density (Figure 4.1). However, EPP was high under low plant population density than at high plant population density (Figure 4.6). Lodging showed a discrepancy distribution under low plant population density (Figure 4.2 to Figure 4.4). The frequency distribution table showed that SL was more under high plant population density (Figure 4.3). However RL and TL were more under low plant population density than high plant population density as shown in Figures 4.2 and 4.4, respectively. In general, genotypes did not differ in days to anthesis based on plant density but at low plant density, MOI was higher than at high plant population density (Figure 4.8). In general plants under high plant population density were taller than those under low plant population density (Figure 4.5).

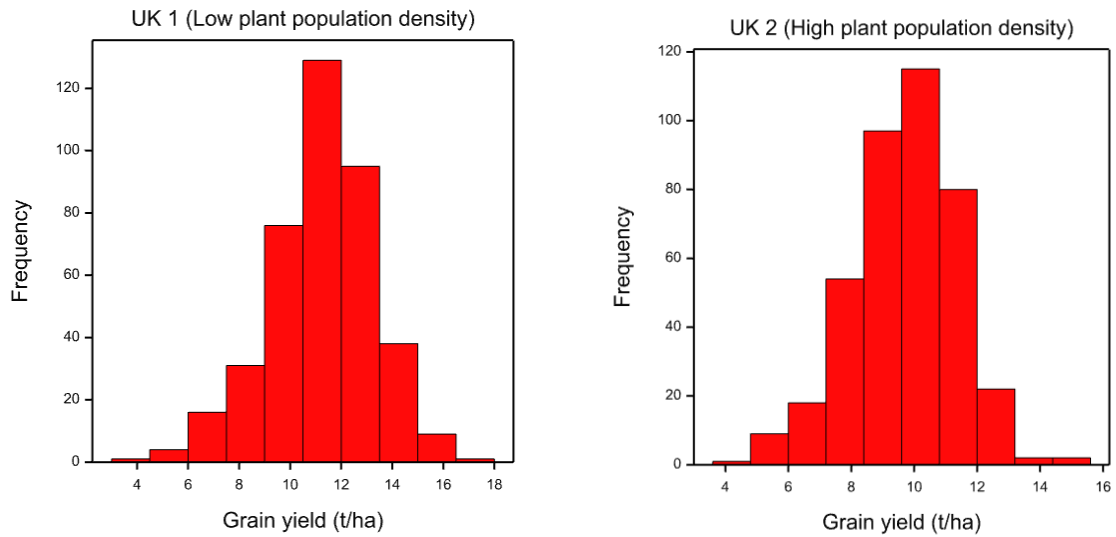


Figure 4.1. Frequency distribution of grain yield for Ukulinga 1 and Ukulinga 2 under high and low plant population densities

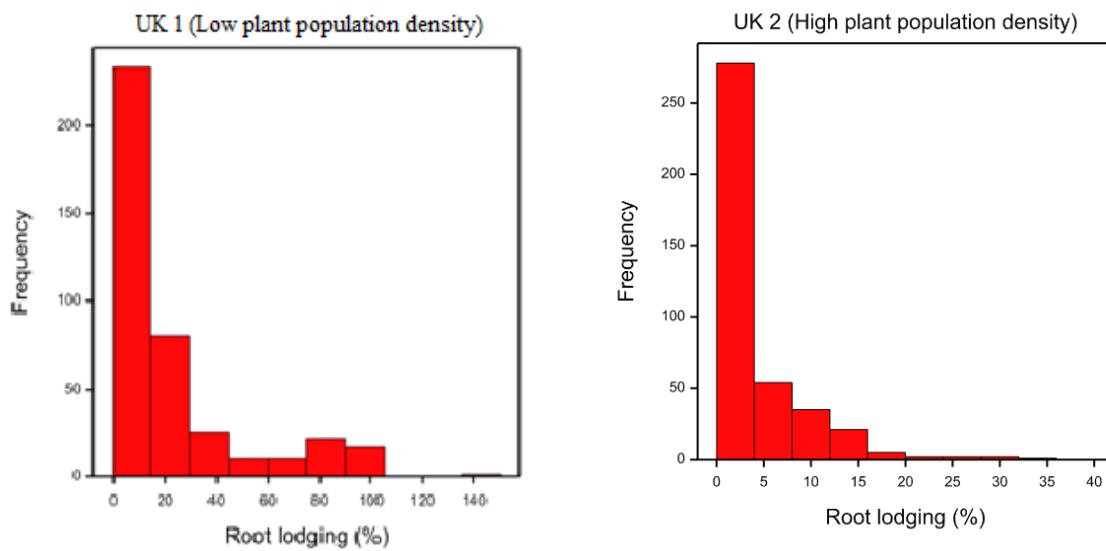


Figure 4.2. Frequency distribution of root lodging for Ukulinga 1 and Ukulinga 2

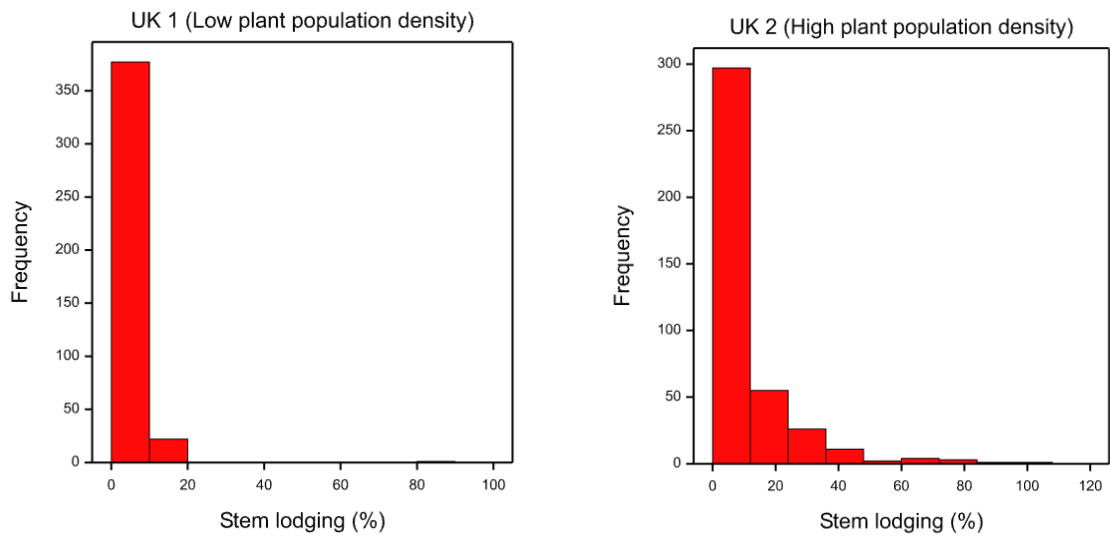


Figure 4.3. Frequency distribution of stem lodging (SL) under high and low plant population densities for Ukulinga 1 and Ukulinga 2.

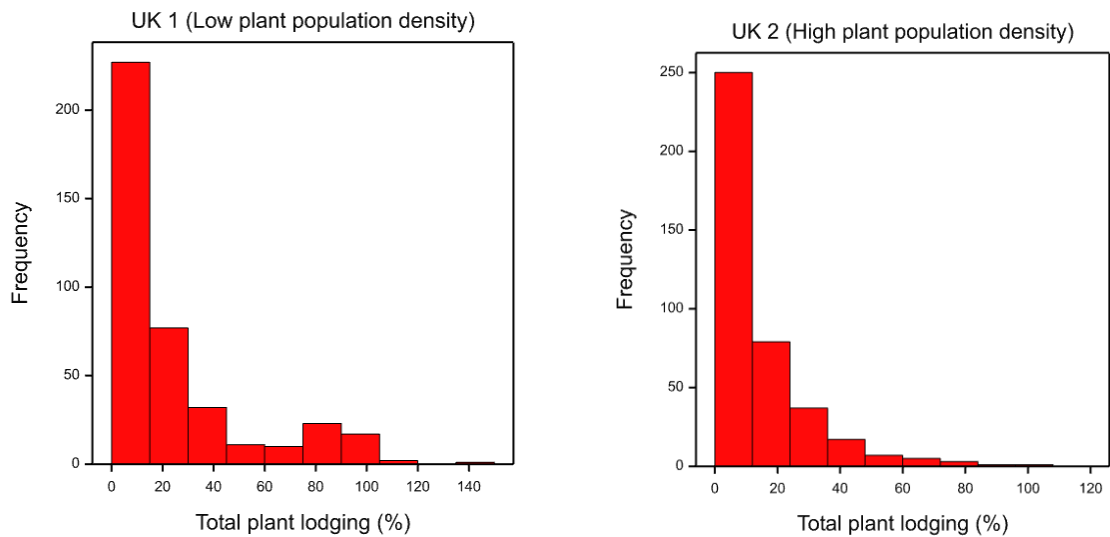


Figure 4.4. Frequency distribution showing total plant lodging (TL) under Ukulinga 1 and Ukulinga 2

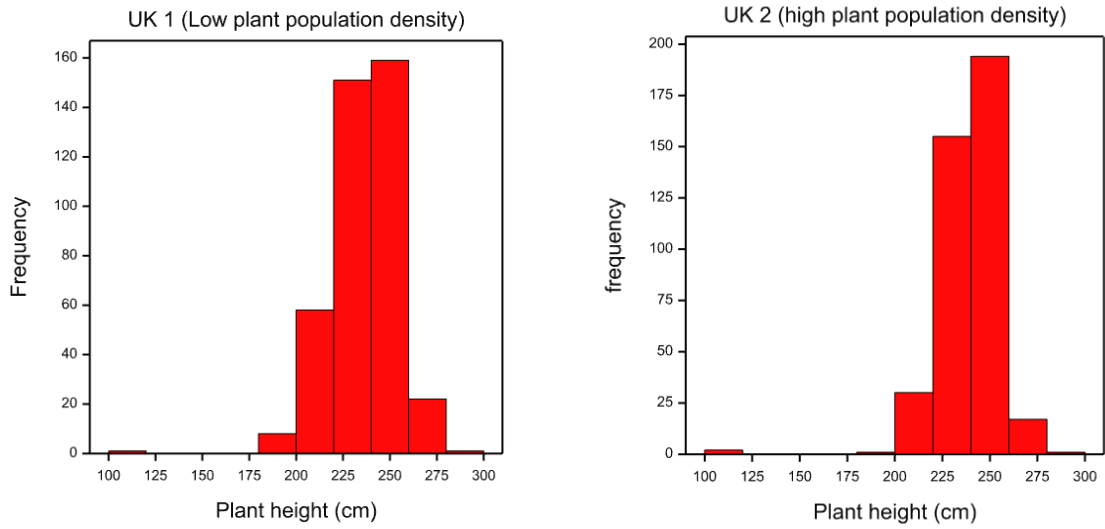


Figure 4.5. Frequency distribution of Plant height (PH) under Ukulinga 1 and Ukulinga 2

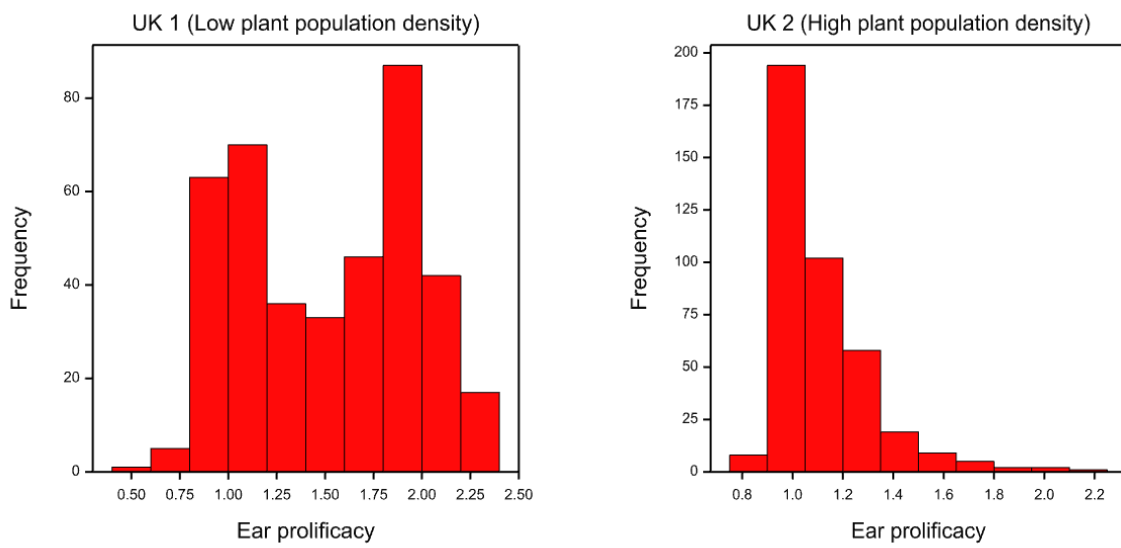


Figure 4.6. Frequency distribution showing ear prolificacy (EPP) for Ukulinga 1 and Ukulinga 2

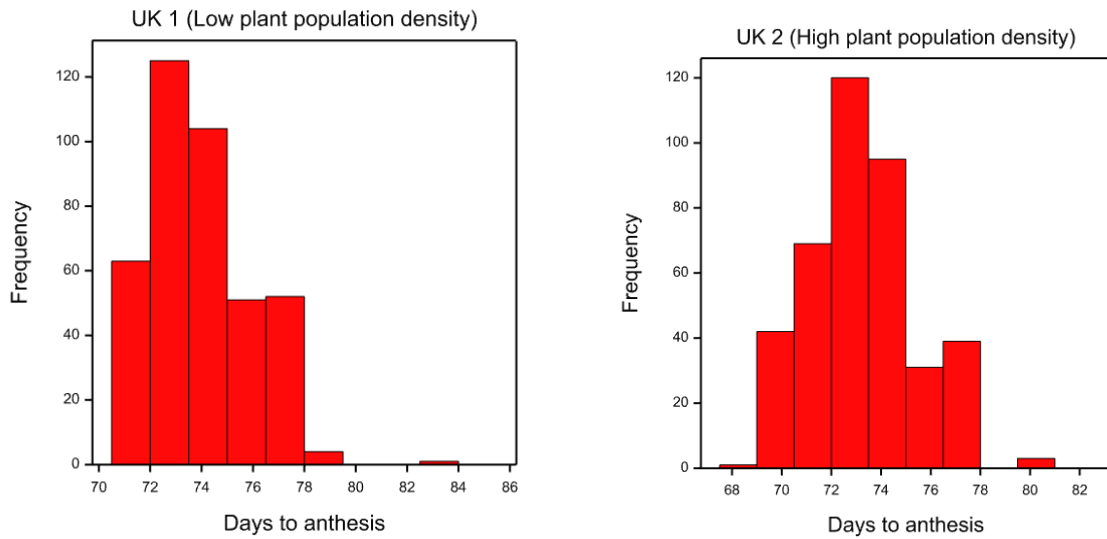


Figure 4.7. Frequency distribution of days to anthesis for Ukulinga 1 and Ukulinga 2

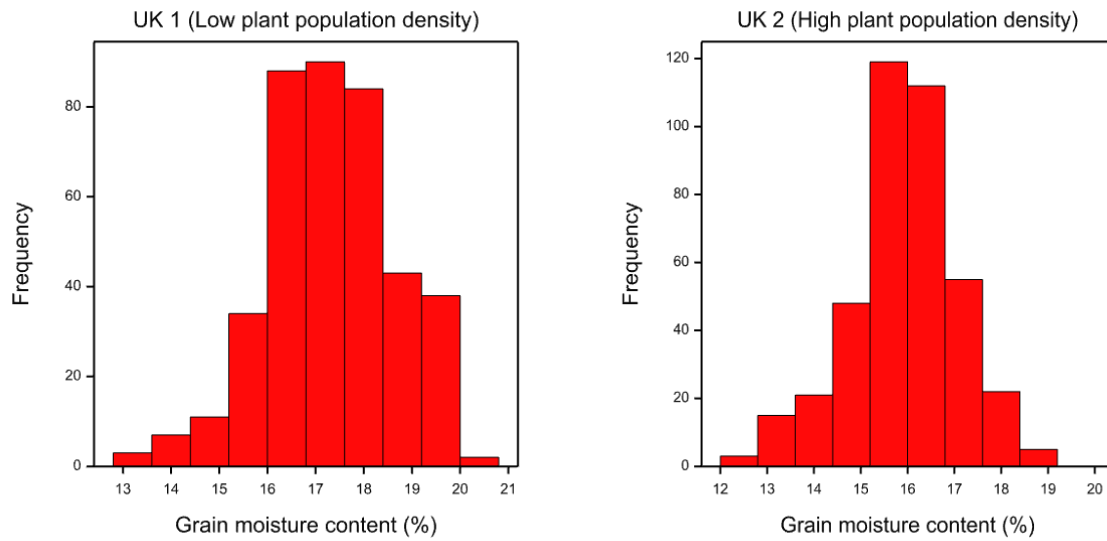


Figure 4.8. Frequency distribution of grain moisture content for Ukulinga 1 and Ukulinga 2

4.5. Hybrid ranking

For the purpose of selecting the best hybrids, they were arranged according to grain yield from the highest yielding to the lowest yielding hybrids in all the sites and within the experimental sites under both testers. Under Tester B, hybrids 179 (15XH214) and 180 (15XH215) outperformed the others in most environments and were the most stable across low and high plant population density. Under Tester A, hybrid number 79 (15XH121) and hybrid number 100 (BG5285) were the best in most environments and hybrid 79 was the most stable across low and high plant population density. The following entries from each site, across sites and within the testers were selected based on the average mean performances for grain yield from mean tables; for Ukulinga 1 under Tester A at low plant population density (Env-1) among the top yielding hybrids selected, the top five hybrids were; PAN 6Q-345 CB, 15XH121, 15XH65, 15XH110 and 15XH135. Commercial hybrid PAN 6Q-345 CB, out-yielded all the experimental hybrids and the advanced hybrids (15.89 t/ha), for Ukulinga 2 (Env-3) under Tester A at high plant population density, hybrids were 15XH121, BG5285, 15XH45, 15XH80 and 15XH87, for Cedara (Env-2) hybrids were; 15XH121, 15XH81, 15XH52, 15XH119 and 15XH70 and for Dundee, hybrids were 15XH121, 15XH110, BG5285, 15XH55 and 15XH130. The hybrids that were stable across the sites under Tester A in terms of grain yield among the top 10 high yielding were; 15XH121, BG5285, 15XH110, PAN 6Q-345 CB and 15XH93 (Table 4.13).

Table 4.14 presents the results of the mean performances of grain yield for all the hybrids in all sites evaluated under Tester B. For Ukulinga 1 under Tester B at low plant population density (Env-1), selected top five hybrids were; 15XH172, 15XH215, 15XH213, 15XH187 and 15XH214, for Ukulinga 2 (Env-3) under Tester B at high plant population density, hybrids were 15XH92, BG5285, 15XH45, 15XH80 and 15XH87, for Cedara (Env-2), hybrids were; 15XH121, 15XH81, 15XH52, 15XH119 and 15XH70 and for Dundee, hybrids were; 15XH215, 15XH189, 15XH198, 15XH166 and 15XH165. The hybrids that showed high performance in terms of grain yield and stability across all the studied experimental sites evaluated under Tester B were; 15XH215, 15XH214, 15XH168, 15XH212 and 15XH186.

Table 4.13. Mean values of the top 10 rated performance hybrids for grain yield in each site and across all the sites evaluated under Tester A

Rank	Ukulinga 1 Low density (Env-1)			Ukulinga 2 high density (Env-3)			CEDARA (Env-2)			Dundee (Env-4)			GYG All Sites (Env_1-4)		
	Entry	Hybrids	Mean GYG	Entry	Hybrids	Mean GYG	Entry	Hybrids	Mean GYG	Entry	Hybrids	Mean GYG	Entry	Hybrids	Mean GYG
1	<u>99</u>	<u>PAN 6Q-345 CB</u>	15.89	79	15XH121	12.91	83	15XH125	11.49	68	15XH110	7.90	79	15XH121	10.67
2	79	15XH121	14.37	<u>100</u>	<u>BG5285</u>	12.00	79	15XH121	11.28	79	15XH121	7.05	68	15XH110	10.05
3	23	15XH65	14.31	3	15XH45	11.97	10	15XH52	11.12	<u>100</u>	<u>BG5285</u>	6.74	<u>100</u>	<u>BG5285</u>	9.75
4	68	15XH110	14.29	38	15XH80	11.81	77	15XH119	10.94	13	15XH55	6.63	<u>99</u>	<u>PAN 6Q-345 CB</u>	9.55
5	93	15XH135	14.21	45	15XH87	11.68	28	15XH70	10.87	88	15XH130	6.18	51	15XH93	9.38
6	87	15XH129	14.09	39	15XH81	11.67	2	15XH44	10.76	64	15XH106	6.01	22	15XH64	9.28
7	22	15XH64	13.87	77	15XH119	11.67	<u>97</u>	<u>11C1483</u>	10.66	25	15XH67	5.62	88	15XH130	9.26
8	29	15XH71	13.83	80	15XH122	11.66	57	15XH99	10.53	40	15XH82	5.37	2	15XH44	9.23
9	81	15XH123	13.74	52	15XH94	11.60	93	15XH135	10.50	22	15XH64	5.29	93	15XH135	9.21
10	51	15XH93	13.65	82	15XH124	11.55	48	15XH90	10.47	2	15XH44	5.27	41	15XH83	9.20

Env-1 = Environment 1, Env-2 = Environment 2, Env-3 = Environment 3, Env-4 = Environment 4, Env_1-4 = Environment 1-4, and GYG = Grain yield

*underlined = control hybrids

Table 4.14. Mean values of the top 10 rated performance hybrids for grain yield in each site and across all the sites evaluated under Tester B

Rank	Ukulinga 1 Low density (Env-1)			Ukulinga 2 high density (Env-3)			CEDARA (Env-2)			Dundee (Env-4)			GYG All Sites (Env_1-4)		
	Entry	Hybrids	Mean GYG	Entry	Hybrids	Mean GYG	Entry	Hybrids	Mean GYG	Entry	Hybrids	Mean GYG	Entry	Hybrids	Mean GYG
1	137	15XH172	13.53	180	15XH215	12.99	179	15XH214	11.35	180	15XH215	7.19	180	15XH215	10.61
2	180	15XH215	13.26	115	15XH150	12.25	120	15XH155	11.29	154	15XH189	6.96	179	15XH214	10.25
3	178	15XH213	13.24	140	15XH175	11.84	110	15XH145	11.29	163	15XH198	6.43	133	15XH168	10.02
4	152	15XH187	13.23	179	15XH214	11.80	133	15XH168	11.17	141	15XH176	6.14	177	15XH212	9.84
5	179	15XH214	13.07	182	15XH217	11.73	123	15XH158	11.00	130	15XH165	6.09	151	15XH186	9.84
6	<u>200</u>	<u>BG5285B</u>	13.05	141	15XH176	11.72	121	15XH156	10.80	151	15XH186	6.06	110	15XH145	9.80
7	177	15XH212	12.68	129	15XH164	11.66	151	15XH186	10.65	193	15XH228	6.00	122	15XH157	9.76
8	121	15XH156	12.64	122	15XH157	11.53	137	15XH172	10.48	191	15XH226	5.95	120	15XH155	9.64
9	139	15XH174	12.64	181	15XH216	11.35	180	15XH215	10.36	<u>198</u>	<u>10HDTX11B</u>	5.86	141	15XH176	9.60
10	103	15XH138	12.59	142	15XH177	11.16	177	15XH212	10.34	122	15XH157	5.85	126	15XH161	9.43

Env-1 = Environment 1, Env-2 = Environment 2, Env-3 = Environment 3, Env-4 = Environment 4, Env_1-4 = Environment 1-4, and GYG = Grain yield

*underlined and bold = control hybrids

4.6. Genotype x environment interaction

Within Tester A, the hybrid 15XH121 was on the vertex of the polygon inside the sectors that contained most of the low and high density plant population environments (Figure 4.9) followed by the rest of the genotypes including the commercial hybrids. Furthermore, this hybrid was found in the inner most circle closer to the ideal genotype (Figure 4.11). Under Tester B, the hybrid 15XH214 followed by 15XH215 were also on the vertexes of the polygon in the sector that contained most of the low and high plant population density environments (Figure 4.10). These hybrids were found closer to ideal genotype where hybrid 179 was closer to the inner most circle followed by hybrids 180 and then the rest of the genotypes including the check hybrids (Figure 4.12). The biplots explained >70 % of the variation. The remaining genotypes (entries) fell within the polygon and were less responsive compared to the vertex genotypes.

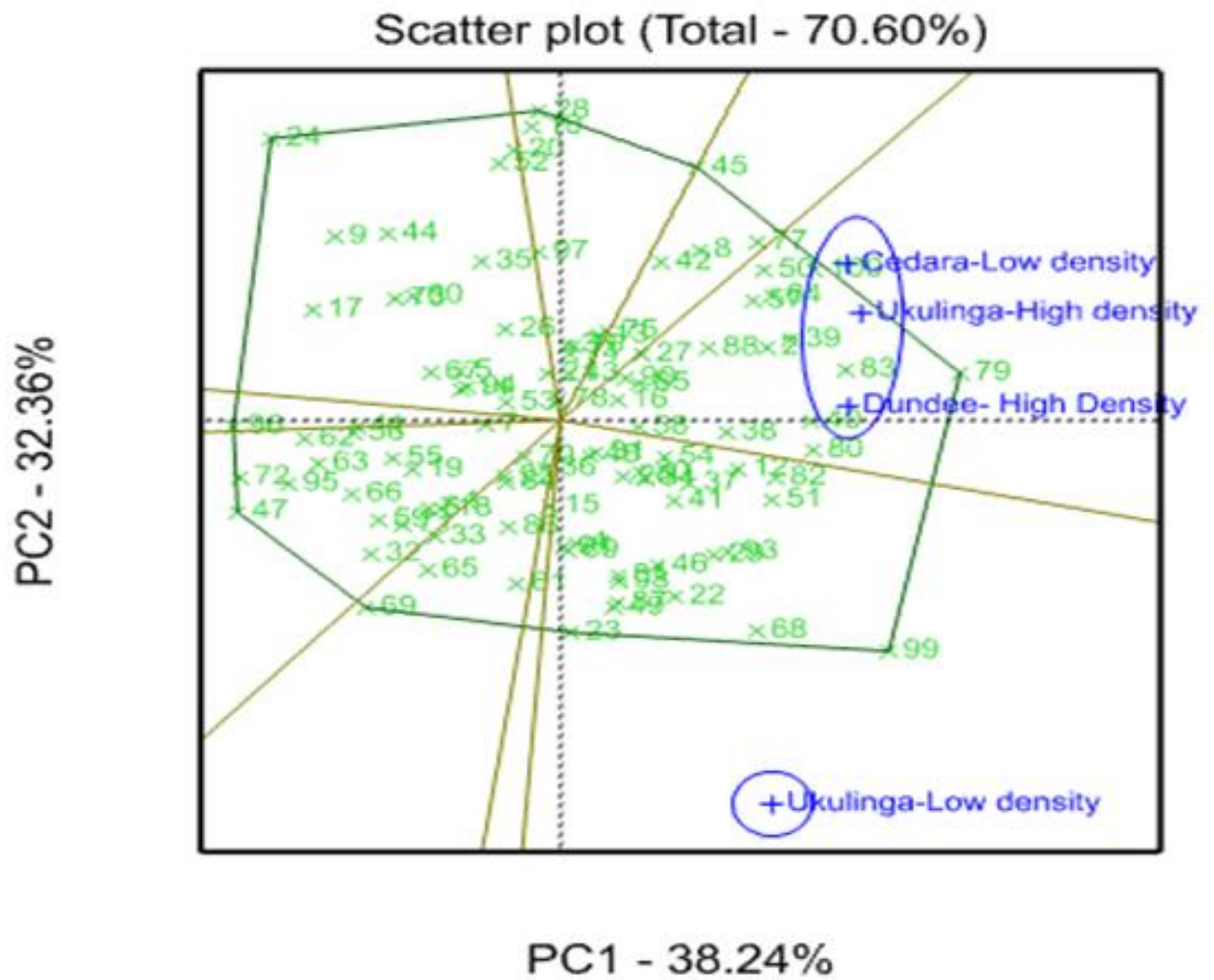


Figure 4.9. Polygon view of the GGE-biplot showing the mega-environments and their respective highest yielding and stable genotypes as well as showing “which won where” or “what is best for what” for grain yield evaluated under Tester A

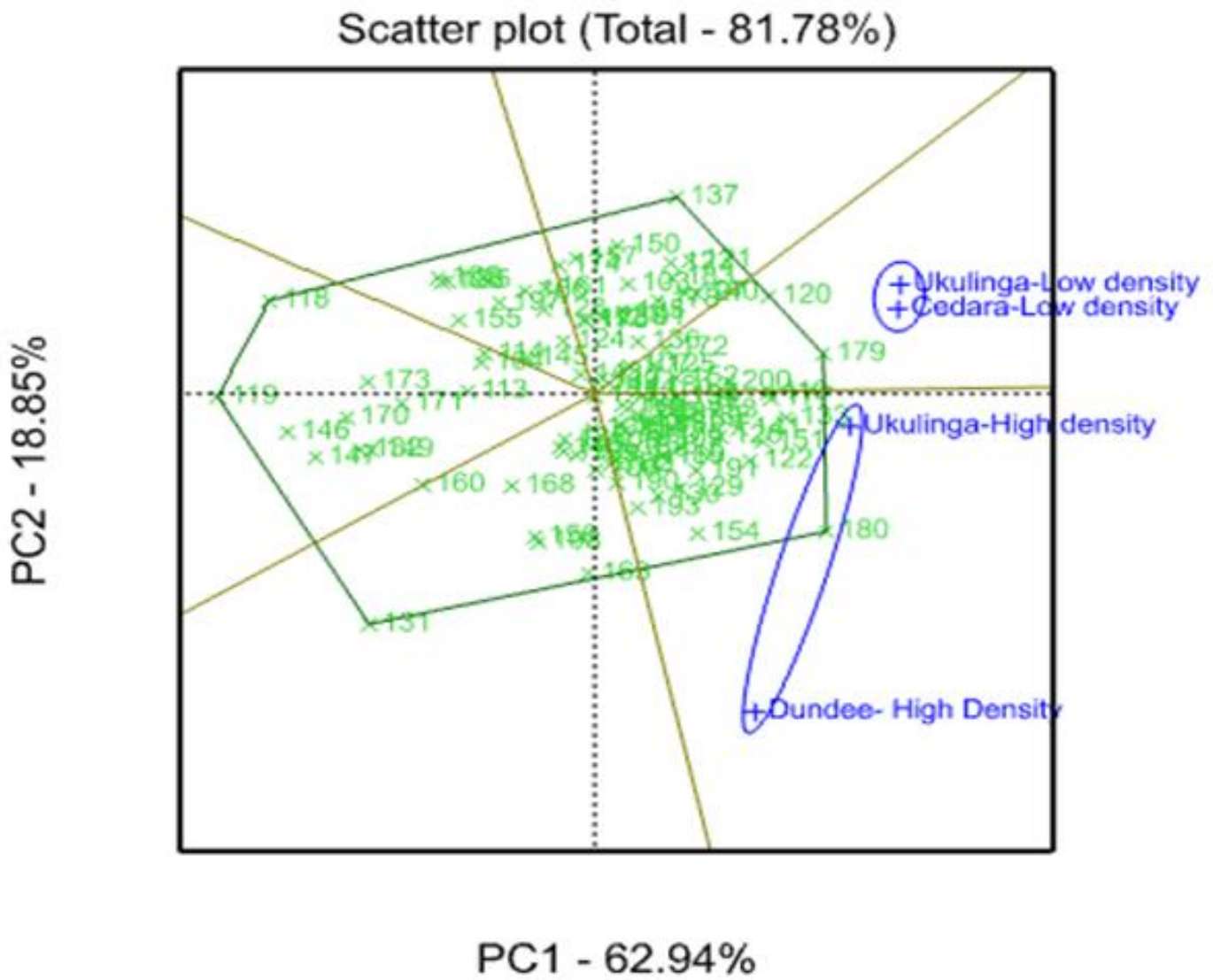


Figure 4.10. Polygon view of the GGE-biplot showing the mega-environments and their respective highest yielding and stable genotypes as well as showing “which won where” or “what is best for what” for grain yield evaluated under Tester B

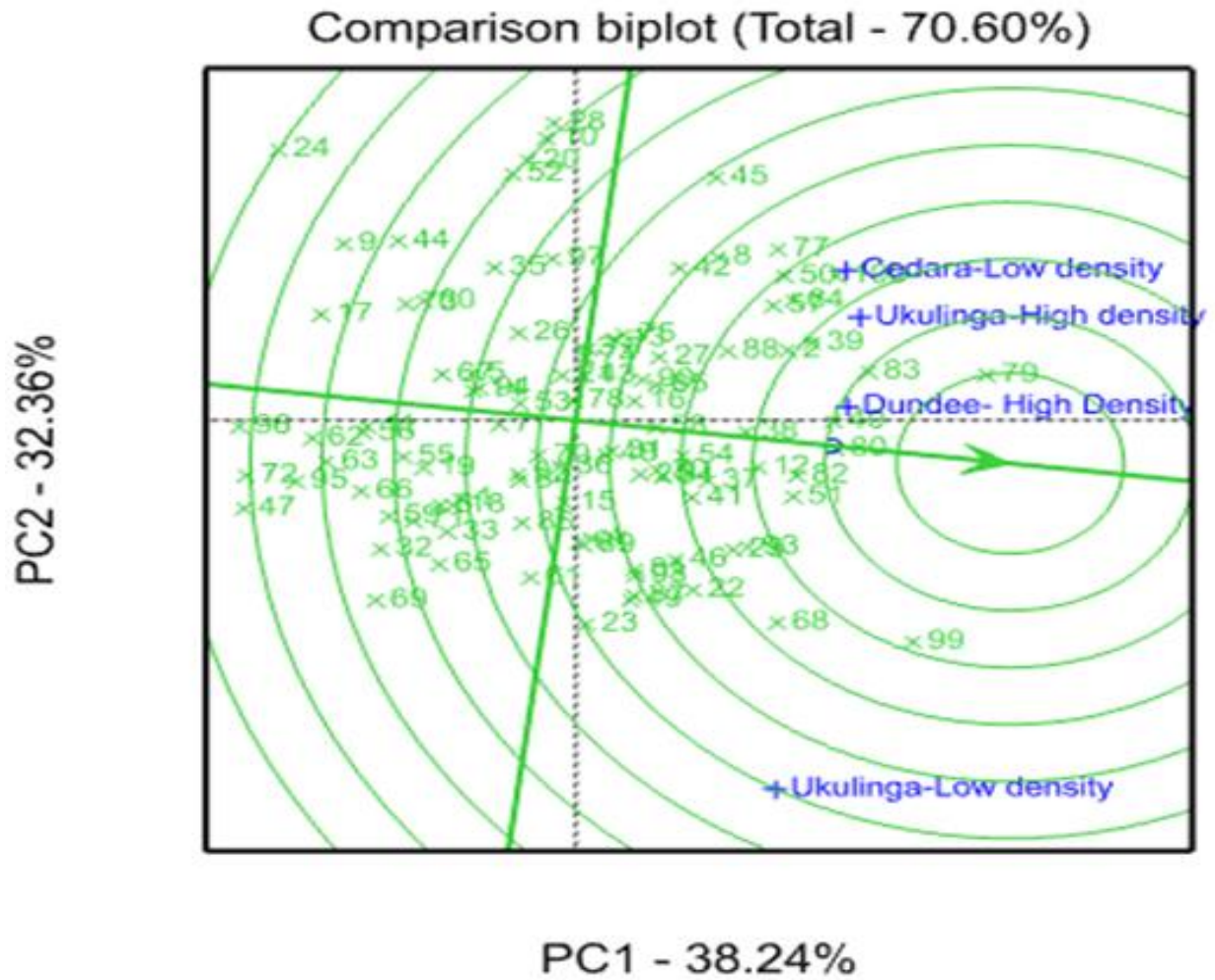


Figure 4.11. GGE-biplot showing ranking of 100 maize genotypes evaluated under Tester A based on grain yield and stability performance across four environments; Env-1 (UK1), Env-2 (CED), Env-3 (UK2) and Env-4 (DUN).

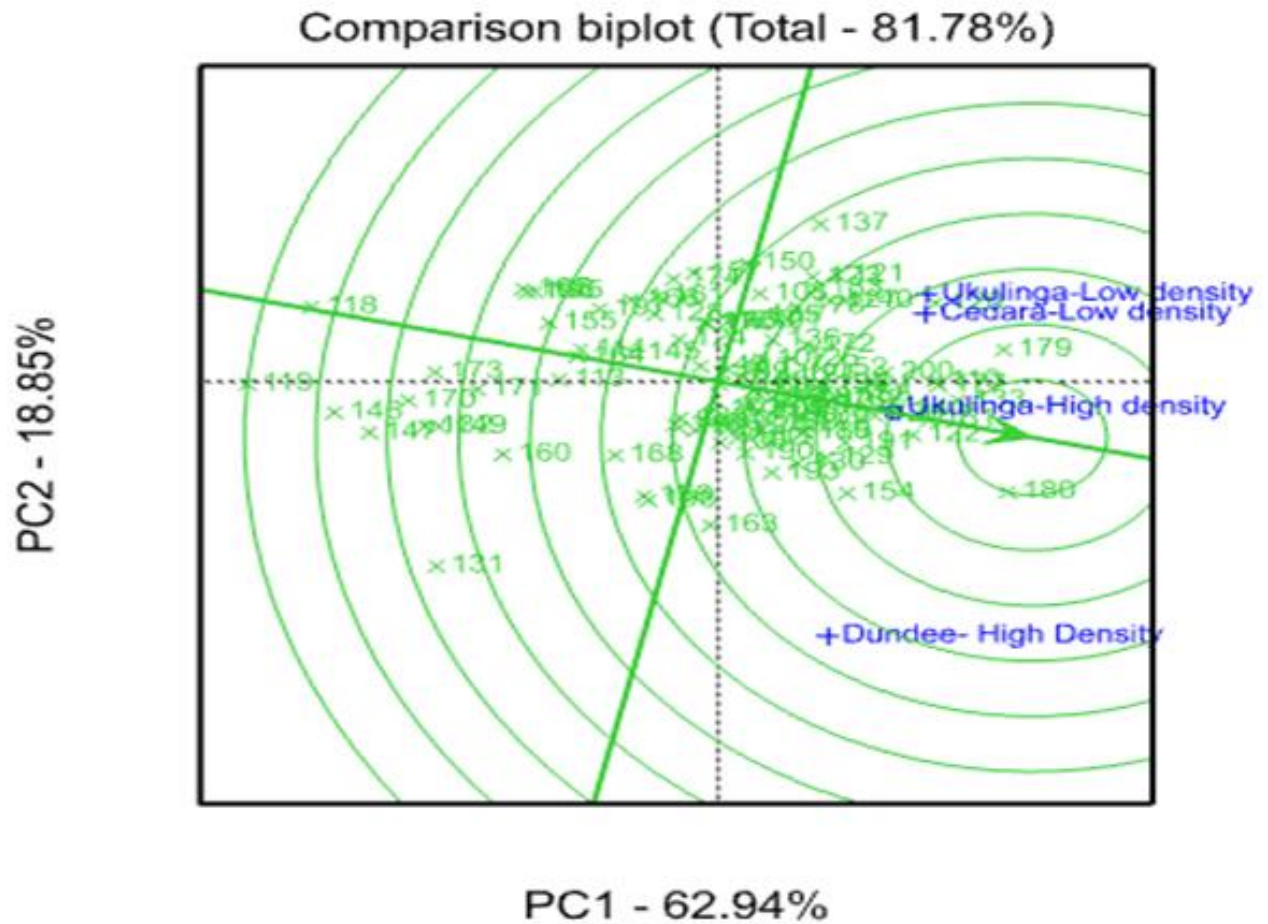


Figure 4.12. GGE-biplot showing ranking of 100 maize genotypes evaluated under Tester B based on grain yield and stability performance across four environments; Env-1 (UK1), Env-2 (CED), Env-3 (UK2) and Env-4 (DUN)

4.7. Stress tolerance index

Under Tester A, hybrids 15XH121 had a high stress tolerant index of 0.97 while under Tester B, hybrids 15XH214 and 15XH215, had high stress tolerant index of 0.91 and 0.98, respectively, whereas the check hybrid BG5285 (hybrid 100) had the least stress tolerant index (0.78). It has also previously been reported that when STI is ≥ 1.0 , it indicates that a genotype is tolerant, while it is sensitive when STI is ≤ 1.0

Table 4.15. Average yields of maize hybrids for Stress tolerance index (STI), standability and ear prolificacy evaluated under non-stress (Yp), Low density (LD) and High density (HD) stress conditions at UK-1 and UK-2. An EPP of below 1.0 indicates partial bareness; an EPP of above 1.0 indicates ear prolificacy

		Stress Tolerance Index				Standability				Ear Prolificacy				
		UK 1		UK 2		UK 1	UK 2	UK 1	UK 2	UK 1	UK 2	UK 1	UK 2	
		Low plant population density		High plant population density										
ENTRY	HYBRIDS	GYG	PopDen	GYG	PopDen	STI	RL	RL	SL	SL	TL	TL	EPP	EPP
79	15XH121	14.59	33333	10.191	64444	0.6985	17.19	1.889	4.52	43.314	21.71	45.2	1.191	1.02
8	15XH50	14.48	37778	11.376	56667	0.7856	40.26	-0.245	0.182	17.65	40.44	17.4	1.028	0.922
52	15XH94	14.36	36667	11.933	65556	0.8309	79.63	10.11	0.305	5.019	79.93	15.13	1.254	0.999
27	15XH69	14.35	38889	11.039	42222	0.7693	11.55	0.976	0.059	6.315	11.61	7.29	1.219	1.171
46	15XH88	14.1	40000	11.111	67778	0.7880	14.27	21.4	2.877	25.96	17.15	47.36	1.212	1.018
57	15XH99	14.05	27778	11.486	65556	0.8175	40.04	8.502	1.288	8.41	41.33	16.91	1.609	0.999
10	15XH52	13.89	34444	10.074	62222	0.725	36.5	19.76	0.551	41.5	37.05	61.28	1.246	0.97
40	15XH82	13.85	37778	11.345	64444	0.8191	42.71	8.418	3.123	1.832	45.83	10.25	1.584	1.006
74	15XH116	13.84	41111	10.997	60000	0.7946	64.02	3.569	8	37.78	72.02	41.35	1.145	0.951
81	15XH123	13.76	42222	9.611	68889	0.6985	52.39	10.08	-0.31	13.85	52.08	23.94	1.374	1.061
Advanced and Commercial hybrids under low and high plant population density stress														
ENTRY	HYBRIDS	GYG	PopDen	GYG	PopDen	YSI	RL	RL	SL	SL	TL	TL	EPP	EPP
100	BG5285A	15.86	41111	12.411	73333	0.7825	33.61	3.148	-0.187	-1.004	33.42	2.14	2.115	1.113
94	11C1774A	13.22	41111	10.241	68889	0.774	7	6.565	-0.187	2.82	6.81	9.38	1.65	1.028
200	BG5285B	13.15	42222	10.577	74444	0.8043	21.28	0.237	-0.31	-1.151	20.97	-0.91	2.069	1.104
98	10HDTX11A	12.7	38889	10.584	62222	0.8334	40.72	8.752	0.059	5.458	40.78	14.21	1.7	1.097

97	11C1483A	11.75	42222	9.135	60000	0.7775	10.29	3.632	-0.31	0.75	9.98	4.38	1.716	1.259
199	PAN 6Q-345 CBB	11.39	40000	9.555	74444	0.8389	3.27	3.463	-0.064	12.24	3.21	15.71	1.984	1.248
95	11C1579A	11.14	36667	8.958	60000	0.8041	6.65	1.768	3.246	9.953	9.9	11.72	1.428	0.97
96	11C2245A	11.06	43333	7.82	54444	0.7071	10.84	-0.306	-0.433	4.113	10.41	3.81	1.626	0.968
99	PAN 6Q-345 CBA	10.65	42222	11.784	76667	1.1065	7.66	1.86	-0.31	-1.443	7.35	0.42	1.979	1.394
194	11C1774B	10.57	40000	9.393	61111	0.8887	16.59	-0.125	-0.064	0.604	16.53	0.48	1.596	0.98
197	11C1483B	10.4	36667	7.385	66667	0.7101	-2.36	0.026	0.305	-0.127	-2.05	-0.1	1.939	1.158
198	10HDTX11B	10.09	42222	9.276	73333	0.9193	10.73	1.722	2.468	2.026	13.2	3.75	1.85	1.111
195	11C1579B	8.99	34444	8.63	64444	0.9599	-0.68	2.049	0.551	1.636	-0.13	3.69	1.502	0.951
196	11C2245B	8.07	30000	9.232	60000	1.1439	-4.72	5.845	5.209	2.474	0.49	8.32	1.313	0.994

GYG = Grain yield; STI = Stress tolerance index; EPP = Number of ear per plant; RL = Root lodging; SL = Stem lodging; TL = Total lodging and PopDen = Plant population density.

4.8. Selection and realized breeding gains

Table 4.16 shows the results of hybrids that were evaluated under Tester A across all the studied experimental sites. The grain yield mean values ranged from 11.69 to 12.13 t/ha among the top-yielding hybrids. The top five selected hybrids (11.89 t/ha) out-yielded the advanced check hybrids (9.78 t/ha). There was a 16.70 % breeding grain yield gained over the population mean. Positive breeding gains were also obtained for most of the desired agronomic traits (Table 4.16). There were significant genetic gains in grain yield, number of ears, ear position, grain moisture content, ear and plant height, root lodging, stem lodging and total plant lodging for selected hybrids against mean of the checks.

Under high plant population density, , the mean grain yield values ranged from 11.44 to 12.04 t/ha among the top-yielding hybrids (Table 4.17). All the selected experimental top five hybrids (11.62 t/ha) out-yielded the commercial check hybrids (10.68 t/ha) across all the three studied experimental sites. The top five selected experimental hybrids (11.62 t/ha) also out-yielded the advanced check hybrids (8.59 t/ha). There was a 22.70 % grain yield gained over the population mean. There were significant genetic gains of selected hybrids in all the traits except for number of tassel branches and number of leaves above the cob when assessed against the population mean and the mean of all the checks. Root lodging, plant height, anthesis silking interval, number of tassel branched and number of leaves above the cob achieved significant genetic loss against mean of the commercial checks, but, grain yield, ear height, days to anthesis, ear position, ear prolificacy, grain moisture content, stem lodging, total plant lodging and days to 50 % cob dryness exhibited significant gains.

Table 4.16. Genetic gain for hybrids evaluated under low plant population density

Entry	Hybrid	GYG	PH	EH	AD	EPO	EPP	ASI	MOI	RL	SL	TL	NTB	NLA C	DCD
Top five hybrids (selected hybrids)															
79	15XH121	12.13	248.70	134.80	78.00	0.54	1.24	-0.50	16.68	7.31	10.99	18.30	12.33	6.67	126.70
23	15XH65	12.03	238.40	136.80	77.04	0.62	1.12	-0.67	16.87	19.99	23.96	43.95	10.66	6.83	126.40
68	15XH110	11.84	247.60	133.50	77.03	0.54	1.02	-0.01	17.65	13.88	24.33	38.21	11.49	7.16	129.70
93	15XH135	11.74	233.10	128.10	77.66	0.55	1.01	0.67	16.88	35.20	24.04	59.24	12.83	5.67	127.20
87	15XH129	11.69	246.30	130.60	78.05	0.53	1.21	-1.17	16.36	17.41	25.08	42.50	11.00	6.66	127.90
Means															
	Mean of selected (S)	11.89	242.82	132.76	77.56	0.56	1.12	-0.34	16.89	18.76	21.68	40.44	11.66	6.60	127.58
	Population mean (P)	10.18	242.57	128.71	77.26	0.53	1.08	-0.61	16.61	15.41	20.28	35.68	11.98	6.60	127.21
	Mean of checks (C)	10.44	239.66	126.06	77.95	0.53	1.28	-0.98	16.81	8.19	8.55	16.75	12.00	6.43	128.03
	Mean of set A checks (A)	9.78	239.80	126.64	78.03	0.53	1.23	-1.17	16.75	7.14	7.04	14.17	11.57	6.30	127.96
	Mean of set B checks (B)	12.08	239.30	124.60	77.75	0.53	1.39	-0.50	16.96	10.84	12.35	23.18	13.08	6.75	128.20
	Genetic gain (S - P)	1.70	0.25	4.05	0.30	0.02	0.04	0.27	0.28	3.35	1.40	4.76	-0.32	-0.01	0.37
Percentage gain															
	S - P	16.70	0.10	3.15	0.39	4.69	3.63	-44.53	1.67	21.73	6.93	13.33	-2.65	-0.10	0.29
	S - C	14.23	1.30	5.21	-0.50	5.39	-14.67	-15.41	0.48	68.56	64.74	66.40	-2.81	2.56	-0.35
	S - A	20.68	1.24	4.75	-0.61	5.47	-10.45	-16.67	0.83	75.41	72.23	73.61	0.80	4.49	-0.30
	S - B	-1.90	1.45	6.34	-0.24	5.21	-25.24	-27.26	-0.40	51.42	46.04	48.37	-11.84	-2.28	-0.49

GYG = Grain yield; PH = plant height; EH = Ear height; AD = Days to anthesis; EPO = Ear position; EPP = Number of ear per plant; MOI = grain moisture content; ASI = Anthesis silking interval; RL = Root lodging; SL = Stem lodging; TL = Total lodging; NTB = Number of tassel branches; NLAC = Number of leaves above the cob and DCD = Number of day to 50% cob, Set A checks = Advanced hybrids and Set B checks = Commercial hybrids.

Table 4.17. Genetic gain for hybrids evaluated under high plant population density

Entry	Hybrid	GYG	PH	EH	AD	EPO	EPP	ASI	MOI	RL	SL	TL	NTB	NLAC	DCD
Top five hybrids (selected hybrids)															
179	15XH214	12.04	263.20	150.20	80.86	0.57	1.64	-1.47	15.37	5.40	21.88	27.28	14.46	5.48	131.80
180	15XH215	11.68	240.10	127.70	80.19	0.53	1.80	-0.69	17.17	0.04	11.64	11.64	11.53	6.18	130.50
115	15XH150	11.49	240.80	130.40	77.50	0.54	1.60	-1.00	16.21	8.23	3.28	11.51	13.16	5.83	128.70
122	15XH257	11.45	246.80	129.20	78.95	0.52	1.61	-1.19	17.03	4.56	27.14	31.70	12.21	5.52	133.00
141	15XH176	11.44	48.10	127.60	78.66	0.51	1.73	-1.18	16.47	2.62	13.92	16.54	11.68	6.01	127.70
Means															
	Mean of selected (S)	11.62	247.80	133.02	78.83	0.54	1.68	-1.11	16.45	4.16	15.57	19.73	12.61	5.80	130.34
	Population mean (P)	9.53	246.30	130.06	77.89	0.53	1.56	-0.94	15.93	2.59	12.40	14.99	12.83	5.81	129.78
	Mean of checks (C)	9.19	246.99	129.61	78.49	0.53	1.44	-0.86	16.00	3.33	10.17	13.51	12.65	5.85	130.07
	Mean of set A checks (A)	8.59	245.26	129.98	78.58	0.53	1.38	-0.73	16.13	2.99	8.19	11.18	12.39	5.74	130.46
	Mean of set B checks (B)	10.68	251.30	128.70	78.27	0.51	1.58	-1.19	15.70	4.18	15.14	19.33	13.30	6.10	129.10
	Genetic gain (S - P)	2.09	1.50	2.96	0.94	0.01	0.11	-0.17	0.52	1.57	3.17	4.75	-0.23	-0.01	0.56
Percentage gain															
	S - P	22.70	0.61	2.29	1.19	1.41	8.00	19.75	3.23	47.25	31.14	35.14	-1.79	-0.11	0.43
	S - C	25.50	0.33	2.62	0.44	2.03	15.45	25.92	2.80	32.04	43.52	41.55	-0.29	-0.75	0.21
	S - A	31.77	1.03	2.34	0.32	1.00	19.23	40.00	2.02	45.21	59.53	57.08	1.73	1.02	-0.09
	S - B	9.81	-1.42	3.32	0.73	4.61	6.00	-9.26	4.74	-0.91	3.48	2.73	-5.35	-5.17	0.96

GYG = Grain yield; PH = plant height; EH = Ear height; AD = Days to anthesis; EPO = Ear position; EPP = Number of ear per plant; MOI = grain moisture content; ASI = Anthesis silking interval; RL = Root lodging; SL = Stem lodging; TL = Total lodging; NTB = Number of tassel branches; NLAC = Number of leaves above the cob and DCD = Number of day to 50% cob, Set A checks = Advanced hybrids and Set B checks = Commercial hybrids.

4.9. Line x Tester analysis

Under low plant population density, lines showed significant differences ($P < 0.05$) for most traits except SL, TL and NTB (Table 4.19). However, at high plant population density SL and TL were significantly different ($P < 0.05$), while PH, EH and EPO were non-significant (Table 4.21). The results for the line x tester analysis variance for grain yield and grain yield related traits are presented in Table 4.19 for the hybrids which were evaluated under low plant population density at UK1. The mean squares for the line x tester of 93 experimental hybrids were highly significant ($P \leq 0.001$) for grain yield, days to anthesis and ear prolificacy (Table 4.19). All traits were highly significant at $P \leq 0.001$ for the tester and lines except for ear position and stem lodging whereas for the lines grain yield, days to anthesis, ear prolificacy, grain moisture content, anthesis silking interval and days to 50% cob dryness were highly significant at $P \leq 0.001$ (Table 4.19).

Under high plant population density, the analysis of variance for the line x tester analysis showed highly significant differences at ($P \leq 0.01$) for all the selected studied traits except for plant height, ear height and ear position, root lodging, number of leaves above the cob and days to 50 % cob dryness (Table 4.21). For the testers and lines, grain yield, days to anthesis, ear prolificacy, grain moisture content, anthesis silking interval, root lodging, stem lodging and total plant lodging were highly significant at $P \leq 0.05$.

4.9.1. Genetic parameters

Genotypic coefficients of variation (GCV) ranged from 0 to 2.00, with the stem lodging showing the highest GCV value as compared to the other traits. Phenotypic coefficients of variation (PCV) ranged from 0 to 1.95, with root lodging showing the highest PCV value as compared to the other traits. GCV was higher than PCV in all traits except for number of plants and number of tassel branches. Plant height, ear position, grain moisture content and number of leaves above the cob showed similar value in both GCV and PCV (Table 4.18). The GCV and PCV of the ear position were both zero. The heritability percentage was categorised as low, moderate and high, as outlined by Robinson *et al.* (1949) and it was expressed as follows: $< 50\%$ = low; 50% = moderate and $> 50\%$ = high. The heritability across the sites ranged from 42 % to 63 % (Table 4.18). Heritability estimates based on mean

scores and final scores are presented in Table 4.26. High heritability estimates were exhibited by grain yield and ear height (Table 4.26). Low heritability estimates were exhibited by number of plants and number of tassel branches (Table 4.19). All other selected studied traits exhibited moderate heritability.

4.9.2. General combining ability effects

The hybrids 15XH214 and 15XH215 came from inbred lines (CML444*/LH82)-B-9-B-B and (CML444*/LH82)-B-11-B-B), respectively. These inbred lines had positive GCA effects for GYG and other desirable traits and a negative GCA effect for SL under low and high plant population density. The GCA effects of the lines for each site are shown in Tables 4.20, 4.22 and 4.24. In the study, positive GCA effects are desired because they reflect contribution of the line in its hybrid. Top ten lines that exhibited positive GCA effects are presented in Tables 4.20, 4.22 and 4.24, all representing GCA effects for lines from UK1, UK2 and CED, respectively. In UK1, there was a highly significant difference at $P \leq 0.001$ in line by tester for grain yield, ear height, plant height, ear prolificacy and days to cob dryness while all traits showed a highly significance difference at $P \leq 0.001$ for the testers (Table 4.19). Lines 79, 27, 10, 20, 8, 40, 37, 39, 75 and 57 showed a highly significant ($p < 0.001$) and positive GCA effects (Table 4.20).

There were highly significant differences at $P \leq 0.01$ in lines, testers and line by tester interaction for all the selected traits except for plant height, ear height and ear position but number of tassel branches was not significantly different for testers and number of leaves above the cob and days to anthesis were not significantly different in line by tester (Table 4.21). Lines 180, 179, 182, 129, 150, 177, 140, 141, 103 and 142 showed highly significant ($p < 0.001$) and positive GCA effects under high plant population density (Table 4.22).

There were high significant differences at $P \leq 0.05$ in testers for all traits except for plant height at Cedara (Table 4.23). Other studied traits for the lines showed significant difference at $P \leq 0.01$, except for days to anthesis, anthesis silking interval, root lodging and days to 50% cob dryness. The entries that showed a high significant level at $P \leq 0.001$ with positive GCA effects were lines 10, 83, 79, 77, 20, 51, 27, 21, 33 and 40.

Table 4.18. Estimation of variance components and related genetic parameters for all the traits across all the sites due to GCA ($\sigma^2\text{GCA}$), SCA ($\sigma^2\text{SCA}$) and additive variance ($\sigma^2\text{A}$)

Source	GYG	PH	EH	AD	EPO	EPP	MOI	NP	ASI	RL	SL	NTB	NLAC	DCD
$\sigma^2\text{GCA}_{\text{line}}$	0.74	8.85	6.93	0.42	0.00	0.01	0.35	0.06	0.06	2.49	9.31	0.00	0.01	0.13
$\sigma^2\text{GCA}_{\text{tester}}$	0.14	0.00	0.00	0.10	0.00	0.10	0.19	0.43	0.00	35.58	22.85	0.31	0.23	1.57
$\sigma^2\text{SCA}$	0.06	2.36	3.84	0.19	0.01	0.00	0.03	0.28	0.02	5.12	11.12	0.14	0.01	0.26
$\sigma^2\text{GCA}_{\text{line}} \times \text{Env.}$	0.02	5.25	5.88	0.10	0.00	0.02	0.00	0.96	0.17	47.00	11.55	0.05	0.07	1.58
$\sigma^2\text{GCA}_{\text{tester}} \times \text{Env.}$	0.59	0.00	3.47	0.09	0.00	0.01	0.00	-0.04	0.02	0.97	7.68	-0.08	0.00	0.19
$\sigma^2\text{SCA} \times \text{Env}$	0.05	8.33	4.58	0.10	0.01	0.00	0.08	0.60	0.01	1.78	5.23	0.15	0.03	0.13
$\sigma^2\text{e}$	1.49	197.90	138.00	1.65	0.00	0.02	0.96	4.69	0.99	170.30	198.50	2.99	0.49	5.38
$\text{GCA}_{\text{line}} + \text{GCA}_{\text{tester}}$	0.87	8.85	6.93	0.52	0.00	0.11	0.55	0.50	0.06	38.07	32.16	0.31	0.24	1.71
$\text{GCA} + \text{SCA}$	1.47	8.85	10.40	0.62	0.01	0.11	0.55	0.46	0.08	39.04	39.85	0.22	0.24	1.90
Total	2.34	17.70	17.33	1.14	0.00	0.22	1.09	0.95	0.13	77.11	72.01	0.53	0.49	3.61
GCV	0.38	0.94	1.02	0.25	0.01	0.11	0.23	0.21	0.09	1.98	2.00	0.15	0.16	0.44
PCV	0.30	0.94	0.83	0.23	0.00	0.10	0.23	0.22	0.07	1.95	1.79	0.18	0.16	0.41
h^2	0.37	0.50	0.40	0.46	0.44	0.49	0.50	0.52	0.42	0.49	0.45	0.58	0.50	0.47
H^2	0.63	0.50	0.60	0.54	0.56	0.51	0.50	0.48	0.58	0.51	0.55	0.42	0.50	0.53

GYG = Grain yield; PH = plant height; EH = Ear height; AD = Days to anthesis; EPO = Ear position; EPP = Number of ear per plant; MOI = grain moisture content; NP = Number of plants harvested; ASI = Anthesis silking interval; RL = Root lodging; SL = Stem lodging; NTB = Number of tassel branches; NLAC = Number of leaves above the cob and DCD = Number of days to 50% cob dryness; $\sigma^2\text{e}$ = experimental error variance; GCA = General combining ability; $\sigma^2\text{GCA}$; $\sigma^2\text{SCA}$; Env = Environment; GCV = Genotypic coefficient of variation; PCV = Phenotypic coefficient of variation; h^2 = Narrow sense heritability; H^2 = Broad sense heritability. *,** and *** significantly different 0.05, 0.01 and 0.001 probability levels, respectively.

Table 4.19. Mean squares of the analyses of variance for grain yield and grain yield related traits of 93 lines evaluated under low plant population density at Ukulinga 1 (Env-1).

Change	d.f.	GYG	PH	EH	AD	EPO	EPP	MOI	ASI	RL	SL	TL	NTB	NLAC	DCD
Rep	1	0.37	7159.7	7943.4	18.95	0.035	0.22	7.523	0.3253	113.2	62.07	343	1.075	1.5484	0.132
Rep.Blk	18	3.114	688.7	615.2	4.23	0.004	0.075	3.036	1.549	1495.1	49.45	1403.2	3.767	1.232	12.95
NP	1	40.59	209.4	357.4	2.631	0.0037	0.07872	0.65	4.913	12857.7	15.33	11985.1	4.838	0.5141	16.34
Line	92	4.87***	280*	180.2*	5.62***	0.0028	0.083***	2.46***	1.68***	601.2*	27.84	590.3	4.669	0.8114**	15.18***
Tester	1	123.65***	8853.5***	5973.4***	99.11***	0.0195**	57.078***	32.18***	188.65***	96565.7***	187.59**	105265.6***	140.76***	56.02***	823.55***
Line.Tester	92	4.03***	313.5**	207.3**	2.008	0.0032	0.051***	1.314	1.0822	504.9	33.12	513.3	4.688	0.6132	7.15***
Residual	166	2.185	194.1	135.1	1.979	0.0028	0.02628	1.13	0.8208	450.2	29.71	482.3	3.318	0.5332	4.022
Total	371	3.78	311.1	224.9	3.307	0.0031	0.20341	1.698	1.6511	843.5	31.52	874.5	4.383	0.8082	10.231
5% LSD		2.803	26.41	22.04	2.667	0.0997	0.3074	2.016	1.718	40.23	10.335	2.933	41.64	3.454	1.384
%cv		13.16	5.89	9.39	1.89	10.04	10.61	6.12	-141.01	103.78	328.41	8.75	99.35	14.98	11.57

d.f. = Degrees of freedom; GYG = Grain yield; PH = plant height; EH = Ear height; AD = Days to anthesis; EPO = Ear position; EPP = Number of ear per plant; MOI = grain moisture content; ASI = Anthesis silking interval; RL = Root lodging; SL = Stem lodging; TL = Total lodging; NTB = Number of tassel branches; NLAC = Number of leaves above the cob; DCD = Number of days to 50% cob dryness and NP = Number of plant. *, **, *** significantly different at p = 0.05, 0.01 and 0.001 probability levels, respectively.

Table 4.20. Estimation of general combining ability effects for grain yield and yield related traits for the top ten positive GCA of lines and GCA of testers evaluated under low plant population density at Ukulinga 1 (Env-1)

Line	GYG	PH	EH	AD	EPO	EPP	MOI	ASI	RL	SL	TL	NTB	NLAC	DCD	PopDen	NP
Top ten positive GCA effects of lines out of 93 tested lines under UK-1																
79	2.50	1.90	8.03	1.84	0.03	0.13	0.98	-1.79	20.31	-1.49	18.81	0.65	-0.29	5.43	-1655.17	-0.74
27	1.94	8.80	16.53	0.60	0.05	0.15	0.78	1.37	-15.32	-1.73	-17.05	1.60	0.68	3.63	32.83	0.02
10	1.82	5.00	3.23	3.60	0.00	0.14	-0.19	-0.28	-3.75	0.21	-3.54	1.09	-0.60	-1.47	-2678.17	-1.20
20	1.73	-11.39	3.63	3.36	0.04	0.20	0.94	0.42	-11.21	1.19	-10.03	-1.32	-0.82	0.23	-1089.17	-0.49
8	1.70	3.70	-2.77	0.10	-0.02	-0.11	1.24	0.68	3.17	-1.57	1.59	1.38	1.21	5.43	-1096.17	-0.49
40	1.70	2.10	3.23	1.08	0.01	0.36	-0.59	-1.11	2.79	-0.37	2.42	-1.03	-0.08	-1.77	1013.83	0.46
37	1.67	5.50	0.93	0.58	-0.01	0.05	0.17	-0.02	22.59	-0.03	22.56	0.90	0.22	0.23	-2268.17	-1.02
39	1.62	10.80	3.53	-0.41	-0.01	0.21	0.30	-0.45	6.89	0.87	7.76	0.11	0.66	-1.77	1683.83	0.76
75	1.54	-5.60	-6.87	0.40	-0.02	-0.06	0.47	0.20	-10.18	1.85	-8.33	-1.31	0.46	-1.47	-2379.17	-1.07
57	1.51	1.50	-4.67	-0.62	-0.02	0.18	0.13	0.80	6.04	0.27	6.31	-0.66	0.22	2.23	-4823.17	-2.17
GCA effects of testers under low plant population density at UK-1																
A	0.59	-4.90	-4.07	-0.51	-0.01	-0.40	0.33	0.74	16.21	0.78	16.99	-0.63	0.39	-1.47	-611.17	-0.27
B	-0.59	5.00	4.13	0.52	0.01	0.40	-0.32	-0.74	-16.46	-0.77	-17.23	0.63	-0.39	1.53	617.83	0.28

GYG = Grain yield; PH = plant height; EH = Ear height; AD = Days to anthesis; EPO = Ear position; EPP = Number of ear per plant; MOI = grain moisture content; ASI = Anthesis silking interval; RL = Root lodging; SL = Stem lodging; TL = Total lodging; NTB = Number of tassel branches; NLAC = Number of leaves above the cob and DCD = Number of days to 50% cob dryness.

Table 4.21. Mean squares of the analyses of variance for grain yield and grain yield related traits of 93 lines evaluated under high plant population density at Ukulinga 2 (Env-3).

S.O.V	d.f.	GYG	PH	EH	AD	EPO	EPP	MOI	ASI	RL	SL	TL	NTB	NLAC	DCD
Rep	1	12.6	421.5	843	38.1	0.0067	0.1	8.2	2.107	569.6	1068.1	3197.8	1.68	0.454	20.82
Rep.Blk	18	3.3	955.7	275.8	6.9	0.0037	0.1	1.5	0.979	33.06	610.9	599.4	1.73	0.421	33.98
NP	1	44.7	47.6	121.2	0.026	0.0032	0.2	4.2	2.236	478.3	75.9	935.2	1.48	43.72	723.99
Line	92	4.7***	193.7	133.3	10.1***	0.0036	0.1***	1.8***	1.2***	37.4***	314.2***	390.5***	2.85*	0.87*	7.47**
Tester	1	53.1***	550.1	60.9	12.2*	0.0092	1.8***	15.6***	4.4**	813.5***	3373.1***	7499.6***	4.98	141.38***	1896.59***
Line.Tester	92	2.3***	204.7	154.2	4.4***	0.0033	0.0***	1.5***	0.9**	25.57	238.4***	285.3***	2.74*	0.7103	5.059
Error	166	1.163	240.4	150.1	1.903	0.0040	0.01218	0.8341	0.603	19.7	108.3	109.9	2.02	0.5913	4.738
Total	371	2.735	255.5	154.6	4.907	0.0037	0.03674	1.3267	0.873	31.04	227.3	277.2	2.39	1.1765	13.995

S.O.V = Source of variation; d.f. = Degrees of freedom; GYG = Grain yield; PH = plant height; EH = Ear height; AD = Days to anthesis; EPO = Ear position; EPP = Number of ear per plant; MOI = grain moisture content; ASI = Anthesis silking interval; RL = Root lodging; SL = Stem lodging; TL = Total lodging; NTB = Number of tassel branches; NLAC = Number of leaves above the cob; DCD = Number of days to 50% cob dryness and NP = Number of plant. *, **, *** significantly different at 0.05, 0.01 and 0.001 probability levels, respectively.

Table 4.22. Estimation of general combining ability effects for grain yield and grain yield related traits for the top ten positive lines as ranked by grain yield and GCA of the testers evaluated under high plant population density at Ukulinga 2 (Env-3)

line	GYG	PH	EH	AD	EPO	EPP	MOI	ASI	RL	SL	TL	NTB	NLAC	DCD
Top ten GCA effects for the lines														
180	2.61572	4.60860	2.75914	0.54258	2.75914	0.04105	0.98709	-0.1919	0.16505	-3.1601	-2.9993	0.30064	0.57122	-0.1258
179	1.94472	13.8086	11.5591	2.23258	11.5591	-0.0519	0.18709	-0.4729	5.78805	-1.0851	4.70064	0.58064	-0.0817	-0.0258
182	1.89272	-6.8914	3.65914	0.05258	3.65914	-0.0029	-0.4929	-0.4357	-2.9129	-7.0551	-9.9693	0.81064	0.61722	1.07419
129	1.86972	-1.0914	5.25914	3.76258	5.25914	-0.0229	0.94709	0.54853	1.60005	-3.8841	-2.2793	0.21064	0.37522	-1.0258
150	1.81972	-4.6914	-3.0408	0.29258	-3.0408	0.17105	0.32709	-0.4340	-1.2019	-8.0051	-9.2093	0.55064	-0.6458	0.37419
177	1.70672	2.70860	8.95914	2.29258	8.95914	-0.0029	0.40709	0.07763	-0.6029	8.32088	7.72064	-1.8893	-0.8968	2.67419
140	1.68972	-6.8914	-0.1408	0.28258	-0.1408	0.13605	-0.2929	-0.1803	2.65405	-8.3441	-5.6893	-0.4593	0.85322	-0.1258
141	1.50072	8.70860	4.45914	-0.0074	4.45914	0.03105	-0.3429	-0.1911	-1.2169	-6.6411	-7.8593	-0.7693	-0.1298	-0.2258
103	1.28972	-5.5914	5.85914	0.01258	5.85914	-0.0239	0.23709	0.56493	-1.3639	-4.3341	-5.6993	0.48064	-0.6518	-0.1258
142	1.24172	7.20860	3.25914	1.31258	3.25914	-0.0329	0.48709	0.08053	2.85205	0.09488	2.95064	1.09064	0.10122	-0.9258
GCA effects for the testers														
A	0.534	-1.691	0.659	0.141	0.00763	-0.0869	0.257	0.137	1.936	3.728	5.700	-0.189	-7.115	-2.925
B	-0.534	1.691	-0.659	-0.139	-0.00761	0.0870	-0.259	-0.136	-1.941	-3.717	-5.689	0.190	7.235	2.874

GYG = Grain yield; PH = plant height; EH = Ear height; AD = Days to anthesis; EPO = Ear position; EPP = Number of ear per plant; MOI = grain moisture content; ASI = Anthesis silking interval; RL = Root lodging; SL = Stem lodging; TL = Total lodging; NTB = Number of tassel branches; NLAC = Number of leaves above the cob and DCD = Number of days to 50% cob dryness.

Table 4.23. Mean squares of the analyses of variance for grain yield and grain yield related traits of 93 lines at CEDARA (Env-2)

S.O.V	d.f.	GYG	PH	EH	AD	EPO	EPP	ASI	MOI	RL	SL	TL	NTB	NLAC	DCD
Rep	1	11.19	440.9	93	3.293	6.0E-06	0	4.301	3.3687	4.9	4593.5	4898.4	4.519	0.2688	11.71
Rep.Blk	18	3.9	669.8	382.6	1.103	2.8E-03	0.06	1.319	5.31	44.68	2916.9	2714.9	2.727	0.3115	12.35
NP	1	49.33	1.3E-05	2.1	1.773	1.3E-05	0.22	3.19	3.99	0.01	143.3	145.1	2.581	0.0869	10.546
Line	92	5.06***	311.2***	321.6***	0.988	0.002**	0.04***	1.457	3.99***	40.17	778.3**	821.2***	6.31**	0.678***	7.764
Tester	1	8.43***	395.2	1285.9**	134.2***	0.011**	39.91***	43.5***	69.07***	551.6***	31241.8***	40095.6***	114.57***	1.78*	61.54**
Line.Tester	92	1.95***	222.5**	156.3	0.795	1.8E-03	0.04***	1.228	1.45**	27.04	473.1	449.5	3.676	0.47*	7.418
Error	166	0.7659	162.2	130.9	1.104	1.7E-03	0.019	1.529	0.9237	35.88	449.6	456.1	3.66	0.3349	7.348
Total	371	2.4589	239.7	199.3	1.365	2.1E-03	0.141	1.551	2.2279	36.39	750	772.5	4.574	0.4553	7.878
5% LSD		1.732	26.7	22.41	2.081	0.084	0.276	2.472	1.957	11.51	41.62	41.82	3.737	1.132	5.463
%cv		10.09	5.23	8.15	1.24	7.86	10.6	-114.5	6.39	205.9	55.6	51.98	15.95	9.66	2.05
Se		0.8744	13.48	11.32	1.051	0.042	0.139	1.248	0.988	5.812	21.02	21.12	1.887	0.572	2.759

S.O.V = Source of variation; d.f. = Degrees of freedom; GYG = Grain yield; PH = plant height; EH = Ear height; AD = Days to anthesis; EPO = Ear position; EPP = Number of ear per plant; MOI = grain moisture content; ASI = Anthesis silking interval; RL = Root lodging; SL = Stem lodging; TL = Total lodging; NTB = Number of tassel branches; NLAC = Number of leaves above the cob; DCD = Number of days to 50% cob dryness and NP = Number of plant. *, **, *** significantly different at 0.05, 0.01 and 0.001 probability levels, respectively.

Table 4.24. Estimation of general combining ability effects for grain yield and grain yield related traits for the top ten positive lines as ranked by grain yield and the GCA of testers at CEDARA (Env-1)

Line	GYG	PH	EH	AD	EPO	EPP	ASI	MOI	RL	SL	TL	NTB	NLAC	DCD
Top ten GCA effect for the lines														
10	2.49	26.28	19.22	-0.43	0.02	0.04	0.08	1.07	-1.43	28.37	26.94	2.43	-0.18	1.92
83	2.25	10.98	4.72	0.02	0.0001	-0.02	0.14	0.24	0.34	-4.77	-4.42	0.88	0.09	0.52
79	2.17	29.48	31.42	-0.73	0.05	0.05	0.54	-0.24	-1.56	25.33	23.78	2.34	-0.48	2.82
77	1.93	1.68	-1.48	-0.46	-0.01	0.11	1.08	1.15	-0.16	19.24	19.09	0.63	-0.95	0.42
20	1.91	2.08	4.72	0.07	0.01	0.20	0.09	1.13	-1.41	-5.95	-7.35	-0.50	0.60	0.62
51	1.68	7.68	0.42	0.32	-0.01	0.01	-0.15	0.70	-1.45	-10.75	-12.18	2.15	0.31	1.22
27	1.47	-2.32	0.72	0.52	0.01	0.08	-0.91	1.82	-2.80	-17.12	-19.91	-1.62	0.08	-1.18
21	1.34	3.98	12.52	0.05	0.04	0.17	0.53	1.18	2.08	-10.15	-8.06	-2.09	0.26	-1.48
33	1.33	-21.52	3.52	-0.18	0.09	0.09	0.08	0.93	-2.81	0.71	-2.09	-2.13	0.06	-1.28
40	1.27	0.88	-2.68	0.30	-0.01	0.10	-0.69	0.09	-2.90	4.53	1.63	-2.11	-0.47	-0.58
GCA effects for the testers														
A	0.14	0.99	1.82	-0.60	0.01	-0.33	-0.34	0.43	1.26	9.16	10.43	-0.57	0.07	0.42
B	-0.14	-1.02	-1.78	0.60	-0.01	0.33	0.35	-0.43	-1.25	-9.05	-10.30	0.56	-0.07	-0.38

GYG = Grain yield; PH = plant height; EH = Ear height; AD = Days to anthesis; EPO = Ear position; EPP = Number of ear per plant; MOI = grain moisture content; ASI = Anthesis silking interval; RL = Root lodging; SL = Stem lodging; TL = Total lodging; NTB = Number of tassel branches; NLAC = Number of leaves above the cob and DCD = Number of days to 50% cob.

4.10. Correlation and path coefficient analysis between yield and yield related traits in maize hybrids

Phenotypic correlations between yield and secondary traits were determined at all three experimental sites under low and high plant population densities under both testers and indicated significant associations ($P < 0.05$) among all the selected agronomic traits of the hybrids. The data showed that there were significant correlations ($P < 0.01$) among all the studied traits (Table 4.25 to Table 4.33).

Under high plant population density, EPP and NTB did not contribute to grain yield across both testers and within each tester (Table 4.26, 4.29 and 4.32) but in most cases EPP directly contributed to GYG across both testers and within each tester under low plant population density (Table 4.25). MOI contributed to high GYG under low plant population density across both testers and within each tester (Tables 4.25, 4.27, 4.28, 4.30, 4.31 and 4.33) but did not contribute to GYG under high plant population density (Tables 4.26, 4.29 and 4.32).

Number of leaves above the cob (NLAC) had a huge direct effect (0.30) on grain yield at $P < 0.001$ under high plant population density across both testers due to Tester B (Tables 4.26 and 4.32). Stem lodging had indirect effects on grain yield under high plant population density within and across testers at $P < 0.05$ due to the effects of Tester A (Tables 4.26, 4.29 and 4.32). Root lodging had huge direct effects (0.35) on grain yield at $P < 0.001$ under high plant population density across testers (Table 4.26) and within Tester B (0.38) at $P < 0.01$ (Table 4.32) but had indirect effects on grain yield across tester and within Tester A under low plant population density (Table 4.25). The direct and indirect effects for DCD, TL, EH, EPO, PH, AD, ASI, NP and PopDen were inconsistent across different plant population densities and within testers. Across testers, under low plant population density NTB and MOI had direct effects of (-0.16) and (0.23) on grain yield, respectively, whereas RL had indirect effects on grain yield via NP. At high plant population density across all testers, DCD and RL had direct effects on grain yield while MOI and DCD had indirect effects on grain yield. There were no traits with direct or indirect effects on grain yield under both low and high plant population density.

Table 4.25. Phenotypic direct (underlined) and indirect effects and total path correlations coefficient analysis of grain yield component characters evaluated at UK1 (Env-1).

Traits	PH	EH	AD	EPO	EPP	ASI	MOI	RL	SL	TL	NTB	NLAC	DCD	PopDen	NP	GYG
PH	<u>-0.17</u>	0.15	0.02	0.01	0.00	0.02	-0.02	0.51	-0.01	-0.54	-0.02	0.00	0.03	0.00	0.01	-0.01
EH	-0.11	<u>0.24</u>	0.02	-0.09	0.01	0.02	-0.01	0.56	0.00	-0.61	-0.02	-0.04	0.03	0.00	0.01	-0.01
AD	-0.04	0.07	<u>0.06</u>	-0.02	0.01	0.03	0.02	0.47	0.03	-0.54	-0.02	-0.06	0.04	0.00	0.00	0.04
EPO	0.01	0.16	0.01	<u>-0.13</u>	0.00	0.01	-0.01	0.31	0.00	-0.34	-0.02	-0.05	0.01	0.00	0.00	-0.02
EPP	-0.05	0.08	0.02	-0.02	<u>0.02</u>	0.05	-0.07	1.05	0.05	-1.19	-0.05	-0.12	0.05	-0.01	0.02	-0.19**
ASI	0.05	-0.06	-0.03	0.01	-0.01	<u>-0.08</u>	0.06	-0.75	-0.03	0.85	0.03	0.09	-0.04	0.01	-0.02	0.09
MOI	0.01	-0.01	0.00	0.00	0.00	-0.02	<u>0.23</u>	-0.36	0.01	0.38	0.01	0.06	0.02	0.00	-0.01	0.34***
RL	0.05	-0.08	-0.02	0.02	-0.01	-0.04	0.05	<u>-1.64</u>	0.00	1.78	0.03	0.10	-0.03	0.00	-0.01	0.22**
SL	0.00	0.00	-0.01	0.00	0.00	-0.01	-0.01	-0.02	<u>-0.24</u>	0.31	0.01	0.03	-0.02	0.01	-0.01	0.04
TL	0.05	-0.08	-0.02	0.02	-0.01	-0.04	0.05	-1.62	-0.04	<u>1.81</u>	0.03	0.10	-0.04	0.00	-0.01	0.22**
NTB	-0.02	0.04	0.01	-0.01	0.00	0.02	-0.02	0.31	0.02	-0.37	<u>-0.16</u>	-0.04	0.03	0.00	0.00	-0.18**
NLAC	0.00	-0.04	-0.01	0.03	-0.01	-0.03	0.06	-0.65	-0.03	0.75	0.02	<u>0.25</u>	-0.02	0.01	-0.01	0.30***
DCD	-0.04	0.06	0.02	-0.01	0.01	0.03	0.04	0.42	0.04	-0.51	-0.04	-0.05	<u>0.13</u>	0.00	0.00	0.09
PopDen	-0.01	0.02	0.00	0.00	0.00	0.02	-0.03	0.16	0.03	-0.21	0.00	-0.04	0.00	<u>-0.04</u>	0.09	-0.02
NP	-0.01	0.02	0.00	0.00	0.00	0.02	-0.03	0.16	0.03	-0.21	0.00	-0.04	0.00	-0.04	<u>0.09</u>	-0.02

GYG = Grain yield; PH = plant height; EH = Ear height; AD = Days to anthesis; EPO = Ear position; EPP = Number of ear per plant; MOI = grain moisture content; NP = Number of plants harvested; ASI = Anthesis silking interval; RL = Root lodging; SL = Stem lodging; TL = Total plant lodging; NTB = Number of tassel branches; NLAC = Number of leaves above the cob; DCD = Number of days to 50% cob dryness and PopDen = Plant population density per plot. *, **, *** significantly different at $p \leq 0.05$, 0.01 and 0.001 probability levels, respectively.

Table 4.26. Phenotypic direct (underlined) and indirect effects and total path correlations coefficient analysis of grain yield component characters evaluated at UK2 (Env-3).

Traits	PH	EH	AD	EPO	EPP	ASI	MOI	RL	SL	TL	NTB	NLAC	DCD	PopDen	NP	GYG
PH	<u>0.052</u>	0.030	-0.002	-0.036	0.007	-1.9E-03	-2.5E-04	0.002	-0.008	0.019	5.36E-04	-0.050	-0.030	8.5E-05	8.5E-05	-0.018
EH	0.017	<u>0.095</u>	-0.002	0.056	0.003	4.5E-04	2.6E-05	0.028	0.022	-0.066	-1.32E-04	0.006	0.008	-6.9E-05	-6.9E-05	0.166
AD	-0.001	-0.001	<u>0.101</u>	-0.001	0.010	-3.6E-03	1.5E-03	-0.022	-0.019	0.056	-7.22E-04	-0.007	0.002	1.0E-04	1.0E-04	0.114
EPO	-0.023	0.064	-0.002	<u>0.083</u>	-0.001	1.4E-03	1.8E-04	0.030	0.020	-0.062	-5.80E-04	0.038	0.028	-1.0E-04	-1.0E-04	0.176**
EPP	0.004	0.003	0.010	-0.001	<u>0.099</u>	-1.3E-02	-1.2E-03	-0.101	-0.047	0.162	2.24E-03	-0.121	-0.050	4.0E-04	4.0E-04	-0.052
ASI	-0.002	0.001	-0.007	0.002	-0.027	<u>4.8E-02</u>	5.4E-04	0.031	0.048	-0.131	-5.36E-04	0.017	0.017	-6.0E-05	-6.0E-05	-0.003
MOI	-0.003	0.001	0.031	0.003	-0.024	5.3E-03	<u>4.9E-03</u>	0.051	-0.012	0.005	-1.29E-03	0.079	0.040	-1.7E-04	-1.7E-04	0.179**
RL	0.000	0.008	-0.007	0.007	-0.029	4.4E-03	7.3E-04	<u>0.345</u>	0.043	-0.270	-9.83E-04	0.105	0.045	-2.2E-04	-2.2E-04	0.251***
SL	-0.002	0.011	-0.010	0.008	-0.024	1.2E-02	-3.1E-04	0.077	<u>0.194</u>	-0.507	2.54E-04	0.063	0.034	-1.6E-04	-1.6E-04	-0.144*
TL	-0.002	0.012	-0.011	0.010	-0.030	1.2E-02	-4.5E-05	0.175	0.185	<u>-0.532</u>	-8.15E-05	0.088	0.044	-2.1E-04	-2.1E-04	-0.049
NTB	0.002	-0.001	-0.005	-0.004	0.016	-1.9E-03	-4.6E-04	-0.025	0.004	0.003	<u>0.01</u>	-0.058	-0.023	2.7E-04	2.7E-04	-0.079
NLAC	-0.009	0.002	-0.002	0.011	-0.040	2.7E-03	1.3E-03	0.121	0.041	-0.156	-2.63E-03	<u>0.300</u>	0.087	-4.5E-04	-4.5E-04	0.355***
DCD	0.013	-0.006	-0.001	-0.019	0.041	-6.7E-03	-1.6E-03	-0.128	-0.055	0.195	2.53E-03	-0.217	<u>-0.121</u>	4.7E-04	4.7E-04	-0.303***
PopDen	0.004	-0.006	0.009	-0.007	0.035	-2.6E-03	-7.2E-04	-0.066	-0.028	0.100	3.24E-03	-0.121	-0.051	<u>1.1E-03</u>	1.1E-03	-0.129
NP	0.004	-0.006	0.009	-0.007	0.035	-2.6E-03	-7.2E-04	-0.066	-0.028	0.100	3.24E-03	-0.121	-0.051	1.1E-03	<u>1.1E-03</u>	-0.129

GYG = Grain yield; PH = plant height; EH = Ear height; AD = Days to anthesis; EPO = Ear position; EPP = Number of ear per plant; MOI = grain moisture content; NP = Number of plants harvested; ASI = Anthesis silking interval; RL = Root lodging; SL = Stem lodging; TL = Total plant lodging; NTB = Number of tassel branches; NLAC = Number of leaves above the cob; DCD = Number of days to 50% cob dryness and PopDen = Plant population density per plot. *, **, *** significantly different at $p \leq 0.05$, 0.01 and 0.001 probability levels, respectively.

Table 4.27. Phenotypic direct (underlined) and indirect effects and total path correlations coefficient analysis of grain yield component characters evaluated at CED (Env-2).

Traits	PH	EH	AD	EPO	EPP	ASI	MOI	RL	SL	TL	NTB	NLAC	DCD	PopDen	NP	GYG
PH	<u>0.98</u>	-0.67	0.00	-0.01	0.00	0.01	0.06	0.01	0.09	-0.09	0.01	0.00	0.00	-0.02	0.01	0.38***
EH	0.63	<u>-1.04</u>	0.01	0.77	-0.02	0.01	0.08	0.00	0.08	-0.09	0.01	-0.02	0.00	0.05	-0.04	0.42***
AD	-0.02	0.05	<u>-0.19</u>	-0.05	0.13	0.04	-0.07	0.01	-0.09	0.11	0.01	-0.01	0.00	-0.03	0.03	-0.10
EPO	-0.01	-0.78	0.01	<u>1.02</u>	-0.03	0.00	0.06	-0.01	0.03	-0.04	0.00	-0.02	0.00	0.08	-0.06	0.26***
EPP	-0.02	0.11	-0.12	-0.13	<u>0.21</u>	-0.04	-0.13	0.02	-0.09	0.12	0.05	-0.01	0.00	0.01	-0.01	-0.03
ASI	-0.05	0.06	0.05	-0.03	0.06	<u>-0.14</u>	-0.03	0.01	0.00	0.02	0.03	0.00	0.00	0.01	-0.01	-0.01
MOI	0.15	-0.23	0.04	0.17	-0.08	0.01	<u>0.37</u>	0.00	0.05	-0.05	-0.03	0.01	0.00	0.01	-0.01	0.42***
RL	-0.13	0.00	0.02	0.12	-0.06	0.03	-0.02	<u>-0.08</u>	0.01	-0.07	-0.01	0.00	0.00	-0.01	0.01	-0.19**
SL	0.33	-0.31	0.07	0.11	-0.08	0.00	0.07	0.00	<u>0.25</u>	-0.30	-0.01	0.00	0.00	0.09	-0.07	0.16*
TL	0.29	-0.30	0.07	0.14	-0.08	0.01	0.06	-0.02	0.25	<u>-0.31</u>	-0.01	0.00	0.00	0.08	-0.06	0.12
NTB	0.08	-0.03	-0.01	-0.01	0.06	-0.03	-0.06	0.01	-0.01	0.02	<u>0.16</u>	0.00	0.00	0.03	-0.03	0.17**
NLAC	0.01	0.20	0.03	-0.26	-0.02	0.00	0.06	0.00	-0.01	0.01	0.00	<u>0.08</u>	0.00	-0.09	0.07	0.08
DCD	0.07	-0.07	0.02	0.02	-0.04	0.01	0.04	-0.01	0.02	-0.03	0.00	0.00	<u>-0.02</u>	-0.07	0.05	0.01
PopDen	-0.03	-0.10	0.01	0.15	0.00	0.00	0.01	0.00	0.04	-0.05	0.01	-0.01	0.00	<u>0.52</u>	-0.40	0.16*
NP	-0.03	-0.10	0.01	0.15	0.00	0.00	0.01	0.00	0.04	-0.05	0.01	-0.01	0.00	0.52	<u>-0.40</u>	0.16*

GYG = Grain yield; PH = plant height; EH = Ear height; AD = Days to anthesis; EPO = Ear position; EPP = Number of ear per plant; MOI = grain moisture content; NP = Number of plants harvested; ASI = Anthesis silking interval; RL = Root lodging; SL = Stem lodging; TL = Total plant lodging; NTB = Number of tassel branches; NLAC = Number of leaves above the cob; DCD = Number of days to 50% cob dryness and PopDen = Plant population density per plot. *, **, *** significantly different at $p \leq 0.05$, 0.01 and 0.001 probability levels, respectively.

Table 4.28. Phenotypic direct (underlined) and indirect effects and total path correlations coefficient analysis of grain yield component characters evaluated at UK1 under Tester A.

Traits	PH	EH	AD	EPO	EPP	ASI	MOI	RL	SL	TL	NTB	NLAC	DCD	PopDen	NP	GYG
PH	<u>-1.11</u>	1.52	-0.02	-0.09	0.03	4E-03	0.01	-0.07	0.02	0.06	0.01	0.04	0.01	0.01	-0.01	0.39***
EH	-0.75	<u>2.25</u>	-0.03	-1.24	0.03	2E-03	0.01	-0.15	0.02	0.13	0.01	2E-04	0.01	6E-04	-9E-04	0.29**
AD	-0.31	0.79	<u>-0.08</u>	-0.37	0.06	5E-03	0.03	-0.09	-0.02	0.12	0.01	-5E-03	0.07	-2E-03	4E-03	0.21*
EPO	-0.06	1.73	-0.02	<u>-1.60</u>	0.01	-1E-03	0.01	-0.13	0.01	0.13	-2E-03	-0.03	3E-03	-5E-03	0.01	0.05
EPP	-0.11	0.21	-0.02	-0.05	<u>0.28</u>	5E-03	0.01	-0.22	-0.03	0.27	8E-04	-0.01	0.03	0.01	-0.02	0.36***
ASI	0.20	-0.18	0.02	-0.09	-0.06	<u>-0.02</u>	0.02	0.09	-8E-04	-0.09	-0.02	-3E-03	0.03	-0.02	0.03	-0.11
MOI	-0.08	0.32	-0.02	-0.22	0.03	-5E-03	<u>0.09</u>	0.01	-0.02	0.01	-0.01	0.01	0.11	-0.01	0.01	0.22*
RL	0.09	-0.36	0.01	0.23	-0.07	-2E-03	9E-04	<u>0.91</u>	-0.02	-0.96	-0.01	0.01	0.03	-1E-03	2E-03	-0.13
SL	-0.13	0.28	0.01	-0.12	-0.05	1E-04	-0.01	-0.11	<u>0.15</u>	-0.08	5E-03	1E-03	-0.02	-0.01	0.02	-0.07
TL	0.06	-0.30	0.01	0.21	-0.08	-2E-03	-1E-03	0.89	0.01	<u>-0.98</u>	-0.01	0.01	0.03	-5E-03	0.01	-0.14
NTB	0.12	-0.15	0.01	-0.03	-2E-03	-6E-03	0.01	0.08	-0.01	-0.07	<u>-0.10</u>	2E-03	0.04	-0.01	0.01	-0.09
NLAC	-0.47	4E-03	4E-03	0.58	-0.02	7E-04	0.01	0.13	2E-03	-0.14	-2E-03	<u>0.09</u>	0.02	-9E-04	1E-03	0.20*
DCD	-0.06	0.08	-0.02	-0.02	0.03	-2E-03	0.04	0.11	-0.01	-0.10	-0.01	0.01	<u>0.27</u>	-0.02	0.03	0.31**
PopDen	-0.10	0.02	0.00	0.11	0.05	6E-03	-0.01	-0.02	-0.03	0.06	0.01	-1E-03	-0.08	<u>0.07</u>	-0.11	-0.03
NP	-0.10	0.02	0.00	0.11	0.05	6E-03	-0.01	-0.02	-0.03	0.06	0.01	-1E-03	-0.08	0.07	<u>-0.11</u>	-0.03

GYG = Grain yield; PH = plant height; EH = Ear height; AD = Days to anthesis; EPO = Ear position; EPP = Number of ear per plant; MOI = grain moisture content; NP = Number of plants harvested; ASI = Anthesis silking interval; RL = Root lodging; SL = Stem lodging; TL = Total plant lodging; NTB = Number of tassel branches; NLAC = Number of leaves above the cob; DCD = Number of days to 50% cob dryness and PopDen = Plant population density per plot. *, **, *** significantly different at $p \leq 0.05$, 0.01 and 0.001 probability levels, respectively.

Table 4.29. Phenotypic direct (underlined) and indirect effects and total path correlations coefficient analysis of grain yield component characters evaluated at UK2 under Tester A.

Traits	PH	EH	AD	EPO	EPP	ASI	MOI	RL	SL	TL	NTB	NLAC	DCD	PopDen	NP	GYG
PH	<u>0.42</u>	-0.04	-0.01	-0.24	-0.01	-3E-04	1E-03	-0.06	-0.06	0.12	-0.02	-1E-03	-0.03	0.03	-0.02	0.08
EH	0.11	<u>-0.15</u>	-0.01	0.24	-4E-04	-2E-04	-8E-05	-0.02	-0.79	0.76	-3E-03	-2E-03	4E-03	-0.06	0.05	0.12
AD	-0.01	0.01	<u>0.26</u>	-0.01	0.01	1E-03	3E-03	0.09	0.74	-0.79	2E-03	-0.01	-4E-03	-0.10	0.07	0.26**
EPO	-0.25	-0.08	-0.01	<u>0.41</u>	4E-03	8E-05	-8E-04	-0.01	-0.31	0.30	0.01	5E-04	0.03	-0.06	0.05	0.07
EPP	-0.05	1E-03	0.04	0.04	<u>0.04</u>	2E-03	-0.01	0.31	0.95	-1.22	0.01	-0.01	0.01	-0.13	0.10	0.09
ASI	0.02	-4E-03	-0.03	-4E-03	-0.01	<u>-0.01</u>	8E-04	0.03	-1.26	1.15	-3E-03	-0.01	0.01	-0.02	0.01	-0.13
MOI	0.02	6E-04	0.04	-0.02	-0.01	-3E-04	<u>0.02</u>	-0.18	1.24	-0.97	-0.01	0.01	2E-03	0.08	-0.06	0.17
RL	0.01	-2E-03	-0.01	3E-03	-0.01	1E-04	2E-03	<u>-1.76</u>	-0.65	2.48	5E-04	0.01	4E-03	-4E-03	3E-03	0.07
SL	4E-03	-0.02	-0.04	0.02	-0.01	-2E-03	-5E-03	-0.22	<u>-5.28</u>	5.16	0.01	0.01	0.03	-0.01	0.01	-0.34***
TL	0.01	-0.02	-0.04	0.02	-0.01	-2E-03	-4E-03	-0.79	-4.97	<u>5.48</u>	0.01	0.01	0.03	-0.01	0.01	-0.28**
NTB	-0.06	2E-03	3E-03	0.02	4E-03	1E-04	-2E-03	-0.01	-0.26	0.25	<u>0.15</u>	3E-03	0.01	-0.06	0.05	0.10
NLAC	-0.01	4E-03	-0.03	3E-03	-0.01	7E-04	3E-03	-0.18	-0.42	0.58	0.01	<u>0.06</u>	0.01	-0.03	0.02	0.03
DCD	0.13	0.01	0.01	-0.11	-3E-03	1E-03	-3E-04	0.07	1.85	-1.80	-0.01	-0.01	<u>-0.10</u>	0.04	-0.03	0.04
PopDen	-0.03	-0.02	0.07	0.07	0.02	-3E-04	-5E-03	-0.02	-0.20	0.21	0.03	0.01	0.01	<u>-0.37</u>	0.27	0.03
NP	-0.03	-0.02	0.07	0.07	0.02	-3E-04	-5E-03	-0.02	-0.20	0.21	0.03	0.01	0.01	-0.37	<u>0.27</u>	0.03

GYG = Grain yield; PH = plant height; EH = Ear height; AD = Days to anthesis; EPO = Ear position; EPP = Number of ear per plant; MOI = grain moisture content; NP = Number of plants harvested; ASI = Anthesis silking interval; RL = Root lodging; SL = Stem lodging; TL = Total plant lodging; NTB = Number of tassel branches; NLAC = Number of leaves above the cob; DCD = Number of days to 50% cob dryness and PopDen = Plant population density per plot. *, **, *** significantly different at $p \leq 0.05$, 0.01 and 0.001 probability levels, respectively.

Table 4.30. Phenotypic direct (underlined) and indirect effects and total path correlations coefficient analysis of grain yield component characters evaluated at CED under Tester A. All the non under lines are the indirect effects.

Traits	PH	EH	AD	EPO	EPP	ASI	MOI	RL	SL	TL	NTB	NLAC	DCD	PopDen	NP	GYG
PH	<u>0.78</u>	-0.38	2E-04	-0.19	3E-03	3E-03	0.02	-0.07	0.74	-0.67	-0.01	0.02	1E-03	0.08	-0.09	0.24*
EH	0.41	<u>-0.73</u>	5E-04	0.69	4E-03	0.01	0.04	-0.03	0.55	-0.53	-0.01	-0.04	-2E-03	-0.13	0.15	0.39***
AD	0.02	-0.04	<u>0.01</u>	0.03	3E-04	-0.03	-0.01	0.05	-0.29	0.22	-0.02	-0.01	0.01	0.25	-0.28	-0.08
EPO	-0.16	-0.52	3E-04	<u>0.96</u>	3E-03	0.01	0.03	0.02	0.07	-0.10	-2E-03	-0.06	-4E-03	-0.22	0.25	0.27**
EPP	0.08	-0.12	9E-05	0.12	<u>0.02</u>	8E-04	0.01	4E-03	0.34	-0.36	0.01	-3E-03	3E-03	-0.22	0.25	0.14
ASI	0.04	-0.12	-0.01	0.14	4E-04	<u>0.05</u>	0.02	-0.02	0.38	-0.37	0.01	-4E-03	-0.01	-0.18	0.20	0.15
MOI	0.10	-0.18	-4E-04	0.17	7E-04	0.01	<u>0.18</u>	-0.06	0.20	-0.11	-0.02	4E-03	-0.01	-0.28	0.32	0.32**
RL	-0.13	0.05	1E-03	0.06	2E-04	-2E-03	-0.03	<u>0.39</u>	-0.30	-0.28	0.01	2E-03	5E-03	0.01	-0.01	-0.22*
SL	0.23	-0.16	-9E-04	0.03	3E-03	0.01	0.01	-0.05	<u>2.52</u>	-2.54	0.02	-0.02	3E-03	-0.13	0.14	0.07
TL	0.20	-0.15	-7E-04	0.04	3E-03	0.01	0.01	0.04	2.46	<u>-2.61</u>	0.02	-0.02	4E-03	-0.12	0.14	0.02
NTB	-0.04	0.04	-7E-04	-0.01	2E-03	3E-03	-0.03	0.03	0.26	-0.31	<u>0.17</u>	0.01	-5E-04	-0.25	0.29	0.15
NLAC	0.10	0.22	-5E-04	-0.40	-5E-04	-2E-03	5E-03	0.01	-0.32	0.32	0.01	<u>0.14</u>	-3E-04	0.23	-0.26	0.04
DCD	0.01	0.02	1E-03	-0.04	8E-04	-0.01	-0.02	0.02	0.11	-0.15	-1E-03	0.00	<u>0.08</u>	0.43	-0.49	-0.03
PopDen	-0.05	-0.08	-2E-03	0.17	4E-03	0.01	0.04	-3E-03	0.26	-0.26	0.03	-0.03	-0.03	<u>-1.22</u>	1.39	0.23*
NP	-0.05	-0.08	-2E-03	0.17	4E-03	0.01	0.04	-3E-03	0.26	-0.26	0.03	-0.03	-0.03	-1.22	<u>1.39</u>	0.23*

GYG = Grain yield; PH = plant height; EH = Ear height; AD = Days to anthesis; EPO = Ear position; EPP = Number of ear per plant; MOI = grain moisture content; NP = Number of plants harvested; ASI = Anthesis silking interval; RL = Root lodging; SL = Stem lodging; TL = Total plant lodging; NTB = Number of tassel branches; NLAC = Number of leaves above the cob; DCD = Number of days to 50% cob dryness and PopDen = Plant population density per plot. *, **, *** significantly different at $p \leq 0.05$, 0.01 and 0.001 probability levels, respectively.

Table 4.31. Phenotypic direct (underlined) and indirect effects and total path correlations coefficient analysis of grain yield component characters evaluated at UK1 under Tester B.

Traits	PH	EH	AD	EPO	EPP	ASI	MOI	RL	SL	TL	NTB	NLAC	DCD	PopDen	NP	GYG
PH	<u>-0.13</u>	0.06	6E-04	0.02	-0.03	-0.01	3E-03	-0.14	-2E-03	0.11	-0.01	0.01	0.02	0.01	-0.01	-0.10
EH	-0.06	<u>0.12</u>	9E-04	-0.04	-0.01	-0.02	-1E-03	-0.12	-0.02	0.10	-0.01	0.01	0.03	-1E-03	2E-03	-0.02
AD	-2E-03	3E-03	<u>0.04</u>	-6E-04	0.04	0.09	0.02	-0.06	0.03	0.03	-2E-03	-5E-03	0.02	0.01	-0.02	0.20*
EPO	0.05	0.08	4E-04	<u>-0.06</u>	0.01	-0.02	-0.01	-0.03	-0.02	0.03	-0.01	3E-03	3E-03	-3E-03	4E-03	0.04
EPP	0.02	-0.01	0.01	-3E-03	<u>0.28</u>	0.06	-0.03	-0.20	0.05	0.13	-2E-03	-0.01	-0.09	-0.04	0.05	0.21*
ASI	-0.01	0.01	-0.01	-4E-03	-0.06	<u>-0.26</u>	-4E-03	0.03	0.04	-0.05	0.01	0.01	-0.01	0.02	-0.03	-0.31**
MOI	-3E-03	-1E-03	0.01	2E-03	-0.06	0.01	<u>0.15</u>	0.03	-5E-03	-0.02	-1E-03	0.01	0.16	0.01	-0.01	0.27**
RL	0.02	-0.02	-3E-03	3E-03	-0.07	-0.01	0.01	<u>0.77</u>	-0.04	-0.57	-0.01	3E-03	0.09	0.01	-0.01	0.16
SL	7E-04	-0.01	4E-03	3E-03	0.04	-0.03	-2E-03	-0.09	<u>0.35</u>	-0.12	-0.01	0.01	-0.04	2E-03	-2E-03	0.11
TL	0.02	-0.02	-2E-03	4E-03	-0.06	-0.02	0.01	0.73	0.07	<u>-0.60</u>	-0.01	0.01	0.07	0.01	-0.01	0.20**
NTB	-0.01	0.02	9E-04	-3E-03	0.01	0.04	2E-03	0.10	0.03	-0.09	<u>-0.10</u>	0.00	0.01	4E-03	-5E-03	0.001
NLAC	-0.01	0.01	-3E-03	-3E-03	-0.03	-0.04	0.02	0.04	0.05	-0.06	-0.01	<u>6E-02</u>	0.04	0.03	-0.03	0.06
DCD	-0.01	0.01	3E-03	-6E-04	-0.07	0.01	0.07	0.19	-0.04	-0.13	-3E-03	0.01	<u>0.36</u>	0.01	-0.01	0.40***
PopDen	0.01	1E-03	-5E-03	-2E-03	0.08	0.05	-0.01	-0.06	-4E-03	0.05	3E-03	-0.01	-0.02	<u>-0.13</u>	0.16	0.11
NP	0.01	1E-03	-5E-03	-2E-03	0.08	0.05	-0.01	-0.06	-4E-03	0.05	3E-03	-0.01	-0.02	-0.13	<u>0.16</u>	0.11

GYG = Grain yield; PH = plant height; EH = Ear height; AD = Days to anthesis; EPO = Ear position; EPP = Number of ear per plant; MOI = grain moisture content; NP = Number of plants harvested; ASI = Anthesis silking interval; RL = Root lodging; SL = Stem lodging; TL = Total plant lodging; NTB = Number of tassel branches; NLAC = Number of leaves above the cob; DCD = Number of days to 50% cob dryness and PopDen = Plant population density per plot. *, **, *** significantly different at $p \leq 0.05$, 0.01 and 0.001 probability levels, respectively.

Table 4.32. Phenotypic direct (underlined) and indirect effects and total path correlations coefficient analysis of grain yield component characters evaluated at UK2 under Tester B.

Traits	PH	EH	AD	EPO	EPP	ASI	MOI	RL	SL	TL	NTB	NLAC	DCD	PopDen	NP	GYG
PH	<u>0.48</u>	-0.41	3E-04	-0.10	0.02	-4E-03	-0.01	0.06	0.01	-0.04	-0.01	-0.01	0.01	-0.03	0.02	-0.02
EH	0.21	<u>-0.94</u>	-1E-03	0.89	0.02	-1E-03	-4E-03	0.06	0.02	-0.07	2E-03	5E-03	-0.01	-0.03	0.02	0.18
AD	-0.01	-0.06	<u>-0.02</u>	0.07	0.02	-9E-04	0.02	-0.07	-0.01	0.05	0.01	-0.01	-1E-03	-0.01	3E-03	-0.01
EPO	-0.05	-0.80	-1E-03	<u>1.04</u>	0.02	1E-03	-1E-03	0.04	0.02	-0.06	0.01	0.01	-0.01	-0.01	0.01	0.21*
EPP	0.05	-0.15	-3E-03	0.12	<u>0.14</u>	-0.01	-2E-03	-0.02	-0.02	0.04	-0.01	-4E-03	0.01	-0.01	0.01	0.15
ASI	-0.06	0.04	5E-04	0.03	-0.03	<u>0.03</u>	0.01	0.05	0.04	-0.09	-3E-03	-0.04	0.01	0.02	-0.01	-5E-03
MOI	-0.05	0.07	-0.01	-0.02	-0.01	3E-03	<u>0.06</u>	-0.02	-0.03	0.06	-9E-04	0.00	-0.02	0.03	-0.02	0.05
RL	0.08	-0.16	3E-03	0.11	-0.01	4E-03	-4E-03	<u>0.38</u>	0.02	-0.15	-0.01	-0.02	-0.01	0.04	-0.02	0.25**
SL	0.02	-0.09	1E-03	0.10	-0.01	5E-03	-0.01	0.03	<u>0.26</u>	-0.49	-0.01	-0.03	0.01	-0.02	0.01	-0.23*
TL	0.03	-0.12	2E-03	0.12	-0.01	0.01	-0.01	0.11	0.25	<u>-0.51</u>	-0.01	-0.03	0.01	-0.01	3E-03	-0.17
NTB	0.05	0.02	2E-03	-0.08	0.02	1E-03	6E-04	0.02	0.02	-0.05	<u>-0.08</u>	-0.03	0.01	0.04	-0.02	-0.08
NLAC	-0.04	-0.03	7E-04	0.08	-3E-03	-0.01	-1E-03	-0.03	-0.05	0.10	0.01	<u>0.17</u>	-0.01	0.01	-0.01	0.20*
DCD	0.05	0.10	3E-04	-0.19	0.02	5E-03	-0.01	-0.03	0.03	-0.05	-0.01	-0.03	<u>0.07</u>	-0.01	4E-03	-0.05
PopDen	-0.12	0.22	6E-04	-0.11	-0.01	5E-03	0.01	0.11	-0.03	0.02	-0.03	0.01	-4E-03	<u>0.14</u>	-0.08	0.14
NP	-0.12	0.22	7E-04	-0.11	-0.01	5E-03	0.01	0.11	-0.03	0.02	-0.03	0.01	-4E-03	0.14	<u>-0.08</u>	0.14

GYG = Grain yield; PH = plant height; EH = Ear height; AD = Days to anthesis; EPO = Ear position; EPP = Number of ear per plant; MOI = grain moisture content; NP = Number of plants harvested; ASI = Anthesis silking interval; RL = Root lodging; SL = Stem lodging; TL = Total plant lodging; NTB = Number of tassel branches; NLAC = Number of leaves above the cob; DCD = Number of days to 50% cob dryness and PopDen = Plant population density per plot. *, **, *** significantly different at $p \leq 0.05$, 0.01 and 0.001 probability levels, respectively.

Table 4.33. Phenotypic direct (underlined) and indirect effects and total path correlations coefficient analysis of grain yield component characters evaluated at CED under Tester B.

Traits	PH	EH	AD	EPO	EPP	ASI	MOI	RL	SL	TL	NTB	NLAC	DCD	PopDen	NP	GYG
PH	<u>1.18</u>	-1.06	-8E-04	0.26	0.02	-4E-04	0.07	0.09	-1.28	1.19	0.04	-3E-03	-0.01	1E-03	1E-03	0.49***
EH	0.92	<u>-1.35</u>	-3E-03	0.77	0.02	-4E-04	0.07	1E-03	-0.91	0.89	0.04	-4E-03	-0.01	2E-03	2E-03	0.44***
AD	0.02	-0.10	<u>-0.04</u>	0.09	0.05	-2E-03	0.01	-0.05	0.44	-0.39	-0.06	-4E-03	3E-03	0.01	0.01	-0.01
EPO	0.33	-1.10	-4E-03	<u>0.95</u>	0.01	-3E-04	0.05	-0.08	-0.20	0.26	0.02	-4E-03	-6E-04	1E-03	1E-03	0.23*
EPP	0.09	-0.10	-0.01	0.04	<u>0.27</u>	-6E-04	-0.09	0.01	0.01	-0.02	-2E-03	2E-03	0.01	3E-03	3E-03	0.22*
ASI	-0.16	0.18	0.04	-0.08	-0.05	<u>3E-03</u>	0.03	0.07	-0.43	0.36	0.02	0.01	-3E-03	-0.01	-0.01	-0.03
MOI	0.18	-0.20	-7E-04	0.09	-0.05	2E-04	<u>0.47</u>	0.13	-0.13	0.02	-2E-03	0.01	-0.01	-0.01	-0.01	0.48***
RL	-0.15	3E-03	-3E-03	0.11	-0.01	-3E-04	-0.09	<u>-0.70</u>	0.19	0.38	-0.01	-1E-03	3E-03	-0.01	-0.01	-0.29**
SL	0.50	-0.41	0.01	0.06	-1E-03	4E-04	0.02	0.04	<u>-3.04</u>	2.94	0.01	-1E-03	-3E-03	0.01	0.01	0.15
TL	0.47	-0.40	0.01	0.08	-2E-03	4E-04	3E-03	-0.09	-2.98	<u>2.99</u>	0.01	-2E-03	-2E-03	0.01	0.01	0.09
NTB	0.26	-0.29	0.01	0.12	-3E-03	4E-04	-5E-03	0.04	-0.18	0.15	<u>0.18</u>	1E-03	-0.01	-2E-03	-2E-03	0.28**
NLAC	-0.12	0.19	0.01	-0.12	0.02	6E-04	0.10	0.03	0.15	-0.17	0.01	<u>0.03</u>	5E-03	-0.01	-0.01	0.10
DCD	0.16	-0.12	1E-03	0.01	-0.04	1E-04	0.05	0.02	-0.08	0.06	0.01	-1E-03	<u>-0.09</u>	0.01	0.01	-0.01
PopDen	0.03	-0.05	-0.01	0.03	0.02	-7E-04	-0.08	0.10	-0.50	0.40	-0.01	-0.01	-0.01	<u>0.05</u>	0.05	0.01
NP	0.03	-0.05	-0.01	0.03	0.02	-7E-04	-0.08	0.10	-0.50	0.40	-0.01	-0.01	-0.01	0.05	<u>0.05</u>	0.01

GYG = Grain yield; PH = plant height; EH = Ear height; AD = Days to anthesis; EPO = Ear position; EPP = Number of ear per plant; MOI = grain moisture content; NP = Number of plants harvested; ASI = Anthesis silking interval; RL = Root lodging; SL = Stem lodging; TL = Total plant lodging; NTB = Number of tassel branches; NLAC = Number of leaves above the cob; DCD = Number of days to 50% cob dryness and PopDen = Plant population density per plot. *, **, *** significantly different at $p \leq 0.05$, 0.01 and 0.001 probability levels, respectively.

4.11. Results summary

All the key findings that help to achieve the objectives of this study were presented categorically. The results revealed different responses in grain yield under both low and high plant population density and across testers as well as the combining abilities for different inbred lines and their hybrids across both Testers A and B. High yielding hybrids were selected and significant genetic advances were achieved especially under high plant population density. The secondary traits that indirectly and directly contributed to grain yield especially stem lodging, root lodging, number of the leaves above the cob and number of ears per plant were identified. Discussion of the results and the findings of this study are presented in the next chapter.

CHAPTER 5

General Discussion

5.1. Introduction

This chapter presents the discussion and interpretation of the study. It focuses on the analysis of variance for each site and across experimental sites, hybrid mean performances, genotype by environment interaction and genetic gains as well as the line by tester analysis and associated genetic parameters. The associations between secondary traits and grain yield under different plant population densities and genetic backgrounds are discussed. This section is limited to the objectives of this study and close attention is paid to traits that were more important in addressing the research problem.

5.2. Performance of hybrids under different plant population densities and testers

The study indicated that plant density effects were influential in determining grain yield of experimental hybrids, which were derived from crosses of temperate x tropical germplasm lines (Tables 4.1, 4.3, 4.5, 4.7, 4.9 and 4.11). Grain yield under low plant population density was higher due to limited interplant competition within the hybrids. In contrast, at high plant population density grain yield was low due to etiolation coming from the interplant competition within hybrids for sunlight and reduction in nutrients uptake. This is consistent with previous findings by Carvalho *et al.* (2010) and Severino *et al.* (2012) among others. Previously, Liu *et al.* (2004) and Luque *et al.* (2006) reported that plant population density is one of the most important cultural practices affecting critical agronomic attributes of the maize crop, such as lodging and grain yield. Stand density affects plant architecture, alters growth and development patterns, reduces sunlight capture, compromises water and nutrients uptake and also influences carbohydrate production and partitioning (Lambert and Johnson 1978; Casal, 1985; Mickelson *et al.*, 2002; Ku *et al.*, 2010; Tokatlidis *et al.*, 2011). In this regard, stand density is considered a major factor determining the degree of competition between plants (Sangakkara *et al.*, 2004; Abuzar *et al.*, 2011) and the resultant grain yield. The observed variation among hybrids under both low and high population density indicated that selection for both density dependent and density independent hybrids from the population under study would be feasible.

The results obtained from this study showed varied distribution of secondary traits due to the differences in plant population density. In line with this observation, Almeida and Sangoi (1996) and Sangoi (2001) reported that maize is more sensitive to changing plant population density as compared to other cereal crops. In most cases genotypes differ in grain yield across plant population densities and other environmental conditions such as soil fertility and moisture supply and cultural practises such as planting date and harvesting time (Gonzalo *et al.*, 2006; Yan *et al.*, 2011). Increasing plant population density increases leaf area index and therefore high amount of water is consumed per unit land area (Adel and Ali, 2015). Consequently, the use of high plant populations under rainfed environments may increase plant water stress and thus operate negatively together with other factors in reducing grain yield (Westgate *et al.*, 1997; Tokatlidis *et al.*, 2011; Adeniyani, 2014).

Consistent with the literature, the study indicated that there were variations among hybrids for secondary traits such as number of ears per plant under both densities. The number of ears per plant (ear prolificacy) is a parameter that is highly correlated to grain yield because grain yield is a function of number of ears, number of kernel rows, number of kernels per row and kernel weight. These are the primary yield components that require attention in order to enhance grain yield of maize hybrids. In this regard, grain yield and ears per plant are expected to vary across different plant population densities. When adequate nutrition is provided, the ears per plant increases as observed in this study where the ears per plant were higher under low plant population density but low under high plant population density. This trend indicated the high population density is a stress factor in maize hybrids. This is consistent with the literature. Previous studies indicated that increasing plant population density decreases the amount of resources available per plant (Abuzar *et al.*, 2011; Tollenaar and Lee, 2002) and thus reducing ear prolificacy (El-Lakany and Russell, 1971). In South Africa, maize is planted under both low and high plant population density in the stress prone western dry environment and the irrigation environments, respectively. This study therefore indicated that products that can be deployed to low population western environments where high level of ear prolificacy is desired would be found in the temperate x tropical breeding population.

Consistent with the literature the study indicated that plant population density stress affects standing ability and ultimately yield of maize hybrids, especially in mechanized agricultural,

systems, such as the large-scale commercial sector in South Africa. In mechanized agriculture all fallen plants or those with broken stems below the ear will not be picked by the combine harvester leading to serious grain yield losses. Therefore, plants with good standability are selected for a better yield. At optimum conditions in terms of plant population density, all plants receive adequate nutrition either from the soil or photosynthesis (Lopes *et al.*, 2008; Severino *et al.*, 2012). Thus, all the plants will grow with limited competition. However, when the plant population density is increased, competition is also increased resulting in etiolated plants with poor standing ability. High plant population density increases stem height and reduces stem diameter (Troyer, 1996), thus causing stem breakage, root lodging, and reduced number and size of ears which translate to reduced harvest index (Tollenaar and Lee, 2011) and ultimately grain yield. In this study, increased stem lodging due to etiolated plants and increased root lodging arising from poor root development explains why root lodging, stem lodging and total lodging, were non-significant at low plant population density, but hybrids were significantly different for these traits at high plant population density (Tables 4.1, 4.3, 4.9 and 4.11). The existence of significant differences among hybrids for stem lodging provided an opportunity to select hybrids that could withstand high density stress. Such hybrids would be deployed to irrigation schemes where farmers plant maize at high population densities exceeding 60000 plants per hectare. The study indicated that tester effects were influential on standing ability. The results showed clearly that Tester A was more susceptible to lodging than Tester B which displayed high level of resistance to lodging in its testcross progenies. The tester used were Tester 9 and DTAB32, which are resistant and susceptible to stem lodging, respectively. This explains why the progenies of Tester A showed significant differences in root lodging with a higher mean for lodging than those of Tester B; while the progenies for Tester B were better in terms of resistance to root lodging (Table 4.5 and Table 4.7). Tester A is susceptible to lodging and in this regard, at high plant population it is expected that most of the progenies of Tester A will be susceptible to lodging with some other genotypes being resistant to lodging depending on the characteristics of the inbred lines that complemented the weakness in that tester. Thus the line effects were also important for explaining lodging among the testcrosses. This explains why some hybrids derived from Tester A were either resistant or susceptible to root lodging. Presumably there was non-additive gene action such as dominance genes in some of the lines which were resistant to lodging when the tester parent A is susceptible. This therefore provided the opportunity to select lines that are resistant to lodging in hybrids.

The study showed different responses of the number of days to flowering and grain moisture content of hybrids to plant population density stress. The rank of hybrids for the number of days to flowering (that is days to anthesis and days to silking) and anthesis-silking interval do not change under related environments in terms of heat units (degree days) as observed at UK1 and UK2. The only changes that will be noticed is the actual number of days which is usually shorter at lower than high altitude but not the rank of hybrids. However, anthesis-silking interval tends to change under some stress conditions such as drought. In this study differences in days to anthesis reflected differences in the days to maturity. Anthesis date is highly heritability thus it is not expected to change under different environments. However, the high grain moisture content observed under low plant population density and the low grain moisture content noticed under high plant population density could be explained by the differences in cob characteristics under those conditions. As opposed to low plant population densities, cobs obtained under high plant population density are smaller and have reduced kernel length and kernel size, thus accelerated dryness (El-Lakany and Russell, 1971). In this study, grain moisture content, can be better used as an indicator of stress tolerance rather than an indicator for days to maturity.

The plant density effects were also reflected in plant architecture traits under low and high density experiments. Tassels of maize hybrids are heavier sinks of photo-assimilates and their sink strength increases with the size of the tassels which is reflected by tassel length and the number of tassel branches. An increased number of tassel branches can be detrimental to final grain yield because it stimulates apical dominance, induces barrenness and ultimately decreases the number of ears produced per plant and kernels set per ear (Sangoi and Salvador, 1998). Furthermore, it has been stated by Duncan (1984) and Edwards (2011) that at higher plant densities, shading of underlying leaves by large maize tassels can decrease light penetration within the canopy, therefore, resulting in reduced photosynthetic rates of lower leaves (Yan *et al.*, 2011). Grain filling in maize is contributed by number of leaves above the cob (a parameter related to leaf area index, a function of leaf number and leaf size). Days to 50 % cob dryness are related to the cob size, kernel size and kernel depth (El-Lakany and Russell, 1971), and all these parameters are increased under optimum conditions. Number of tassel branches, leaf area index (related to number of leaves above the cob) and days to 50 % cob dryness tend to increase under optimum conditions. Under stress conditions, tassel size

(related to number of tassel branches), leaf area index (related to leaf size and number of leaves above the cob) and number of days to 50 % cob dryness are greatly reduced. However, some genotypes are tolerant to these factors while others are not. This explains why the number of days to 50 % cob dryness, number of leaves above the cob and number of tassel branches were significantly different among hybrids under high plant population density alone. This implies that due attention should be paid to plant architecture in breeding hybrids for high population density environments and that these traits are less important for hybrids that will be deployed in low population density environments.

At high plant population densities, most genotypes will be etiolated thus the ear positions will be much higher compared to low plant population densities where there will be limited etiolation (Severino *et al.*, 2012). Plant height at high plant population density is expected to increase due to etiolation because of competition while at low plant population density plant height is greatly reduced (Soratto *et al.*, 2012). In this regard, plant height becomes a plastic trait that would be difficult to associate either with high or low plant population density.

The hybrids were different for agronomic performance and there is therefore an opportunity to perform selection of genotypes for advancement in the programme. The outstanding performance of the experimental hybrids over checks (Table 4.13 and Table 4.14) is a good indication of significant genetic improvements, because they out-performed variety (BG5285) which is a widely grown hybrid in South Africa. Otegui (1997) and İlker *et al.* (2011) asserted that intolerant genotypes to abiotic stresses under low plant population densities usually have higher grain yields and larger ears as compared to the tolerant hybrids, whereas the opposite is true at high plant population density. Similar results were further explained by stating that maize grain yield differs significantly under varying plant density levels due to differences in genetic potential (Liu *et al.*, 2004; Rossini, 2011).

Results indicated a progress in breeding for high population density stress tolerance and high yielding potential in the new maize hybrids 15XH215, 15XH214 and 15XH121 under this studied environment using tropical by temperate maize germplasm. Tropical germplasm lacks abiotic stress tolerance while temperate germplasm is resistant to abiotic stresses such root and stem lodging and has high grain yield potential. The best performing hybrids 15XH215, 15XH214 and 15XH121, had high number of ears per plant and were early maturing

qualifying them as suitable candidates for further testing in short season environments. This suggested that these selected hybrids exhibit progressive stability in different environments, which is a desirable attribute for the smallholder farming conditions, where management conditions are variable and the production seasons are increasingly becoming shorter. In South Africa, DAFF (2014) reported that there are farmers practising high, low and medium plant density culture. Thus, selected hybrids 15XH215 and 15XH214 under high plant population density stress can be recommended under irrigation since they showed potential to respond positively to improved environmental conditions. However, hybrids 15XH121 and 15XH65 specifically performed well under low plant population density conditions, thus, these hybrids can be recommended for use in western part of South Africa where low plant population density cultural practise is applied. In this regard, selected experimental hybrids 15XH215, 15XH214 and 15XH121 are considered to have wide adaptation ability and can be recommended for advancement in the following season. Further yield improvements would be achieved by improving plant population density stress tolerance through improving resistance to stem lodging and increasing ear prolificacy in both the lines and testers, especially Tester A.

The study reveals, genetic gains for yield which were obtained by breeding from temperate x tropical germplasm populations at the University of KwaZulu-Natal. Across all sites genetic gains of selected entries were realised over the mean of checks, thus the means of the commercial and advanced hybrids as well as the population mean were positive. This is encouraging and would go a long way in finding new hybrids that will be advanced in the programme. Under high plant population density (Table 4.17), there was 26 % genetic gains of maize grain yield which was displayed by the top five high-yielding experimental hybrids over means of the commercial and advanced hybrids. The hybrids, 15XH214, 15XH215, 15XH115, 15XH212 and 15XH168 are recommended for proceed to advancement the following season. Under low plant population density (Table 4.16), the genetic gain of 14 % for grain yield for the top five high-yielding experimental hybrids (15XH121, 15XH92, 15XH81, 15XH50 and 15XH119) was observed which then suggest that the current study revealed high genetic variability of traits among hybrids, which can be exploited to obtain further breeding gains.

Positive genetic gains were observed for secondary traits that are associated with yield in the temperate x tropical germplasm populations. Genetic gains were also observed with respect

to early physiological maturity of maize hybrids which could be inferred from the low grain moisture data of hybrids at harvest. The earliness of maize can be measured using physiological maturity where long-season hybrids reach maturity in 140-150 days, medium-season hybrids in 130-145 and short season hybrids in 115-130 days (Smith, 2006; Gasura *et al.*, 2014) depending on the altitude. In the current study, hybrids which attained days to silking and anthesis less than those of PAN6Q-345 CB, between 70 and 71, under Tester B and 68 to 70 under Tester A, had grain moisture content below 12.5%, and were considered to be early maturing. These hybrids include 10HDTX11 and the rest which poorly performed in terms of grain yield (Appendix C). Unfortunately the earlier the hybrid, the low the grain yield potential. This proves to be the main challenge of breeding for early-maturing maize which is the negative correlation between yield and early physiological maturity. Lastly earliness can be measured using grain moisture. With regards to the realised genetic gains of selected hybrids for the numbers of ears per plant over the population mean were positive, with about 4 % and 8% genetic gains under low and high plant population density, respectively. This shows that selection has the potential to improve grain yield by exploiting temperate x tropical populations under both low and high population density conditions.

The hybrids displayed genotype x management interaction effects and the study was powerful in discriminating hybrids according to their behavior under the low and high population density stress. This observation enabled inferences to be made about the G x E effects on hybrid performance. Differences in ranking of genotypes under high and low plant population density implied differential yield performance among the maize genotypes as a result of the significant cross over genotype by environment interaction (Frashadfar *et al.*, 2012). The genotype by environment interaction (G x E) may be managed by using specific cultivars for each environment or exploited by using cultivars with wide adaptability. In this study entries 79 (15XH121), 179 (15XH215) and 180 (15XH214) were the most ideal genotypes across stress levels and sites (high mean grain yield) and highly stable under Tester A and B. These hybrids could also have the greatest commercial success because they showed the high stability across stress levels (Abay *et al.*, 2009). Grain yield stability is a highly heritable trait (Yan and Kang, 2003) and most genotypes that tolerate stress have been associated with high grain yield stability. The ideal genotype basically has the highest average value of all genotypes and is absolutely stable in that it exhibits less genotype by environment interaction hence broad adaptation (Yan and Kang, 2003; Sharma *et al.*, 2010; Akcura *et al.*, 2011).

Rossini *et al.* (2011) defined plant population density tolerance in plants as the extent to which the crop maintains high yield level when plant population density increases above average levels. The capacity of the new testcross hybrids to produce higher grain yield may be attributed to their ability to adapt to the biotic or abiotic stress conditions (Betran *et al.*, 2003a; Carena *et al.*, 2010) and thus better stability.

The components contributing to stability have been dissected in many studies. Yan and Kang (2003) reported that a stable genotype is associated with a combination of genes that allow that genotype to perform under different conditions. A cultivar is said to be successful if it is stable and possesses high grain yield potential over a wide range of environments (Eberhart and Russel, 1969; Wricke and Weber, 1986; Becker and Leon, 1988; Fasoula and Fasoula, 2002). Indeed, in this situation, the stable genotypes had genes that allowed them to have high yield under low stress conditions while performing above average under stress conditions. In this regard, the data from the current study (Tables 4.2, 4.4, 4.6, 4.8, 4.10 and 4.12 and Figures 4.9 to 4.12) showed that stable genotypes were associated with resistance to stem lodging and root lodging as well as negative ASI. Yan *et al.* (2011) reported that future gains in yield can be made by improving maize for resistance to high plant population density stress through resistance to stem lodging. In line with this idea, Duvick (2005b) and Van Roekel and Coulter (2011) reported that maize grain yield had increased since the 1930s due to the adaptability to higher planting densities. Sangoi *et al.* (2002) observed that the highest plant population in the study resulted in the highest grain yield at three locations evaluated in Indiana. Similarly, the current study showed high yield among the stable varieties to be associated with increased plant density. This indicates that productivity of hybrids derived from the tropical and temperate germplasm genetic backgrounds can be enhanced by selecting for population yield under high density stress rather than focusing on high single plant yield which is an adaptation to low density stress.

Some hybrids had high stress tolerance indices, a parameter which shows the relationship in performance of yield under stress condition and non-stress. The yield gains observed among the selected hybrids could be attributed to their yield stability due to their high stress tolerance index due to resistance to stem lodging and high number of ears per plant. These hybrids have several desirable attributes that give them high yield and stability better than the existing commercial hybrids. Indeed most of these hybrids were derived from the Tester B

which is associated with a huge contribution to stress resistance including resistance to lodging. This agrees with reports in the literature with respect to temperate maize germplasm. Past genetic gains in modern hybrids were associated with tolerance to stress (Tollenaar and Wu, 1999; Tokatlidis and Koutroubas, 2004; Duvick, 2005b) and that include tolerance to high plant population density as reported by many researchers (Rossman and Cook, 1966; Karlen *et al.*, 1987; Almeida and Sangoi, 1996; Porter *et al.*, 1997; Johnson *et al.*, 1998; Farnham, 2001; Rossini *et al.*, 2011; Yan *et al.*, 2011; Zamir *et al.*, 2011; Ray *et al.*, 2012). Genetic advance is the expected genetic progress resulting from selection of the best-performing genotypes for a given character. The genetic gain that can be obtained for a particular trait through selection is the product of its heritability, phenotypic standard deviation and selection intensity (Zinaw *et al.*, 2013). The grain yield of hybrids grown at low density stress does not change compared to high density conditions (Duvick and Smith, 2004; Duvick, 2005b). Thus, the exponential and continuous gains in maize grain yield observed over the years can be attributed to tolerance to high plant densities rather than an increase in yield per plant (Duvick, 1984; Tollenaar *et al.*, 1989; Troyer, 1996; Duvick, 1999; 2005a). Currently, it can be concluded that the highest density (74 000 plants per ha) is still below the potential maximum yield densities because some plants could still produce more than one cob, an indicator of reduced stress. This indicated that the hybrids could still produce high yield at higher density levels. Future studies should test these hybrids at 80000 plants per hectare.

5.3. Genetic parameters of maize hybrids under low and high plant population density stress

The moderate genotypic coefficient of variation (GCV) and narrow sense heritability values estimated (Table 4.18) suggest that it is possible to select desirable genotypes from the germplasm that was evaluated. Higher value of genotypic coefficient of variation (GCV) than phenotypic coefficient of variation (PCV) would be desirable in breeding programmes since the genetic variance component will be high and hence high repeatability and selection gains. The heritability estimates for different traits varies with the population and environment studied (Dixit *et al.*, 2013; Mostafavi *et al.*, 2013). In this study, estimates of heritability for secondary traits were higher than for grain yield thus calling for a need to identify the traits which could be targeted for improving the grain yield of the hybrids based

on indirect selection in the temperate x tropical population under study. Indirect selection is suitable for grain yield when there are traits of high heritability, easy to measure but have high correlation with grain yield (Gasura *et al.*, 2014).

5.4. Combining ability for grain yield and related agronomic traits under low and high plant population density stress

For all the traits GCA effects were greater than 50 % under both low and high plant population density and across the environments. This showed that additive gene action was more important than dominance gene action, hence selection of the parents with desirable GCA effects for essential traits will be effective in developing suitable hybrids. Under low plant population density, grain yield, number of ears per plant, grain moisture content and number of tassel branches had positive GCA effects while stem lodging had a negative GCA effect among the high yielding selected experimental hybrids. However, under high plant population density number of leaves above the cob had a negative GCA effect in high yielding and selected experimental hybrids which could mean that this trait needs further improvement to enhance maize grain yield under stress conditions. Stem lodging is a major challenge of yield reduction in maize hybrids under high plant population density stress. In breeding for high plant population density, selection for low stem lodging must be taken as a major factor.

Tollenaar and Lee (2011) stated that maize grain yield drops when plant population density is increased above the ideal plant population density as a result of decline in the harvest index and increased stem lodging. Consequently, it will be a requirement to select inbred lines that have positive GCA effects for grain yield and negative GCA effects for lodging. Such lines were identified in this study as 179 and 180. These inbred lines were complimented by Tester DTAB32 that has been shown to have resistance to lodging and other abiotic stresses (Mafu, 2013). The hybrids from inbred line 179 produced high yield and had less lodging when combined with either Tester A or B. This suggested that this line has desirable GCAs for several desired traits in this study that contributed to high maize grain yield. In this study, the hybrids with tolerance to high plant population density stress were identified. The identification of the best genotypes based on the increase of plant population density stress

tolerance was achieved through selection of the hybrids which possessed good standability, yield stability and high grain yielding ability.

Identification of suitable testers in breeding is a critical component of a breeding program (Pswarayi and Vivek, 2008). Desirable testers have been reported to possess parameters that include a good performance under diverse environmental conditions, reveals large variation between testcrosses, has desirable combining ability, has high and significant correlation with average of the testers used, and has acceptable *per se* performance (Castellanos *et al.*, 1998). Such features have been satisfied by Tester B in this study. This strategy is slightly different from the one that is commonly used in breeding maize under optimum plant population conditions. In such situations, emphasis has been given on the selection for high source efficiency such as the number of leaves above the cob, days to anthesis and plant height. However, in the present situation, selection must be emphasized on increasing the grain yield of hybrids though selection for high number of ears per plant and resistance to lodging under stress conditions. Although number of ears per plant tends to decrease under stress conditions (Figure 4.6), there is need to select genotypes that maintain high number of ears per plant under stress condition. Ears per plant has been used as a secondary trait for selection under stress in drought breeding (Derera *et al.*, 2008a; Banziger *et al.*, 2010; Weber *et al.*, 2012) and also under low nitrogen conditions (Badu-Apraku *et al.*, 2011) as well as under *Striga* infestation (Badu-Apraku *et al.*, 2012).

5.5. Relationships of grain yield and related traits under different plant densities and testers

Direct and indirect effects from this study were ranked similar to those of Lenka and Mishra (1973), as follows: 0.00 to 0.09 = negligible, 0.10 to 0.19 = low, 0.20 to 0.29 = moderate and >0.30 = high path coefficients. Traits such as number of days to 50 % cob dryness, total plant lodging, ear height, ear position, plant height, days to anthesis, anthesis-silking interval, number of plants per row and plant population density were not associated with grain yield, suggesting that they are not ideal candidates to utilize during breeding for stress tolerance in this population of temperate x tropical germplasm lines. Directional selection from plant breeding overtime has resulted in the reduction of genetic variability for some important

traits. Lee and Tollenaar (2007) noted that not all traits are useful in the current and future breeding of maize because of lack of enough variability.

Number of ears per plant and number of tassel branches were highly correlated with grain yield and had huge positive direct effects on grain yield under low plant population density. Under low plant population density, number of tassel branches and grain moisture content had high correlation with yield with a huge positive direct effect on grain yield. Number of ears per plant and number of tassel branches are parameters associated with high nutrition which is associated with low plant population density. This explains why number of ears per plant and number of tassel branches were high under low plant population density. However, in breeding for increased grain yield under stress it will be ideal to improve the number of ears per plant while reducing the number of tassel branches. Mostafavi *et al.* (2013) stated ear prolificacy to be highly significant and to have a positive correlation with grain yield in maize. Grain yield is the key trait in maize-breeding programmes (Peng *et al.*, 2011). However, for it to be improved to a greater extent, the contribution of other allied traits, such as the number of ears per plant must be considered. Under low plant population density, number of tassel branches were more than number of tassel branches under high plant population density which then explains the reason why there was high maize grain yield under low plant population density because tassels are normally strong sinks in maize nutrition due to their apical dominance and if the number of tassel branches (NTB) increase they may also result in reduced grain yield. Normally only adequate (not excess) pollen grains are required in pollination. Sangoi (2001) asserted that genotypes with many tassel branches are likely to have reduced grain yield due to suppression of ear development and high assimilate expenditure for head maintenance. Under low plant population density grain moisture content had a positive direct effect (0.23) on grain yield (Table 4.25). However, it had an indirect effect (4.9E-03), high plant population density since high grain moisture content at harvesting maturity is associated with longer days to maturity (Table 4.26).

Maize that takes long to reach maturity (late season maize) is generally higher yielding because it has taller plants, higher leaf area index and have longer leaf area duration thus resulting in the accumulation of more dry matter during the growing season. However, at high plant population density, the plants become etiolated and such weak plants can only support smaller cobs that will be having relatively smaller grains. When the cobs and grains

are smaller, they tend to dry much faster, thus contributing to the non-significant relationship between grain yield and moisture content. El-Shouny *et al.* (2005) indicated that primary selection for traits which are positively correlated with yield, such as plant and ear height, ear length and girth, contributes to high single plant yield potential in maize. In South Africa, moisture content is largely used to group maize into different maturity groups as well as in maize grading at the market. Maize grains with >12.5 % moisture content is rejected by the grain marketing board. Number of leaves above the cob is one of the most important traits in maize grain filling. Under both low and high plant population density, number of leaves above the cob was highly correlated with grain yield with a positive direct effects on maize grain yield (Table 4.25 and Table 4.26) suggesting the importance of these trait under this conditions. In line with the study by Alvim *et al.* (2011) which found that grain filling is only affected by the leaves above the cob and leaves located above the cob provide most of the photoassimilates necessary for grain filling in the ear. Thus, the more and the bigger the leaves above the cob the better the efficiency of grain filling. Under stress conditions the leaves are reduced and genotypes that maintain relatively more and bigger leaves above the cob will be better in terms of the efficiency of grain filling. Because of etiolation due to high plant population density, the plants that produce more leaves and relatively bigger leaves above the ear will withstand plant to plant competition for sunlight. In breeding for maize with better yield under stress it will be logical to select genotypes with more and bigger leaves above the ear. Furthermore, selection of plants that have more of erectophile type of leaves is desirable since this can reduce mutual shading but rather increase light penetration into the canopy (Brekke *et al.*, 2011; Edwards, 2011; Mock and Pearce, 1975). Hammer *et al.* (2009), showed that erectophile leaves reduce canopy light extinction coefficient, increased light penetration to lower leaves, and enabled more uniform photosynthetic rates within the canopy. Tester B contributed more to NLAC, and this tester is well known for its wide adaptability across different production conditions.

In order to improve gains from selection, it is desirable to have positive significant correlations between yield and agronomic characteristics that contribute towards higher yield. Stem lodging and root lodging had indirect effects on grain yield because this trait reduces the number of plants per hectare and bareness (reduced EPP) and thus grain yield. Tokatlidis and Koutroubas (2004) observed the adverse effects of high plant population densities on maize grain yield stability because of high incidence of root and stem lodging and increased

barrenness. Grain yield is mainly a function of the number of plants per hectare, number of cobs per plant, number of kernel rows and kernels per row together with 1000 kernel weight. The purpose of increasing plant population density is to improve of the number of plants per hectare and thus grain yield. However, lodging has a negative effect of this approach because it reduces the number of plants per hectare. If lodging occurs before grain filling the, lodged plants suffer shading and may not produce grains at all. If lodging occurs after grain filling, the fallen plants may not be harvested by the combine harvester. In general, under high plant population density grain yield was low as compared to low plant population density for certain hybrids. Stem lodging had indirect effects on grain yield under high plant population density within and across testers as a result of the effects of Tester A (Tables 4.26, 4.29 and 4.32) which explains the maize grain yield reduction under stress condition, similarly, the study conducted by Tollenaar and Wu (1997) and Hashemi *et al.* (2005) also stated that maize grain yield declines when plant density is increased beyond the optimum plant density primarily because of decline in the harvest index and increased stem lodging. Maize grain yield decreases as a response to decreasing light and other environmental resources available to each plant in the area (Widdicombe and Thelen, 2002). Reduction in grain yield is due mainly to fewer cobs or barrenness, fewer grains per cob, lower grain weight, or a combination of all these components (Ahmed *et al.*, 2015). However, our results have shown that it is possible to improve maize grain yield through increasing plant population density per unit area. Thus future improvement of maize yield will primarily occur through tolerance to higher planting density (Ci *et al.*, 2011; Tollenaar and Lee, 2002; Duvick, 2005a) and this involves improving the maize for tolerance to lodging and increased EPP under high density stress. In most cases, farmers in sub-Saharan Africa plant more plants per unit areas and they get less yield because the current hybrids on the market are not resistant to high plant population density stress. Thus promotion of the hybrids that are tolerant to stress, will result in increased grain yield per unit area.

Under high plant population density, occurrence of stem lodging was high as compared to the low plant population density environment (Figure 4.3) which suggests that the two conditions were different. Across the environments, high total plant lodging (Table 4.4) was contributed largely by high root lodging which was observed under low plant population density (Table 4.2). The effects of environments that include variability in soil moisture content and drought must be considered when determining the optimum number of plants per unit area.

Consequently it is extremely important to consider water supply to define the optimum plant population for any particular region and cropping system (Van Roekel and Coulter, 2011). Stem lodging under high plant population density had high correlation with yield with a huge positive indirect effects of (0.194) on grain yield at $P < 0.05$ (Table 4.26). However, it was non-significant under low plant population density (Table 4.25). In this regards, high plant population densities may not be practical in drier regions where the number of plants have to be reduced in order to cater for soil water competition. Severino *et al.* (2012) and Soratto *et al.* (2012) indicated that increasing plant population density increases leaf area index and the photosynthetic capacity of a canopy (Brekke *et al.*, 2011; Edwards, 2011). Selection of secondary traits has been helped by statistical analyses which can compute genetic correlations and carry out path coefficient analysis (Kashiani and Saleh, 2010). Knowledge of the association of yield components and their traits as well as association between the yield components themselves, can improve selection efficiency (Raghu *et al.*, 2011) based on indirect selection using a trait that is easy to select but highly correlated with grain yield. In this study, the selection efficiency for grain yield based on EPP and stem lodging could be high because of the easy in selecting for number of ears per plant (EPP) and stem lodging, high heritability of these traits and their high correlation with grain yield. The use of indirect traits in selection has improved useful for selection of grain yield under stress conditions (Banziger *et al.*, 2004; Derera *et al.*, 2008b; Badu-Apraku, 2008) and non-stress conditions (Gasura *et al.*, 2014). There is great potential of increasing the plant density and hence grain yield above the levels reported in this study based on the careful use indirect selection traits such as ears per plant and resistance to stem lodging.

5.6. Conclusions

In this study, hybrids (and their inbred lines) that performed better under low and high plant population density stress were selected. There were three experimental hybrids which performed better than the commercial hybrid BG5285, these hybrids are; 15XH214, 15XH215 and 15XH121. This means that these experimental hybrids have potential to be recommended in the agro-ecological zones represented by low and high plant population density in South Africa where hybrid BG5285, and is currently grown. The traits associated with high yield under high plant population density were the number of ears per plant, number of the leaves above the cob and stem lodging. Thus, increasing number of ears per plant and number of leaves above the cob as well as reducing stem lodging per unit area will

result in increased maize grain yield. In contrast, under low plant population density across different genetic backgrounds traits associated with high yield were identified as the number of tassel branches and grain moisture content. Thus, reducing the number of tassel branches in maize and increasing grain moisture content promote high maize grain yield since maize large tassels suppresses ear development and moisture content at harvest maturity is associated with longer days to maturity which makes the late maturing maize to be generally higher yielding because it has taller plants, higher leaf area index and have longer leaf area duration which tend to results in the accumulation of more dry matter during the growing season. The overall conclusions for the study, implications and recommendations for future breeding programs are drawn in chapter 6.

CHAPTER 6

Conclusions, Implications and Recommendations

6.1. Introduction

This chapter presents conclusions and recommendations to fulfil objectives of this study as laid out in Chapter 1. This chapter is based on the findings presented in the general results and discussion in chapter 4 and 5, respectively. It also outlines the research by summarizing the main objectives, findings, challenges and implications of the study for breeding and accentuating the major outcomes. The implications of the study findings and recommendations for the future studies are also discussed briefly. Preceding chapters have highlighted the effect of low and high plant population density stress on maize yield. Introgression of favorable genes of interest that are tolerance to density stress into adapted germplasm was therefore pursued in order to enhance grain yield by developing lodging resistant maize hybrids with high number of ears per plant.

6.2. The findings from the study in line with the specific objectives are outlined as follows:

1. Determining the stability and genetic gains for breeding new hybrids from temperate x tropical germplasm, under low and high plant population density stress.

Hybrid 15XH121 under Tester A and hybrids 15XH214 and 15XH215 under Tester B were high yielding and stable across low and high plant population density stress. The hybrids yielded above the commercial check hybrids BG5285 and PAN6Q-345 CB. The high genetic gains and stress tolerance indices of these hybrids over the checks were related to resistance to stem lodging and increased number of ears per plant. Most of these hybrids were derived from crosses of the new lines with the Tester B which is associated with a huge contribution to stress resistance including lodging. Hybrids 15XH65, 15XH110 and 15XH135 were specifically adapted to low plant population density and 15XH150, 15XH157 and 15XH176 were specifically adapted to high plant population density stress environment. These hybrids

will be advanced in the programme and will be deployed appropriately and in accordance with their environment of adaptation.

2. Determining the combining ability between the new lines derived from temperate x tropical germplasm background under low and high population density stress

Inbred lines with resistance to stem lodging and high ear prolificacy were identified as, 179 and 180 under Tester B and 79 under Tester A. Under low plant population density, a positive GCA for grain yield, number of ears per plant, grain moisture content and number of tassel branches and a negative GCA for stem lodging in high yielding selected experimental hybrids was achieved, which is a good indication of the selection criteria for maize grain yield potential hybrid with good combining ability. However, under high plant population density number of leaves above the cob had a negative GCA for high yielding selected experimental hybrids which could mean that this trait needs further improvement to enhance maize grain yield under stress conditions. In producing better hybrids, such inbred lines were complimented by Tester B that has been shown to have resistance to lodging and other abiotic stresses. The identification of the best genotypes based on the increase of plant population density stress tolerance was achieved through the selection of hybrids which possessed good standability, yield stability and high grain yielding ability.

3. To determine the contribution of secondary traits to grain yield of maize hybrids under both low and high plant population density

Number of ears per plant and stem lodging were highly correlated with grain yield and had huge positive direct effects on grain yield under high plant population density. Under low plant population density, number of tassel branches and grain moisture content had high correlation with yield with a huge positive direct effect on grain yield. Across both environments, number of leaves above the cob was highly correlated with grain yield and had a positive direct effect on maize grain yield. These traits did not only have huge correlations with grain yield but have high narrow sense heritability and are easy to select for, thus making them ideal candidates for indirect selection for improved grain yield under high plant population density stress.

6.3. Conclusions and implications for breeding and way forward

The foregoing indicates that high plant population density reduces the number of ears per plant and increases stem lodging thus reducing grain yield potential of the hybrids derived from tropical x temperate germplasm. Development of ideal breeding strategies that can improve grain yield under high plant population density is desired. High yielding and stable hybrids, such as 15XH214, 15XH215 and 15XH121 were resistant to lodging and had higher ear prolificacy, and thus performed better in terms of grain yield under both low and high plant population density conditions across different testers used. The high genetic gains and stress tolerance indices of these hybrids made them better performers over the commercial check hybrids under high plant population density stress. Inbred lines 179 and 180 together with Tester B contributed resistance to stem lodging and high yielding ability. At high plant population density yield was correlated to stem lodging and ears per plant. These traits can be used for indirect selection of the best hybrids in terms of high grain yielding potential. The future gains in grain yield of these hybrids derived from temperate x tropical maize germplasm can be achieved by exploiting direct selection for resistance to stem lodging and increased number of ears per plant under high plant density conditions which represent the production culture in South Africa.

6.4. Recommendations

The high yielding and stable genotypes from this study including, hybrid 15XH215, 15XH214 and 15XH121, must be advanced and earmarked for release targeting high density stress environments. Furthermore, the association of grain yield and two traits (stem lodging and ears per plant) under high density stress must be confirmed under other abiotic stress environments such as drought stress. These two traits must be highly considered for direct selection for grain yield of hybrids from the temperate x tropical germplasm under high plant population density stress.

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APPENDICES

Appendix A. List of evaluated hybrids formulated based on Tester A (Tester 9)

Entry	Stock	Name	Origin
1	HIGH DENSITY HYBRIDS-1	15XH43	MAKATHINI-14MAK1-1/14MAK1-2
2	HIGH DENSITY HYBRIDS-2	15XH44	MAKATHINI-14MAK1-3/14MAK1-4
3	HIGH DENSITY HYBRIDS-3	15XH45	MAKATHINI-14MAK1-5/14MAK1-6
4	HIGH DENSITY HYBRIDS-4	15XH46	MAKATHINI-14MAK1-7/14MAK1-8
5	HIGH DENSITY HYBRIDS-5	15XH47	MAKATHINI-14MAK1-9/14MAK1-10
6	HIGH DENSITY HYBRIDS-6	15XH48	MAKATHINI-14MAK1-11/14MAK1-12
7	HIGH DENSITY HYBRIDS-7	15XH49	MAKATHINI-14MAK1-13/14MAK1-14
8	HIGH DENSITY HYBRIDS-8	15XH50	MAKATHINI-14MAK1-15/14MAK1-16
9	HIGH DENSITY HYBRIDS-9	15XH51	MAKATHINI-14MAK1-17/14MAK1-18
10	HIGH DENSITY HYBRIDS-10	15XH52	MAKATHINI-14MAK1-19/14MAK1-20
11	HIGH DENSITY HYBRIDS-11	15XH53	MAKATHINI-14MAK1-21/14MAK1-22
12	HIGH DENSITY HYBRIDS-12	15XH54	MAKATHINI-14MAK1-23/14MAK1-24
13	HIGH DENSITY HYBRIDS-14	15XH55	MAKATHINI-14MAK1-27/14MAK1-28
14	HIGH DENSITY HYBRIDS-15	15XH56	MAKATHINI-14MAK1-29/14MAK1-30
15	HIGH DENSITY HYBRIDS-16	15XH57	MAKATHINI-14MAK1-31/14MAK1-32
16	HIGH DENSITY HYBRIDS-17	15XH58	MAKATHINI-14MAK1-33/14MAK1-34
17	HIGH DENSITY HYBRIDS-18	15XH59	MAKATHINI-14MAK1-35/14MAK1-36
18	HIGH DENSITY HYBRIDS-19	15XH60	MAKATHINI-14MAK1-37/14MAK1-38
19	HIGH DENSITY HYBRIDS-21	15XH61	MAKATHINI-14MAK1-41/14MAK1-42
20	HIGH DENSITY HYBRIDS-30	15XH62	MAKATHINI-14MAK1-59/14MAK1-60
21	HIGH DENSITY HYBRIDS-31	15XH63	MAKATHINI-14MAK1-61/14MAK1-62
22	HIGH DENSITY HYBRIDS-32	15XH64	MAKATHINI-14MAK1-63/14MAK1-64
23	HIGH DENSITY HYBRIDS-33	15XH65	MAKATHINI-14MAK1-65/14MAK1-66
24	HIGH DENSITY HYBRIDS-34	15XH66	MAKATHINI-14MAK1-67/14MAK1-68
25	HIGH DENSITY HYBRIDS-35	15XH67	MAKATHINI-14MAK1-69/14MAK1-70
26	HIGH DENSITY HYBRIDS-36	15XH68	MAKATHINI-14MAK1-71/14MAK1-72
27	HIGH DENSITY HYBRIDS-38	15XH69	MAKATHINI-14MAK1-75/14MAK1-76
28	HIGH DENSITY HYBRIDS-39	15XH70	MAKATHINI-14MAK1-77/14MAK1-78
29	HIGH DENSITY HYBRIDS-40	15XH71	MAKATHINI-14MAK1-79/14MAK1-80
30	HIGH DENSITY HYBRIDS-41	15XH72	MAKATHINI-14MAK1-81/14MAK1-82
31	HIGH DENSITY HYBRIDS-42	15XH73	MAKATHINI-14MAK1-83/14MAK1-84
32	HIGH DENSITY HYBRIDS-43	15XH74	MAKATHINI-14MAK1-85/14MAK1-86
33	HIGH DENSITY HYBRIDS-44	15XH75	MAKATHINI-14MAK1-87/14MAK1-88
34	HIGH DENSITY HYBRIDS-45	15XH76	MAKATHINI-14MAK1-89/14MAK1-90
35	HIGH DENSITY HYBRIDS-46	15XH77	MAKATHINI-14MAK1-91/14MAK1-92
36	HIGH DENSITY HYBRIDS-47	15XH78	MAKATHINI-14MAK1-93/14MAK1-94
37	HIGH DENSITY HYBRIDS-48	15XH79	MAKATHINI-14MAK1-95/14MAK1-96
38	HIGH DENSITY HYBRIDS-49	15XH80	MAKATHINI-14MAK1-97/14MAK1-98

Entry	Stock	Name	Origin
39	HIGH DENSITY HYBRIDS-50	15XH81	MAKATHINI-14MAK1-99/14MAK1-100
40	HIGH DENSITY HYBRIDS-51	15XH82	MAKATHINI-14MAK1-101/14MAK1-102
41	HIGH DENSITY HYBRIDS-52	15XH83	MAKATHINI-14MAK1-103/14MAK1-104
42	HIGH DENSITY HYBRIDS-53	15XH84	MAKATHINI-14MAK1-105/14MAK1-106
43	HIGH DENSITY HYBRIDS-54	15XH85	MAKATHINI-14MAK1-107/14MAK1-108
44	HIGH DENSITY HYBRIDS-55	15XH86	MAKATHINI-14MAK1-109/14MAK1-110
45	HIGH DENSITY HYBRIDS-56	15XH87	MAKATHINI-14MAK1-111/14MAK1-112
46	HIGH DENSITY HYBRIDS-57	15XH88	MAKATHINI-14MAK1-113/14MAK1-114
47	HIGH DENSITY HYBRIDS-58	15XH89	MAKATHINI-14MAK1-115/14MAK1-116
48	HIGH DENSITY HYBRIDS-59	15XH90	MAKATHINI-14MAK1-117/14MAK1-118
49	HIGH DENSITY HYBRIDS-60	15XH91	MAKATHINI-14MAK1-119/14MAK1-120
50	HIGH DENSITY HYBRIDS-61	15XH92	MAKATHINI-14MAK1-121/14MAK1-122
51	HIGH DENSITY HYBRIDS-62	15XH93	MAKATHINI-14MAK1-123/14MAK1-124
52	HIGH DENSITY HYBRIDS-63	15XH94	MAKATHINI-14MAK1-125/14MAK1-126
53	HIGH DENSITY HYBRIDS-64	15XH95	MAKATHINI-14MAK1-127/14MAK1-128
54	HIGH DENSITY HYBRIDS-65	15XH96	MAKATHINI-14MAK1-129/14MAK1-130
55	HIGH DENSITY HYBRIDS-66	15XH97	MAKATHINI-14MAK1-131/14MAK1-132
56	HIGH DENSITY HYBRIDS-67	15XH98	MAKATHINI-14MAK1-133/14MAK1-134
57	HIGH DENSITY HYBRIDS-68	15XH99	MAKATHINI-14MAK1-135/14MAK1-136
58	HIGH DENSITY HYBRIDS-69	15XH100	MAKATHINI-14MAK1-137/14MAK1-138
59	HIGH DENSITY HYBRIDS-70	15XH101	MAKATHINI-14MAK1-139/14MAK1-140
60	HIGH DENSITY HYBRIDS-71	15XH102	MAKATHINI-14MAK1-141/14MAK1-142
61	HIGH DENSITY HYBRIDS-72	15XH103	MAKATHINI-14MAK1-143/14MAK1-144
62	HIGH DENSITY HYBRIDS-73	15XH104	MAKATHINI-14MAK1-145/14MAK1-146
63	HIGH DENSITY HYBRIDS-74	15XH105	MAKATHINI-14MAK1-147/14MAK1-148
64	HIGH DENSITY HYBRIDS-75	15XH106	MAKATHINI-14MAK1-149/14MAK1-150
65	HIGH DENSITY HYBRIDS-76	15XH107	MAKATHINI-14MAK1-151/14MAK1-152
66	HIGH DENSITY HYBRIDS-77	15XH108	MAKATHINI-14MAK1-153/14MAK1-154
67	HIGH DENSITY HYBRIDS-78	15XH109	MAKATHINI-14MAK1-155/14MAK1-156
68	HIGH DENSITY HYBRIDS-79	15XH110	MAKATHINI-14MAK1-157/14MAK1-158
69	HIGH DENSITY HYBRIDS-80	15XH111	MAKATHINI-14MAK1-159/14MAK1-160
70	HIGH DENSITY HYBRIDS-81	15XH112	MAKATHINI-14MAK1-161/14MAK1-162
71	HIGH DENSITY HYBRIDS-82	15XH113	MAKATHINI-14MAK1-163/14MAK1-164
72	HIGH DENSITY HYBRIDS-83	15XH114	MAKATHINI-14MAK1-165/14MAK1-166
73	HIGH DENSITY HYBRIDS-84	15XH115	MAKATHINI-14MAK1-167/14MAK1-168
74	HIGH DENSITY HYBRIDS-85	15XH116	MAKATHINI-14MAK1-169/14MAK1-170
75	HIGH DENSITY HYBRIDS-86	15XH117	MAKATHINI-14MAK1-171/14MAK1-172
76	HIGH DENSITY HYBRIDS-87	15XH118	MAKATHINI-14MAK1-173/14MAK1-174
77	HIGH DENSITY HYBRIDS-88	15XH119	MAKATHINI-14MAK1-175/14MAK1-176
78	HIGH DENSITY HYBRIDS-89	15XH120	MAKATHINI-14MAK1-177/14MAK1-178
79	HIGH DENSITY HYBRIDS-90	15XH121	MAKATHINI-14MAK1-179/14MAK1-180
80	HIGH DENSITY HYBRIDS-91	15XH122	MAKATHINI-14MAK1-181/14MAK1-182
81	HIGH DENSITY HYBRIDS-92	15XH123	MAKATHINI-14MAK1-183/14MAK1-184
82	HIGH DENSITY HYBRIDS-93	15XH124	MAKATHINI-14MAK1-185/14MAK1-186
83	HIGH DENSITY HYBRIDS-94	15XH125	MAKATHINI-14MAK1-187/14MAK1-188

Entry	Stock	Name	Origin
84	HIGH DENSITY HYBRIDS-95	15XH126	MAKATHINI-14MAK1-189/14MAK1-190
85	HIGH DENSITY HYBRIDS-96	15XH127	MAKATHINI-14MAK1-191/14MAK1-192
86	HIGH DENSITY HYBRIDS-97	15XH128	MAKATHINI-14MAK1-193/14MAK1-194
87	HIGH DENSITY HYBRIDS-98	15XH129	MAKATHINI-14MAK1-195/14MAK1-196
88	HIGH DENSITY HYBRIDS-99	15XH130	MAKATHINI-14MAK1-197/14MAK1-198
89	HIGH DENSITY HYBRIDS-100	15XH131	MAKATHINI-14MAK1-199/14MAK1-200
90	HIGH DENSITY HYBRIDS-101	15XH132	MAKATHINI-14MAK1-201/14MAK1-202
91	HIGH DENSITY HYBRIDS-102	15XH133	MAKATHINI-14MAK1-203/14MAK1-204
92	HIGH DENSITY HYBRIDS-103	15XH134	MAKATHINI-14MAK1-205/14MAK1-206
93	HIGH DENSITY HYBRIDS-104	15XH135	MAKATHINI-14MAK1-207/14MAK1-208
94	11C1774	11C1774	
95	11C1579	11C1579	
96	11C2245	11C2245	
97	11C1483	11C1483	
98	10HDTX11	10HDTX11	
99	PAN 6Q-345 CB	PAN 6Q-345 CB	
100	BG5285	BG5285	

Appendix B. List of evaluated hybrids formulated based on Tester B (DTAB32)

Entry	Stock ID	Name	Origin
101	HIGH DENSITY HYBRIDS-105	15XH136	MAKATHINI-14MAK1-209/14MAK1-210
102	HIGH DENSITY HYBRIDS-106	15XH137	MAKATHINI-14MAK1-211/14MAK1-212
103	HIGH DENSITY HYBRIDS-107	15XH138	MAKATHINI-14MAK1-213/14MAK1-214
104	HIGH DENSITY HYBRIDS-108	15XH139	MAKATHINI-14MAK1-215/14MAK1-216
105	HIGH DENSITY HYBRIDS-109	15XH140	MAKATHINI-14MAK1-217/14MAK1-218
106	HIGH DENSITY HYBRIDS-110	15XH141	MAKATHINI-14MAK1-219/14MAK1-220
107	HIGH DENSITY HYBRIDS-111	15XH142	MAKATHINI-14MAK1-221/14MAK1-222
108	HIGH DENSITY HYBRIDS-112	15XH143	MAKATHINI-14MAK1-223/14MAK1-224
109	HIGH DENSITY HYBRIDS-113	15XH144	MAKATHINI-14MAK1-225/14MAK1-226
110	HIGH DENSITY HYBRIDS-114	15XH145	MAKATHINI-14MAK1-227/14MAK1-228
111	HIGH DENSITY HYBRIDS-115	15XH146	MAKATHINI-14MAK1-229/14MAK1-230
112	HIGH DENSITY HYBRIDS-116	15XH147	MAKATHINI-14MAK1-231/14MAK1-232
113	HIGH DENSITY HYBRIDS-117	15XH148	MAKATHINI-14MAK1-233/14MAK1-234
114	HIGH DENSITY HYBRIDS-118	15XH149	MAKATHINI-14MAK1-235/14MAK1-236
115	HIGH DENSITY HYBRIDS-119	15XH150	MAKATHINI-14MAK1-237/14MAK1-238
116	HIGH DENSITY HYBRIDS-120	15XH151	MAKATHINI-14MAK1-239/14MAK1-240
117	HIGH DENSITY HYBRIDS-121	15XH152	MAKATHINI-14MAK1-241/14MAK1-242
118	HIGH DENSITY HYBRIDS-122	15XH153	MAKATHINI-14MAK1-243/14MAK1-244
119	HIGH DENSITY HYBRIDS-123	15XH154	MAKATHINI-14MAK1-245/14MAK1-246
120	HIGH DENSITY HYBRIDS-134	15XH155	MAKATHINI-14MAK1-267/14MAK1-268
121	HIGH DENSITY HYBRIDS-135	15XH156	MAKATHINI-14MAK1-269/14MAK1-270
122	HIGH DENSITY HYBRIDS-136	15XH157	MAKATHINI-14MAK1-271/14MAK1-272
123	HIGH DENSITY HYBRIDS-137	15XH158	MAKATHINI-14MAK1-273/14MAK1-274
124	HIGH DENSITY HYBRIDS-138	15XH159	MAKATHINI-14MAK1-275/14MAK1-276
125	HIGH DENSITY HYBRIDS-139	15XH160	MAKATHINI-14MAK1-277/14MAK1-278
126	HIGH DENSITY HYBRIDS-140	15XH161	MAKATHINI-14MAK1-279/14MAK1-280
127	HIGH DENSITY HYBRIDS-142	15XH162	MAKATHINI-14MAK1-283/14MAK1-284
128	HIGH DENSITY HYBRIDS-143	15XH163	MAKATHINI-14MAK1-285/14MAK1-286
129	HIGH DENSITY HYBRIDS-144	15XH164	MAKATHINI-14MAK1-287/14MAK1-288
130	HIGH DENSITY HYBRIDS-145	15XH165	MAKATHINI-14MAK1-289/14MAK1-290
131	HIGH DENSITY HYBRIDS-146	15XH166	MAKATHINI-14MAK1-291/14MAK1-292
132	HIGH DENSITY HYBRIDS-147	15XH167	MAKATHINI-14MAK1-293/14MAK1-294
133	HIGH DENSITY HYBRIDS-148	15XH168	MAKATHINI-14MAK1-295/14MAK1-296
134	HIGH DENSITY HYBRIDS-149	15XH169	MAKATHINI-14MAK1-297/14MAK1-298
135	HIGH DENSITY HYBRIDS-150	15XH170	MAKATHINI-14MAK1-299/14MAK1-300
136	HIGH DENSITY HYBRIDS-151	15XH171	MAKATHINI-14MAK1-301/14MAK1-302
137	HIGH DENSITY HYBRIDS-152	15XH172	MAKATHINI-14MAK1-303/14MAK1-304
138	HIGH DENSITY HYBRIDS-153	15XH173	MAKATHINI-14MAK1-305/14MAK1-306
139	HIGH DENSITY HYBRIDS-154	15XH174	MAKATHINI-14MAK1-307/14MAK1-308
140	HIGH DENSITY HYBRIDS-155	15XH175	MAKATHINI-14MAK1-309/14MAK1-310
141	HIGH DENSITY HYBRIDS-156	15XH176	MAKATHINI-14MAK1-311/14MAK1-312

Entry	Stock ID	Name	Origin
142	HIGH DENSITY HYBRIDS-157	15XH177	MAKATHINI-14MAK1-313/14MAK1-314
143	HIGH DENSITY HYBRIDS-158	15XH178	MAKATHINI-14MAK1-315/14MAK1-316
144	HIGH DENSITY HYBRIDS-159	15XH179	MAKATHINI-14MAK1-317/14MAK1-318
145	HIGH DENSITY HYBRIDS-160	15XH180	MAKATHINI-14MAK1-319/14MAK1-320
146	HIGH DENSITY HYBRIDS-161	15XH181	MAKATHINI-14MAK1-321/14MAK1-322
147	HIGH DENSITY HYBRIDS-162	15XH182	MAKATHINI-14MAK1-323/14MAK1-324
148	HIGH DENSITY HYBRIDS-163	15XH183	MAKATHINI-14MAK1-325/14MAK1-326
149	HIGH DENSITY HYBRIDS-164	15XH184	MAKATHINI-14MAK1-327/14MAK1-328
150	HIGH DENSITY HYBRIDS-165	15XH185	MAKATHINI-14MAK1-329/14MAK1-330
151	HIGH DENSITY HYBRIDS-166	15XH186	MAKATHINI-14MAK1-331/14MAK1-332
152	HIGH DENSITY HYBRIDS-167	15XH187	MAKATHINI-14MAK1-333/14MAK1-334
153	HIGH DENSITY HYBRIDS-168	15XH188	MAKATHINI-14MAK1-335/14MAK1-336
154	HIGH DENSITY HYBRIDS-169	15XH189	MAKATHINI-14MAK1-337/14MAK1-338
155	HIGH DENSITY HYBRIDS-170	15XH190	MAKATHINI-14MAK1-339/14MAK1-340
156	HIGH DENSITY HYBRIDS-171	15XH191	MAKATHINI-14MAK1-341/14MAK1-342
157	HIGH DENSITY HYBRIDS-172	15XH192	MAKATHINI-14MAK1-343/14MAK1-344
158	HIGH DENSITY HYBRIDS-173	15XH193	MAKATHINI-14MAK1-345/14MAK1-346
159	HIGH DENSITY HYBRIDS-174	15XH194	MAKATHINI-14MAK1-347/14MAK1-348
160	HIGH DENSITY HYBRIDS-175	15XH195	MAKATHINI-14MAK1-349/14MAK1-350
161	HIGH DENSITY HYBRIDS-176	15XH196	MAKATHINI-14MAK1-351/14MAK1-352
162	HIGH DENSITY HYBRIDS-177	15XH197	MAKATHINI-14MAK1-353/14MAK1-354
163	HIGH DENSITY HYBRIDS-178	15XH198	MAKATHINI-14MAK1-355/14MAK1-356
164	HIGH DENSITY HYBRIDS-179	15XH199	MAKATHINI-14MAK1-357/14MAK1-358
165	HIGH DENSITY HYBRIDS-180	15XH200	MAKATHINI-14MAK1-359/14MAK1-360
166	HIGH DENSITY HYBRIDS-181	15XH201	MAKATHINI-14MAK1-361/14MAK1-362
167	HIGH DENSITY HYBRIDS-182	15XH202	MAKATHINI-14MAK1-363/14MAK1-364
168	HIGH DENSITY HYBRIDS-183	15XH203	MAKATHINI-14MAK1-365/14MAK1-366
169	HIGH DENSITY HYBRIDS-184	15XH204	MAKATHINI-14MAK1-367/14MAK1-368
170	HIGH DENSITY HYBRIDS-185	15XH205	MAKATHINI-14MAK1-369/14MAK1-370
171	HIGH DENSITY HYBRIDS-186	15XH206	MAKATHINI-14MAK1-371/14MAK1-372
172	HIGH DENSITY HYBRIDS-187	15XH207	MAKATHINI-14MAK1-373/14MAK1-374
173	HIGH DENSITY HYBRIDS-188	15XH208	MAKATHINI-14MAK1-375/14MAK1-376
174	HIGH DENSITY HYBRIDS-189	15XH209	MAKATHINI-14MAK1-377/14MAK1-378
175	HIGH DENSITY HYBRIDS-190	15XH210	MAKATHINI-14MAK1-379/14MAK1-380
176	HIGH DENSITY HYBRIDS-191	15XH211	MAKATHINI-14MAK1-381/14MAK1-382
177	HIGH DENSITY HYBRIDS-192	15XH212	MAKATHINI-14MAK1-383/14MAK1-384
178	HIGH DENSITY HYBRIDS-193	15XH213	MAKATHINI-14MAK1-385/14MAK1-386
179	HIGH DENSITY HYBRIDS-194	15XH214	MAKATHINI-14MAK1-387/14MAK1-388
180	HIGH DENSITY HYBRIDS-195	15XH215	MAKATHINI-14MAK1-389/14MAK1-390
181	HIGH DENSITY HYBRIDS-196	15XH216	MAKATHINI-14MAK1-391/14MAK1-392
182	HIGH DENSITY HYBRIDS-197	15XH217	MAKATHINI-14MAK1-393/14MAK1-394
183	HIGH DENSITY HYBRIDS-198	15XH218	MAKATHINI-14MAK1-395/14MAK1-396
184	HIGH DENSITY HYBRIDS-199	15XH219	MAKATHINI-14MAK1-397/14MAK1-398
185	HIGH DENSITY HYBRIDS-200	15XH220	MAKATHINI-14MAK1-399/14MAK1-400

Entry	Stock ID	Name	Origin
186	HIGH DENSITY HYBRIDS-201	15XH221	MAKATHINI-14MAK1-401/14MAK1-402
187	HIGH DENSITY HYBRIDS-202	15XH222	MAKATHINI-14MAK1-403/14MAK1-404
188	HIGH DENSITY HYBRIDS-203	15XH223	MAKATHINI-14MAK1-405/14MAK1-406
189	HIGH DENSITY HYBRIDS-204	15XH224	MAKATHINI-14MAK1-407/14MAK1-408
190	HIGH DENSITY HYBRIDS-205	15XH225	MAKATHINI-14MAK1-409/14MAK1-410
191	HIGH DENSITY HYBRIDS-206	15XH226	MAKATHINI-14MAK1-411/14MAK1-412
192	HIGH DENSITY HYBRIDS-207	15XH227	MAKATHINI-14MAK1-413/14MAK1-414
193	HIGH DENSITY HYBRIDS-208	15XH228	MAKATHINI-14MAK1-415/14MAK1-416
194	11C1774	11C1774	
195	11C1579	11C1579	
196	11C2245	11C2245	
197	11C1483	11C1483	
198	10HDTX11	10HDTX11	
199	PAN 6Q-345 CB	PAN 6Q-345 CB	
200	BG5285	BG5285	

Appendix C. Average yields of maize hybrids for Yield stability index (YSI), standability and ear prolificacy evaluated under non-stress (Yp), Low density (LD) and High density (HD) stress conditions at UK-1 and UK-2. An EPP of below 1.0 indicates partial bareness; an EPP of above 1.0 indicates ear prolificacy

ENTRY	HYBRIDS	Yield Stability Index					Standability				Ear Prolificacy			
		UK 1		UK 2		YSI	UK 1	UK 2	UK 1	UK 2	UK 1	UK 2		
		Low plant population density	PopDen	High plant population density	PopDen									
		GYG	PopDen	GYG	PopDen		RL	RL	SL	SL	TL	TL	EPP	EPP
76	15XH118	7.24	37778	10.959	67778	1.513674	62.48	1.908	0.182	-0.273	62.66	1.63	0.997	1.036
3	15XH45	9.15	37778	12.256	62222	1.339454	26.49	-0.094	0.182	2.182	26.67	2.09	0.668	1.167
80	15XH122	8.97	33333	11.999	65556	1.337681	44.32	1.663	0.673	13.525	44.99	15.19	0.742	1.033
115	15XH150	10.03	41111	12.021	68889	1.198504	4.22	0.087	-0.187	-0.42	4.04	-0.33	1.631	1.092
19	15XH61	9.52	41111	10.994	66667	1.154832	98.81	1.541	-0.187	1.388	98.63	2.93	1.114	1.419
156	15XH191	8.47	42222	9.751	74444	1.15124	5.03	3.268	-0.31	0.32	4.72	3.59	2.005	1.211
196	11C2245B	8.07	30000	9.232	60000	1.14399	-4.72	5.845	5.209	2.474	0.49	8.32	1.313	0.994
99	PAN 6Q-345 CBA	10.65	42222	11.784	76667	1.106479	7.66	1.86	-0.31	-1.443	7.35	0.42	1.979	1.394
165	15XH200	8.94	36667	9.809	72222	1.097204	-2.36	6.332	3.43	0.704	1.07	7.04	1.822	1.286
163	15XH198	9.32	41111	10.223	68889	1.096888	1.44	0.087	-0.187	1.193	1.26	1.28	2.01	1.689
131	15XH166	7.06	40000	7.522	66667	1.065439	0.49	1.693	-0.064	-0.127	0.43	1.57	2.012	1.325
182	15XH217	10.71	41111	11.342	75556	1.05901	1.44	0.268	-0.187	0.132	1.26	0.4	2.114	1.266
69	15XH111	9.59	38889	10.131	71111	1.056413	40.23	0.147	3	8.663	43.23	8.81	1.022	1.344
181	15XH216	10.67	42222	11.27	60000	1.056232	2.39	-0.155	-0.31	0.75	2.08	0.6	2.086	1.76
146	15XH181	6.63	41111	6.996	68889	1.055204	1.44	0.087	-0.187	-0.42	1.26	-0.33	1.956	1.253
116	15XH151	10.16	41111	10.627	66667	1.045965	7	0.026	2.445	3.221	9.44	3.25	1.74	1.086
142	15XH177	10.38	41111	10.782	76667	1.038728	25.86	1.726	-0.187	-0.014	25.67	1.71	1.553	1.138
4	15XH46	9.91	32222	10.263	63333	1.035621	86.52	1.788	0.796	14.941	87.32	16.73	0.732	0.98
105	15XH140	10.02	41111	10.368	71111	1.034731	17.53	1.709	-0.187	2.413	17.34	4.12	1.605	1.125
61	15XH103	9.1	41111	9.397	72222	1.032637	98.67	23.425	-0.187	14.483	98.48	37.91	1.172	1.103
78	15XH120	10.83	40000	11.004	53333	1.016066	62.99	4.21	2.436	8.096	65.43	12.31	0.849	0.893
147	15XH182	6.74	38889	6.812	57778	1.010682	5.43	-0.215	0.059	7.292	5.49	7.08	1.85	1.182

141	15XH176	11.36	41111	11.43	72222	1.006162	4.22	1.692	5.076	2.219	9.3	3.91	1.896	1.349
113	15XH148	8.94	38889	8.993	67778	1.005928	-0.46	0.056	3	4.543	2.54	4.6	1.96	1.3
129	15XH164	11.34	42222	11.405	70000	1.005732	2.39	1.679	2.322	-0.566	4.72	1.11	2.111	1.196
26	15XH68	10.56	40000	10.531	65556	0.997254	33.83	10.019	11.047	11.655	44.87	21.67	1.179	1.017
180	15XH215	12.8	34444	12.647	74444	0.988047	14.49	6.298	0.551	0.32	15.04	6.62	1.97	1.284
50	15XH92	13.42	38889	13.256	66667	0.987779	5.1	5.199	0.059	5.045	5.16	10.24	1.425	1.276
109	15XH144	10.22	41111	10.073	70000	0.985616	6.71	6.417	2.591	5.835	9.3	12.25	2.009	1.179
134	15XH169	10.84	41111	10.67	71111	0.984317	6.71	4.79	-0.187	-0.712	6.52	4.08	2.064	1.221
38	15XH80	12.31	42222	12.104	63333	0.983266	28.71	1.788	-0.31	3.83	28.4	5.62	1.005	1.054
54	15XH96	11.47	38889	11.218	61111	0.97803	50.7	20.875	0.059	12.27	50.75	33.15	0.973	1.02
79	15XH121	11.83	36667	11.521	43333	0.97388	58.75	11.893	0.305	9.193	59.06	21.09	0.815	0.874
21	15XH63	11.24	40000	10.946	68889	0.973843	17.21	6.356	5.818	12.538	23.03	18.89	1.12	1.09
77	15XH119	12.4	35556	12.055	71111	0.972177	90.81	6.397	0.428	3.976	91.24	10.37	0.949	1.047
1	15XH43	10.47	38889	10.167	55556	0.97106	64.35	5.558	7.954	12.168	72.3	17.73	0.889	0.912
29	15XH71	12.07	38889	11.69	54444	0.968517	60.66	8.993	0.059	12.446	60.71	21.44	1.018	0.998
16	15XH58	11.39	37778	11.008	57778	0.966462	35.79	3.631	5.445	8.735	41.23	12.37	1.066	0.951
140	15XH175	11.9	43333	11.483	75556	0.964958	3.34	4.679	-0.433	1.644	2.91	6.32	2.185	1.512
87	15XH129	10.13	38889	9.772	67778	0.964659	27.81	0.056	0.059	6.34	27.87	6.4	1.107	1.034
31	15XH73	10.98	41111	10.573	71111	0.962933	4.08	6.598	2.591	6.962	6.67	13.56	1.349	1.047
195	11C1579B	8.99	34444	8.63	64444	0.959956	-0.68	2.049	0.551	1.636	-0.13	3.69	1.502	0.951
149	15XH184	7.62	38889	7.312	73333	0.95958	-0.46	1.77	0.059	-1.004	-0.4	0.77	1.991	1.385
173	15XH208	7.71	41111	7.393	64444	0.958885	6.44	-0.034	-0.187	0.165	6.26	0.13	1.872	1.135
62	15XH104	8.77	40000	8.401	58889	0.957925	59.94	6.958	-0.064	22.039	59.87	29	1.123	1.053
12	15XH54	11.97	33333	11.462	60000	0.957561	7.29	3.417	4.245	2.673	11.54	6.09	1.28	0.951
193	15XH228	10.39	38889	9.898	68889	0.952647	-0.46	0.087	0.059	-0.42	-0.4	-0.33	1.672	1.12
34	15XH76	10.77	41111	10.242	64444	0.950975	30.98	3.414	2.445	0.165	33.42	3.58	1.007	0.989
2	15XH44	11.38	37778	10.78	62222	0.947276	28.45	-0.094	0.182	8.522	28.64	8.43	0.973	0.99
104	15XH139	10.73	40000	10.086	72222	0.939981	9.32	1.74	-0.064	2.172	9.25	3.91	1.537	1.088
124	15XH159	9.88	42222	9.263	68889	0.937551	18.18	3.316	-0.31	27.81	17.87	31.13	1.979	1.028

119	15XH154	6.27	36667	5.871	71111	0.936364	-2.36	0.147	0.305	-0.712	-2.05	-0.57	1.926	1.248
122	15XH157	12.02	40000	11.211	74444	0.932696	3.27	0.237	-0.064	1.835	3.21	2.07	2.234	1.475
185	15XH220	10.96	37778	10.172	74444	0.928102	1.93	4.649	0.182	3.35	2.11	8	1.848	1.181
83	15XH125	12.14	42222	11.263	64444	0.927759	81.34	5.138	-0.31	7.062	81.03	12.2	1.084	0.989
82	15XH124	12.78	38889	11.856	63333	0.9277	36.06	1.66	0.059	5.669	36.12	7.33	0.968	0.98
36	15XH78	10.72	42222	9.923	56667	0.925653	62.92	-0.245	2.322	14.32	65.24	14.07	1.005	1.286
22	15XH64	11.05	41111	10.212	64444	0.924163	4.08	3.299	2.591	10.165	6.67	13.46	1.165	1.007
138	15XH173	10.53	40000	9.73	74444	0.924027	0.49	1.753	-0.064	-1.151	0.43	0.6	1.956	1.302
158	15XH193	10.72	37778	9.903	74444	0.923787	6.49	1.753	6.147	9.188	12.64	10.94	2.054	1.573
198	10HDTX11B	10.09	42222	9.276	73333	0.919326	10.73	1.722	2.468	2.026	13.2	3.75	1.85	1.111
11	15XH53	9.23	34444	8.483	50000	0.919068	11.97	1.426	3.182	13.177	15.15	14.6	0.814	0.864
72	15XH114	8.69	42222	7.979	64444	0.918182	62.92	4.805	-0.31	14.92	62.61	19.72	1.058	1.005
9	15XH51	10.97	42222	10.06	64444	0.917046	33.97	3.414	2.322	1.889	36.3	5.3	1.058	1.024
39	15XH81	12.99	41111	11.903	57778	0.91632	56.12	5.489	-0.187	5.042	55.94	10.53	1.167	1.183
118	15XH153	6.99	38889	6.393	73333	0.914592	8.37	0.207	0.059	8.087	8.43	8.29	1.955	1.339
112	15XH147	10.69	42222	9.723	63333	0.909542	10.29	1.498	-0.31	0.311	9.98	1.81	1.742	1.282
162	15XH197	10.6	41111	9.636	72222	0.909057	1.44	6.38	5.369	2.267	6.81	8.65	2.304	1.469
135	15XH170	10.69	41111	9.711	75556	0.908419	1.44	3.209	2.591	4.586	4.04	7.79	1.93	1.114
73	15XH115	11.61	36667	10.531	53333	0.907063	15.42	7.477	9.194	61.002	24.62	68.48	1.187	0.925
179	15XH214	12.86	37778	11.632	65556	0.90451	5.26	6.835	0.182	8.525	5.44	15.36	1.959	1.269
130	15XH165	10.49	38889	9.471	71111	0.90286	-0.46	0.147	0.059	0.955	-0.4	1.1	2.076	1.329
144	15XH179	11.02	41111	9.947	74444	0.902632	4.22	9.284	-0.187	0.32	4.04	9.6	1.522	1.06
188	15XH223	10.65	42222	9.606	68889	0.901972	2.39	6.599	-0.31	2.522	2.08	9.12	1.926	1.197
45	15XH87	12.97	40000	11.697	38889	0.90185	75.49	20.701	2.714	3.528	78.21	24.23	1.123	0.923
160	15XH195	8.47	38889	7.632	52222	0.901063	2.32	-0.366	0.059	4.898	2.38	4.53	1.907	1.411
189	15XH224	10.96	38889	9.86	75556	0.899635	11.31	1.738	0.059	0.174	11.37	1.91	1.845	1.203
35	15XH77	11.47	41111	10.285	67778	0.896687	19.87	4.744	-0.187	-0.273	19.68	4.47	1.089	1.018
70	15XH112	12.1	41111	10.814	58889	0.893719	35.41	-0.185	2.754	0.896	38.17	0.71	1.157	1
64	15XH106	13.03	38889	11.64	61111	0.893323	11.15	3.513	5.941	6.027	17.09	9.54	1.018	0.978

58	15XH100	12.12	43333	10.822	62222	0.892904	19.13	5.418	-0.433	20.329	18.7	25.75	1.031	1.003
128	15XH163	10.24	40000	9.118	74444	0.89043	0.49	3.268	-0.064	23.894	0.43	27.16	1.956	1.152
25	15XH67	11.8	41111	10.499	62222	0.889746	15.04	-0.094	-0.187	7.637	14.85	7.54	1.089	1.044
190	15XH225	9.54	37778	8.488	72222	0.889727	-1.41	3.302	0.182	0.704	-1.22	4.01	1.76	1.04
194	11C1774B	10.57	40000	9.393	61111	0.888647	16.59	-0.125	-0.064	0.604	16.53	0.48	1.596	0.98
125	15XH160	11.4	42222	10.124	47778	0.88807	7.66	-0.486	2.322	2.358	9.98	1.87	1.821	0.851
42	15XH84	12.54	40000	11.13	66667	0.88756	54.67	11.65	-0.064	19.784	54.61	31.43	1.065	1.043
60	15XH102	10.46	42222	9.269	63333	0.886138	44.5	5.231	-0.31	19.708	44.19	24.94	1.137	1.068
107	15XH142	10.4	32222	9.203	77778	0.884904	4.11	0.328	0.796	0.975	4.9	1.3	1.775	1.069
175	15XH210	10.79	41111	9.538	68889	0.883967	4.08	1.699	2.445	10.871	6.52	12.57	1.743	1.044
15	15XH57	10.87	40000	9.567	56667	0.880129	8.83	-0.245	2.714	23.112	11.54	22.87	1.04	0.922
30	15XH72	11.96	42222	10.511	48889	0.878846	28.71	1.627	2.322	7.212	31.03	8.84	1.269	0.93
174	15XH209	10.65	40000	9.303	68889	0.873521	0.49	0.087	-0.064	25.286	0.43	25.37	1.845	1.028
136	15XH171	11.17	40000	9.756	33333	0.873411	0.49	-0.879	-0.064	4.259	0.43	3.38	2.262	1.721
28	15XH70	12.74	36667	11.101	68889	0.87135	4.31	9.774	0.305	22.705	4.62	32.48	1.11	1.028
159	15XH194	10.07	38889	8.745	72222	0.868421	2.49	1.692	0.059	3.687	2.54	5.38	2.023	1.52
114	15XH149	9.4	42222	8.141	71111	0.866064	2.39	0.147	-0.31	0.851	2.08	1	1.663	0.953
111	15XH146	10.26	40000	8.868	72222	0.864327	0.49	0.177	2.568	2.083	3.06	2.26	2.123	1.351
33	15XH75	11.3	36667	9.763	58889	0.863982	13.27	13.656	0.305	7.563	13.57	21.22	1.158	0.963
120	15XH155	12.53	41111	10.82	73333	0.863528	1.44	0.207	5.369	-1.004	6.81	-0.8	2.167	1.278
153	15XH188	12.13	44444	10.438	71111	0.860511	4.29	0.147	-0.555	2.318	3.74	2.47	1.927	1.109
101	15XH136	11.03	36667	9.464	67778	0.858024	-2.36	0.056	0.305	3.006	-2.05	3.06	1.761	0.871
88	15XH130	12.6	36667	10.809	66667	0.857857	46.72	10.071	0.305	23.98	47.03	34.05	1.097	1.008
53	15XH95	11.42	37778	9.769	61111	0.855429	19.43	3.542	44.626	9.937	64.05	13.48	0.914	1
84	15XH126	12.26	41111	10.458	56667	0.853018	4.08	13.412	5.076	1.189	9.15	14.6	0.981	0.959
102	15XH137	10.12	40000	8.605	74444	0.850296	3.27	0.237	-0.064	-1.151	3.21	-0.91	2.012	1.137
177	15XH212	12.79	42222	10.865	74444	0.849492	16.01	0.237	-0.31	32.094	15.7	32.33	1.847	1.193
154	15XH189	11.34	41111	9.628	73333	0.84903	9.78	3.24	-0.187	-1.004	9.59	2.24	2.061	1.125
191	15XH226	11.89	42222	10.018	65556	0.842557	2.39	-0.004	-0.31	5.019	2.08	5.02	2.19	1.032

23	15XH65	10.94	42222	9.195	67778	0.840494	9.54	6.723	-0.31	11.34	9.23	18.06	1.258	1.084
117	15XH152	10.81	41111	9.084	71111	0.840333	1.44	0.147	-0.187	0.803	1.26	0.95	1.716	1.014
199	PAN 6Q-345 CBB	11.39	40000	9.555	74444	0.838894	3.27	3.463	-0.064	12.246	3.21	15.71	1.984	1.248
44	15XH86	11.64	41111	9.761	62222	0.838574	25.42	7.058	2.591	2.182	28.01	9.24	1.035	0.97
51	15XH93	12.61	33333	10.558	30000	0.837272	10.18	6.449	0.673	4.697	10.85	11.15	1.27	1.25
150	15XH185	11.73	41111	9.817	73333	0.836914	4.08	0.207	-0.187	-1.004	3.89	-0.8	1.985	1.309
143	15XH178	10.3	43333	8.611	73333	0.836019	16.5	0.207	-0.433	10.852	16.07	11.06	1.952	1.353
98	10HDTX11A	12.7	38889	10.584	62222	0.833386	40.72	8.752	0.059	5.458	40.78	14.21	1.7	1.097
133	15XH168	12.47	40000	10.378	72222	0.832237	0.49	7.99	2.568	2.219	3.06	10.21	2.13	1.302
106	15XH141	10.4	38889	8.651	76667	0.831827	2.04	0.298	0.059	-1.443	2.1	-1.15	1.272	1.066
49	15XH91	11.68	37778	9.712	50000	0.831507	-1.41	4.074	0.182	6.566	-1.22	10.64	1.4	1.074
176	15XH211	11.35	35556	9.432	74444	0.831013	29.24	6.164	0.428	4.776	29.67	10.94	1.44	1.092
52	15XH94	14.36	36667	11.933	65556	0.830989	79.63	10.111	0.305	5.019	79.93	15.13	1.254	0.999
41	15XH83	13.18	40000	10.947	58889	0.830577	43.06	3.59	2.568	4.742	45.63	8.33	1.1	0.96
56	15XH98	10.16	36667	8.422	48889	0.828937	21.17	5.313	3.43	22.297	24.6	27.61	0.974	0.855
68	15XH110	11.59	42222	9.606	70000	0.828818	55.03	0.117	-0.31	13.698	54.72	13.82	1.742	1.671
167	15XH202	11.31	37778	9.373	68889	0.828736	-1.41	0.087	0.182	-0.42	-1.22	-0.33	2.087	1.289
20	15XH62	13.32	35556	10.942	63333	0.821471	18.52	1.788	0.428	10.682	18.95	12.47	1.245	1.109
40	15XH82	13.85	37778	11.345	64444	0.819134	42.71	8.418	3.123	1.832	45.83	10.25	1.584	1.006
157	15XH192	11.56	41111	9.451	73333	0.817561	14.89	10.777	2.445	18.573	17.34	29.35	1.763	1.081
57	15XH99	14.05	27778	11.486	65556	0.817509	40.04	8.502	1.288	8.41	41.33	16.91	1.609	0.999
170	15XH205	7.9	36667	6.439	71111	0.815063	-2.36	1.76	6.371	-0.712	4.01	1.05	1.978	1.125
183	15XH218	11.69	41111	9.517	75556	0.814115	7	4.679	-0.187	14.88	6.81	19.56	1.846	1.041
32	15XH74	10.06	37778	8.173	37778	0.812425	56.93	5.145	6.432	15.479	63.36	20.62	1.018	0.87
37	15XH79	12.3	33333	9.951	44444	0.809024	84.61	8.798	0.673	4.88	85.29	13.68	1.066	0.9
14	15XH56	11.39	37778	9.185	66667	0.806409	3.86	6.693	3.515	11.539	7.37	18.23	1.02	1.008
91	15XH133	12.22	40000	9.848	60000	0.805892	65.66	5.294	-0.064	23.715	65.6	29.01	1.097	0.968
55	15XH97	10.22	41111	8.231	62222	0.805382	39.89	7.341	10.632	9.56	50.53	16.9	1.305	1.202
151	15XH186	12.38	40000	9.967	70000	0.805089	8.83	0.117	-0.064	2.559	8.76	2.68	1.984	1.099

200	BG5285B	13.15	42222	10.577	74444	0.804335	21.28	0.237	-0.31	-1.151	20.97	-0.91	2.069	1.104
7	15XH49	12.69	40000	10.206	67778	0.804255	68.61	4.895	-0.064	22.522	68.54	27.42	1.065	1.431
108	15XH143	11.34	38889	9.12	78889	0.804233	8.04	0.358	0.059	2.952	8.1	3.31	1.786	1.094
95	11C1579A	11.14	36667	8.958	60000	0.804129	6.65	1.768	3.246	9.953	9.9	11.72	1.428	0.97
186	15XH221	9.78	40000	7.818	72222	0.799387	9.32	1.606	-0.064	0.57	9.25	2.18	1.678	1.047
126	15XH161	11.96	40000	9.543	74444	0.79791	0.49	0.237	-0.064	13.689	0.43	13.93	2.012	1.3
67	15XH109	12.61	41111	10.049	60000	0.796907	25.57	9.105	-0.187	4.454	25.38	13.56	1.199	1.043
127	15XH162	11.97	40000	9.522	73333	0.795489	0.49	1.77	-0.064	6.808	0.43	8.58	2.095	1.276
172	15XH207	12.42	42222	9.879	80000	0.795411	2.39	3.185	7.746	-0.366	10.14	2.82	2.144	1.174
74	15XH116	13.84	41111	10.997	60000	0.794581	64.02	3.569	8	37.784	72.02	41.35	1.145	0.951
92	15XH134	12.86	37778	10.197	56667	0.792924	60.36	1.755	0.182	1.189	60.54	2.94	1.054	0.942
110	15XH145	12.33	38889	9.722	74444	0.788483	-0.46	0.237	3.184	15.992	2.73	16.23	2.03	1.105
46	15XH88	14.1	40000	11.111	67778	0.788014	14.27	21.4	2.877	25.963	17.15	47.36	1.212	1.018
161	15XH196	9.77	34444	7.693	71111	0.78741	10.45	4.79	6.433	19.376	16.88	24.17	1.609	1.142
8	15XH50	14.48	37778	11.376	56667	0.785635	40.26	-0.245	0.182	17.648	40.44	17.4	1.028	0.922
71	15XH113	12.04	34444	9.434	70000	0.783555	53.52	1.73	0.551	-0.566	54.07	1.16	1.164	1.499
100	BG5285A	15.86	41111	12.411	73333	0.782535	33.61	3.148	-0.187	-1.004	33.42	2.14	2.115	1.113
103	15XH138	12.46	38889	9.735	68889	0.7813	-0.46	4.925	0.059	9.258	-0.4	14.18	1.816	1.028
168	15XH203	9.84	41111	7.674	71111	0.779878	7	0.147	2.445	2.416	9.44	2.56	2.061	1.418
97	11C1483A	11.75	42222	9.135	60000	0.777447	10.29	3.632	-0.31	0.75	9.98	4.38	1.716	1.259
93	15XH135	12.9	38889	10.002	48889	0.775349	16.7	10.982	0.059	11.798	16.76	22.78	1.103	0.855
94	11C1774A	13.22	41111	10.241	68889	0.77466	7	6.565	-0.187	2.82	6.81	9.38	1.65	1.028
164	15XH199	9.38	43333	7.229	73333	0.770682	3.34	0.207	-0.433	46.514	2.91	46.72	1.442	1.05
5	15XH47	13.57	37778	10.441	50000	0.769418	32.97	3.922	2.96	6.512	35.93	10.43	0.994	0.841
27	15XH69	14.35	38889	11.039	42222	0.769268	11.55	0.976	0.059	6.315	11.61	7.29	1.219	1.171
192	15XH227	10.26	42222	7.875	75556	0.767544	2.39	0.268	-0.31	2.87	2.08	3.14	1.584	1.057
6	15XH48	11.6	40000	8.903	51111	0.7675	42.16	-0.396	-0.064	15.367	42.1	14.97	1.012	0.897
59	15XH101	11.26	38889	8.611	63333	0.764742	55.43	4.774	0.059	11.602	55.49	16.38	1.045	1.015
155	15XH190	9.76	41111	7.45	63333	0.76332	15.19	-0.064	-0.187	17.191	15	17.13	2.064	1.437

43	15XH85	12.66	37778	9.595	65556	0.757899	47.55	5.353	0.182	16.494	47.73	21.85	1.251	1.017
169	15XH204	11.08	43333	8.369	72222	0.755325	3.34	0.177	-0.433	0.704	2.91	0.88	2.107	1.213
65	15XH107	10.47	41111	7.888	67778	0.753391	60.22	10.003	2.445	51.931	62.66	61.93	1.115	1.018
66	15XH108	11.28	37778	8.476	51111	0.751418	10.36	1.985	6.064	10.681	16.42	12.67	1.495	0.962
63	15XH105	11.23	34444	8.4	63333	0.747996	4.08	12.128	4.397	16.013	8.47	28.14	1.177	1.05
90	15XH132	12.54	41111	9.379	41111	0.747927	17.82	5.215	8.147	11.618	25.96	16.83	1.063	0.847
85	15XH127	13.2	37778	9.864	72222	0.747273	52.45	3.207	3.515	8.469	55.97	11.68	1.245	1.087
139	15XH174	12.66	41111	9.425	71111	0.744471	1.44	4.834	5.369	14.913	6.81	19.75	2.25	1.5
184	15XH219	11.99	38889	8.905	74444	0.742702	-0.46	1.708	0.059	6.247	-0.4	7.95	1.754	1.045
86	15XH128	12.88	41111	9.531	66667	0.739984	48.67	11.762	-0.187	8.382	48.48	20.14	1.194	1.008
123	15XH158	11.87	43333	8.764	71111	0.738332	8.11	0.147	1.948	-0.712	10.05	-0.57	1.887	1.108
13	15XH55	12.27	41111	9.004	68889	0.733822	7	3.42	-0.187	28.539	6.81	31.96	1.088	1.028
24	15XH66	12.72	41111	9.226	58889	0.725314	23.23	1.898	2.445	71.37	25.67	73.27	1.091	0.962
10	15XH52	13.89	34444	10.074	62222	0.72527	36.5	19.765	0.551	41.518	37.05	61.28	1.246	0.97
187	15XH222	12.02	41111	8.668	74444	0.721131	4.08	4.694	-0.187	0.365	3.89	5.06	1.95	1.06
178	15XH213	13.03	37778	9.308	71111	0.714351	16.24	6.598	3.123	18.35	19.36	24.95	1.937	1.159
152	15XH187	13.1	38889	9.347	73333	0.713511	2.32	0.207	0.059	-1.004	2.38	-0.8	2.045	1.248
132	15XH167	8.3	36667	5.897	67778	0.710482	-2.36	1.781	0.305	20.201	-2.05	21.98	1.945	1.02
171	15XH206	9.62	41111	6.834	74444	0.710395	1.44	1.753	-0.187	10.614	1.26	12.37	2.139	1.135
197	11C1483B	10.4	36667	7.385	66667	0.710096	-2.36	0.026	0.305	-0.127	-2.05	-0.1	1.939	1.158
96	11C2245A	11.06	43333	7.82	54444	0.707052	10.84	-0.306	-0.433	4.113	10.41	3.81	1.626	0.968
47	15XH89	11.18	41111	7.896	62222	0.706261	30.98	1.757	8.147	26.831	39.12	28.59	1.06	0.989
166	15XH201	10.99	38889	7.747	71111	0.704914	7.93	0.147	0.059	0.955	7.99	1.1	2.176	1.344
75	15XH117	14.59	33333	10.191	64444	0.698492	17.19	1.889	4.52	43.314	21.71	45.2	1.191	1.02
81	15XH123	13.76	42222	9.611	68889	0.698474	52.39	10.087	-0.31	13.851	52.08	23.94	1.374	1.061
48	15XH90	13.52	38889	9.421	65556	0.69682	25.36	1.72	0.059	11.858	25.42	13.58	1.046	1.134
89	15XH131	12.95	40000	8.946	58889	0.690811	62.1	6.065	5.509	20.58	67.61	26.65	1.041	0.962
148	15XH183	10.22	38889	6.956	71111	0.680626	-0.46	3.272	5.941	60.226	5.49	63.5	1.587	1.265
18	15XH60	12.58	35556	8.533	65556	0.678299	9.63	3.387	3.761	11.801	13.4	15.19	0.987	0.999

121	15XH156	12.59	40000	8.456	70000	0.671644	8.83	0.117	-0.064	14.394	8.76	14.51	2.151	1.224
17	15XH59	12.01	41111	7.881	61111	0.656203	9.63	5.645	-0.187	59.291	9.44	64.94	1.009	0.96
137	15XH172	13.56	41111	7.716	73333	0.569027	1.44	1.678	2.591	35.944	4.04	37.62	2.064	1.126
145	15XH180	10.96	37778	4.585	72222	0.418339	-1.41	0.177	0.182	-0.858	-1.22	-0.68	1.584	1.028
