

**COMBINING ABILITY AND YIELD PERFORMANCE STUDIES OF TROPICAL
MAIZE (*Zea mays* L.) GERMPLASM UNDER DROUGHT STRESS AND WELL-
WATERED ENVIRONMENTS**

BY

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DECLARATION

I hereby declare that except for references to works of other researchers, which have been duly cited, this work is my original research and that neither part nor whole has been presented elsewhere for the award of a degree.



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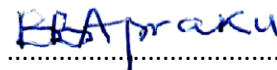
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ABSTRACT

Maize is increasingly consumed by Nigerien households. Limited studies have been conducted on the production and productivity of this crop in Niger and very few cultivars (mostly open pollinated varieties) are available to farmers. Knowledge and understanding of farmers' preferences for new varieties would be invaluable in designing a successful maize breeding program. Maize cultivars grown in Niger are derived mainly from tropical yellow-grained extra-early and early-maturing lowland germplasm sources. Lack of availability of appropriate early and extra-early testers as well as information on the combining ability, the mode of gene action, and the heterotic patterns of the available early and extra-early inbreds impede the successful development and adoption of maize hybrids in West Africa.

Three activities were conducted in the present study. The first was a Rapid Rural Appraisal to assess the appropriateness of maize crop management practices used by farmers in Niger, to identify major factors limiting maize production and productivity, and to identify traits preferred by farmers. The study revealed that the production of maize in the country is carried out using few inputs and poor crop management practices. The current level of production is very low due to many factors including drought, low soil fertility, poor crop management and lack of availability of improved varieties. Yellow maize cultivars that combine earliness and high yield potential are desired by farmers.

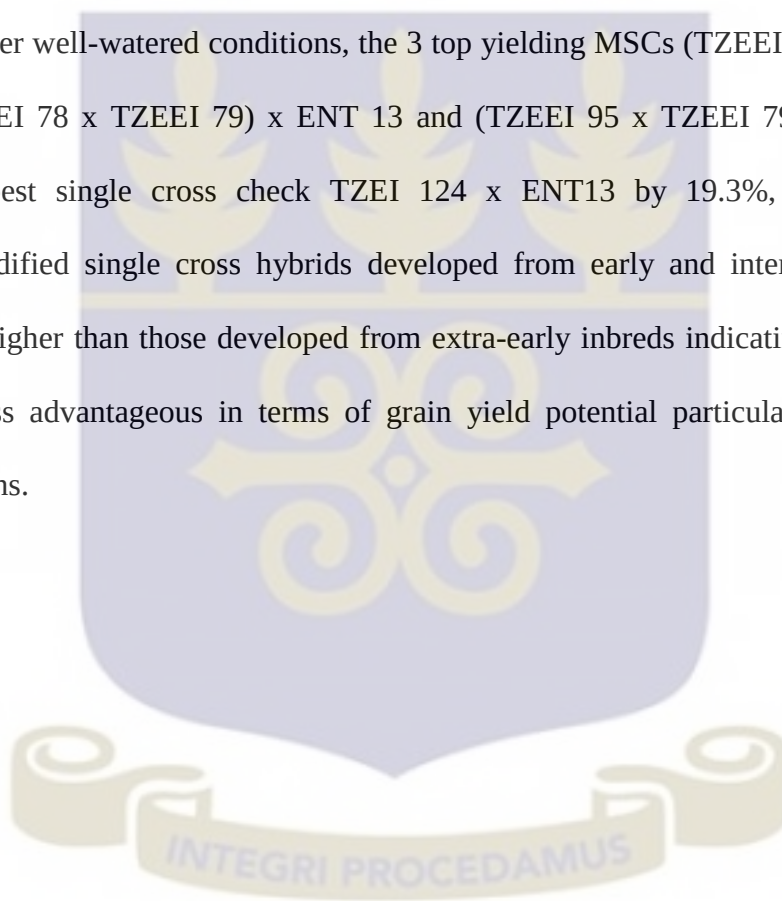
The second activity consisted of two parts including an experiment to determine the right time to impose water stress in maize drought trials in Niger and a diallel study to explore the combining ability of grain yield and other traits of early maturing, yellow-grained maize inbreds under drought and well-watered conditions. The objectives of this activity were to test the efficiency of the CIMMYT/IITA screening method for drought tolerance in Niger, examine the

combining ability and the mode of gene action for drought tolerance among 15 early maturing inbred lines, classify the inbreds into contrasting heterotic groups using two different classification methods i.e. the SCA effects of grain yield and the HSGCA, and assess the yield performance and stability of hybrids under contrasting environments. The findings of the activity revealed that the drought screening method that involved (i) stopping irrigation 3 to 2 weeks before anthesis, (ii) applying a “rescue irrigation” 13 to 15 days after imposing drought stress, and (iii) resuming the normal irrigation 10 to 12 days later until crop maturity was the most appropriate for maize drought trials in Niger. A moderate yield reduction under drought of 36.84% of the yield under well-watered environment was observed.

Significant GCA and SCA effects for grain yield and most measured traits were detected with predominance of GCA effects over SCA effects, indicating that most traits were controlled predominantly by additive gene action. Two heterotic groups were identified based on the classification with the SCA_PY method. Inbreds ENT 13, TZEI1 124 and TZEI 129 displayed the highest GCA values in well- watered environments and were the best parents that are likely to contribute favorable alleles to progeny. Inbred ENT 13 was the best combiner under both drought and well-watered conditions suggesting its inclusion in population improvement and in the development of hybrids and synthetics. Significant differences were observed among the single cross hybrids under the two water treatments. The single cross hybrids TZEI 124 x ENT 13; TZEI 160 x TZEI 157; TZEI 182 x ENT 13 and TZEI 167 x ENT 13 were the highest yielding hybrids across test environments and out-yielded all the checks.

In the third activity, three related single cross (RSC) parents, two single cross checks and 103 modified single crosses (MSCs) derived from crosses of the three RSCs to 36 inbreds of varying maturity groups were evaluated under drought and well-watered conditions to assess the yield

performance of MSCs and examine the relationship between grain yield of MSCs and their maturity groups. Results revealed a moderate but adequate level of moisture stress (62.3% yield reduction). Significant differences were observed among the MSCs under the two moisture regimes. Under drought stress, the 3 highest yielding MSCs (TZEEI 76 x TZEEI 82) x CMK ENT 23; (TZEEI 76 x TZEEI 82) x CMZ ENT 8; and (TZEEI 95 x TZEEI 79) x CMK ENT 8 outyielded the best single cross check (ENT 13 x CamInbgp.1-17) by 91%, 67%, and 66%, respectively. Under well-watered conditions, the 3 top yielding MSCs (TZEEI 76 x TZEEI 82) x TZEI 124; (TZEEI 78 x TZEEI 79) x ENT 13 and (TZEEI 95 x TZEEI 79) x CMZ ENT 5 outyielded the best single cross check TZEI 124 x ENT13 by 19.3%, 17.8% and 17% respectively. Modified single cross hybrids developed from early and intermediate maturing inbreds yielded higher than those developed from extra-early inbreds indicating that extra-early germplasm is less advantageous in terms of grain yield potential particularly under optimal growing conditions.



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DEDICATION

*To African resource poor farmers,
those who are struggling to feed Africa
despite the lack of resources and their
limited access to modern farming technologies*



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LISTE OF ABBREVIATIONS

AMMI: Additive Main effects and Multiplicative Interaction
ANOVA: Analysis of Variance
ATA: average tester coordinate abscissa
ATO: average tester coordinate ordinate
CIMMYT: International Maize and Wheat Improvement Center
FAOSTAT: Statistical Database of the Food and Agriculture of the United Nations
FESA: Ferme Semenciere Amate (Amate Seed Company)
FGD: Focus Group Discussion
GCA: General Combining Ability
GGE: Genotypes + Genotypes by environments interactions
GEI: Genotypes by environments interactions
HGCAMT: Heterotic grouping based on GCA of Multiple Traits
HSGCA: Heterotic groups' Specific and General Combining Ability
IITA: International Institute of Tropical Agriculture
INRAN: Institut National de la Recherche Agronomique du Niger (National Agronomic Research Institute of Niger)
IRAT: Tropical Agriculture Research Institute (Niger)
JAICAF: Japan Association for International Collaboration of Agriculture and Forestry
MSC: Modified Single Cross
OPV: Open Pollinated Varieties
PC: Principal Component
PPCR: Pilot Programme for Climate Resilience in Niger
PRA: Participatory Rural Appraisal
QTL: Quantitative Trait Loci
RCBD: Randomized complete blocks design
RRA: Rapid Rural Appraisal
RSC: Related Single Cross
SCA: Specific Combining Ability
SVP: Singular Value Partitioning
WCA: West and Central Africa
WSC: Water Stress Conditions
WWC: Well-watered Conditions

CHAPTER ONE

1.0. GENERAL INTRODUCTION

Maize (*Zea mays* L.) is an important cereal crop grown worldwide for various purposes. It occupies the second position after wheat in terms of area of production but represents the most important cereal crop in terms of quantity produced worldwide (FAOSTAT, 2015). The USA is the leading producer of maize in the world accounting for about 37% of the total production, followed by China, Brazil, and Mexico. The whole continent of Africa contributes only 7% of the global production (FAOSTAT, 2015). Maize is mostly used as an animal feed in the developed countries but it is an important staple crop in developing countries. It is consumed as food at various developmental stages from baby corn to matured grain. It is estimated that 65 percent of the total world maize production is used for feed, about 15 percent for food and the remaining for various types of industrial uses (Abbassian, 2008).

Maize production worldwide is constrained by biotic and abiotic stresses. The two types of stresses are responsible for yield reduction of 22% and 43% respectively (Gibbon *et al.*, 2007). Drought is the most important abiotic stress constraining and destabilizing maize grain production in both temperate and tropical environments (Edmeades, 2008; Ribaut *et al.*, 2009). Yield losses due to drought average 15 percent annually in sub-Saharan Africa (Badu-Apraku and Lum, 2010; Badu-Apraku *et al.*, 2011a) even in areas where total rainfall is reasonably high (Fischer *et al.*, 1982). Total yield losses may be observed when severe drought occurs at the reproductive stages of plant development. Besides drought low soil fertility, particularly low soil nitrogen (Gibbon *et al.*, 2007) and *Striga* infestation constitute the major constraints to maize production in West and Central Africa (Badu-Apraku *et al.*, 2013a; Akinwale *et al.*, 2014). *Striga hermonthica* can cause yield reduction of 20 to 80% and even complete yield losses under

severe infestation (Badu-Apraku and Akinwale, 2011) whereas annual yield losses due to low-N are estimated to vary from 10 to 50% (Wolfe *et al.*, 1988).

Maize is ranked fourth among the cereals grown in Niger i.e. millet, sorghum, rice and maize. There are three types of maize production in the country. The most important production is done under irrigation in areas where irrigation facilities are available e.g. public irrigation schemes of Jiratawa and Konni. The second type is maize production under rain fed conditions. This production is mostly restricted to the region of Gaya where the annual rainfall ranges from 650 mm to 900 mm. The third type of production is the "decrue maize" where maize is cultivated along seasonal flowing rivers (Komadougou yobe, goulbi Maradi etc.) that inundate maize fields during the rainy season (JAICAF, 2009). Maize is planted after water withdrawal from the fields. The high water holding capacity of the soils allows the production of extra early varieties without any additional irrigation. Maize is often produced in association with legume and vegetable crops (Habsatou *et al.*, 2010; Mossi *et al.*, 2010). Extra-early and early maturing yellow varieties are mostly grown by farmers and used for green maize consumption.

The overall climatic conditions in Niger, however, are not suitable for rain-fed maize production. Niger has semi-arid tropical climate with two seasons: a long dry season (from October to May) and a short rainy season (from June to September) (PPCR, 2010). The climate is characterized by high variability especially in terms of rainfall which is not only irregularly distributed throughout the year, but also erratically dispersed over the country (PPCR, 2010). From north to south, four main agro-climatic zones are recognized in the country:

- *The Saharan zone*, which covers 77% of the country has an annual precipitation hardly reaching 150 mm. Irrigated farming is practiced in this zone.
- *The Sahelo-Saharan zone* covers 12% of Niger's total area. The annual precipitation is between 150 mm and 300 mm.

- *The Sahelian zone*, which covers 10% of Niger's total area and receives 400 to 600 mm of annual precipitation. It is conducive to agro-pastoralism.
- *The Sahelo-Sudanian zone*, which covers about 1% of Niger's total surface area and receives 600 to 800 mm of annual precipitation. It is conducive to food production and animal husbandry (PPCR, 2010).

Maize production in Niger is constrained by low soil fertility, drought, poor crop management and the lack of availability of improved varieties. However, drought remains the most important limiting factor that dissuades farmers from producing maize under rainfed conditions. The national maize production remains low and averages 4,000 tons annually. The grain yield is around 0.8 t ha^{-1} , being the lowest in West Africa. This situation is mostly due to the aforementioned complex limiting factors. To meet the increasing demand of maize grain in the country, around 46,000 tons of maize grain is imported each year from neighboring countries (Nigeria, Benin, Togo, Burkina, and Mali).

Maize is an orphan cereal crop in Niger which has not been extensively studied by the research community unlike millet and sorghum. The research conducted so far on maize in the country was limited to: (i) the improvement of a local OPV P₃ Kollo for earliness and resistance to maize streak virus, (ii) conduct of regional trials, and (iii) identification of appropriate planting dates (Jika, 1991). The other available information on maize is the basic crop statistics (area cultivated, average grain yield etc.). There is therefore a need to conduct more studies in maize production areas of the country to develop a better understanding of the maize production system. This will allow setting appropriate maize breeding priorities for the national maize breeding program. A Rapid Rural Appraisal study was conducted in different maize production sites of the country for this purpose.

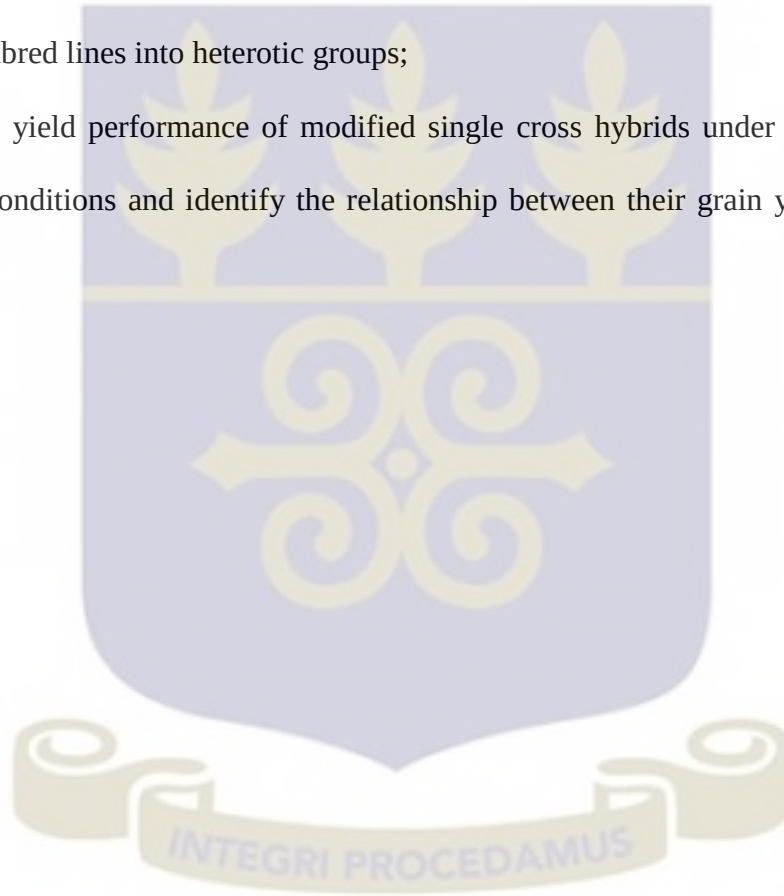
To boost the national maize production from its current level, both productions under irrigation and rain-fed conditions should be increased. This requires an increased availability and accessibility to high yielding and stable maize varieties by Nigerien farmers. These varieties should also carry drought tolerance genes for a better production of maize under rainfed conditions where drought remains an important threat. Currently limited genetic variability is available to maize breeders in the country to develop such superior maize genotypes. It is therefore important to introduce new maize germplasm into the country to increase the genetic variability which can be exploited to enable farmers to have access to a wide range of improved maize genotypes such as single crosses and modified single crosses. These are expected to perform higher than the old and low yielding OPVs currently grown by farmers in the country.

The international centres for maize improvement IITA and CIMMYT have developed a wide range of maize germplasm which is adapted to the climatic conditions of sub-Saharan African countries such as Niger. A large number of their inbred lines were developed under stress conditions such as *Striga*, drought and low nitrogen. IITA and CIMMYT early and extra-early maize inbreds represent an important source of maize genetic diversity for the national maize breeding program in Niger. However, information on the combining abilities and the heterotic patterns of these lines is limited. Knowledge and understanding of the heterotic patterns of the inbreds will be very useful in developing high yielding and stable maize hybrids to enhance the national maize production in Niger.

The overall objective of this study is to exploit the genetic diversity existing in IITA and CIMMYT maize inbreds to develop high yielding and stable maize single cross and modified single cross hybrids across contrasting environments in Niger.

The specific objectives of this study are to:

- identify maize production constraints and maize agronomic traits desired by farmers;
- estimate the combining ability and the mode of gene action for yield and drought tolerance of early maturing inbred lines;
- evaluate the agronomic performance of F1 single-cross hybrids under drought and well-watered conditions and estimate their yield stability across varying environments;
- classify inbred lines into heterotic groups;
- assess the yield performance of modified single cross hybrids under drought and well-watered conditions and identify the relationship between their grain yield and maturity.



CHAPTER TWO

2.0. LITERATURE REVIEW

2.1. Inbreeding depression and heterosis

Inbreeding depression and heterosis are two important genetic phenomena that are observed in the reproduction of species with out-crossing mating system. Inbreeding depression refers to the overall reduction in fitness, fertility, and survival of individuals in a population brought about by breeding genetically related individuals (Charlesworth and Willis, 2009). Inbreeding increases homozygosity, hence, it leads to the reduction of the within families genetic variance and the increase of the among families variance (Moorad and Wade, 2005). It causes a decline in mean fitness of individuals owing to the manifestation of recessive deleterious alleles, the reduction in frequency of favorable overdominant heterozygous loci and the disruption of advantageous gene interactions (Moorad and Wade, 2005). On the other hand, heterosis as defined by George H. Shull (Shull, 1948) refers to the phenomenon in which the hybrid progeny exhibits superior phenotypic characteristics compared to the mean of the two parents or to the best parent (Springer and Stupar, 2007).

2.2. Inbreeding depression and heterosis in hybrid maize development

Heterosis is responsible for the success of the maize hybrid seed industry that uses the inbred/hybrid production method (Duvick, 1999). The inbreeding depression *per se* is not a desirable phenomenon in inbred line development. It however, indicates that there exists genetic variation in traits controlling fitness, survival and fertility in natural populations (Charlesworth and Willis, 2009). It plays an important role (Charlesworth and Willis, 2009) in the control of the stability and uniformity of inbred lines. In the development of maize inbred lines, a good level of

stability is reached when the reduction in plant vigor slows down and plants become uniform from one generation of selfing to the next.

Heterosis has been extensively exploited to develop commercial hybrids. Traits like grain yield, plant height and number of days to flowering have been significantly improved by exploiting heterosis (Duvick, 1999). However, heterosis *per se* is a desirable phenomenon only when it is associated with high performance of the hybrid for the trait under improvement. A low yielding hybrid exhibits a high but useless heterosis for yield when its two parents are also very low yielding (Duvick, 1999). Furthermore, high heterosis for grain yield alone cannot explain the dramatic increase in yield that has been achieved in modern commercial hybrids grown in developed countries. The yield improvement is also due to the adoption of efficient crop management practices by farmers and also to significant improvement of many important defensive traits that may not show any heterosis (Duvick, 1999).

2.3. Genetic basis of inbreeding depression and heterosis

Inbreeding depression and heterosis have been under investigation since Darwin's era in 1876 (Birchler *et al.*, 2010). Current advances in genetic studies have confirmed that both are genetic phenomena (Charlesworth and Willis, 2009). However the genetic causes underlying these phenomena are still not fully understood (Tang *et al.*, 2010). Shull (1948) acknowledged that no single cause or mechanism can be properly assumed to apply to all the cases. Several hypotheses that are not mutually exclusive have been proposed to explain heterosis (Shull, 1948) but they have proven difficult to test. The most prominent of them are the dominance hypothesis, the overdominance hypothesis, and the epistasis hypothesis (Reif *et al.*, 2005). The dominance hypothesis attributes the superiority of hybrids to the suppression of detrimental alleles that are

largely recessive from one parent by dominant alleles from the other. The overdominance hypothesis attributes heterosis to the superior fitness of heterozygous genotypes over homozygous genotypes. The epistasis hypothesis explains heterosis by the presence and the magnitude of favorable non allelic interactions between many loci. Charlesworth and Willis (2009) indicated that classical genetic studies and modern molecular evolutionary approaches suggest that inbreeding depression and heterosis are predominantly caused by the presence of recessive deleterious mutations in populations, probably with a contribution from overdominance at few loci. However other QTL studies revealed that epistasis also plays a much more significant role in the manifestation of heterosis than previously believed (Melchinger *et al.*, 2007a; Melchinger *et al.*, 2007b). Despite the fact that the genetic dissection of heterosis is not fully resolved, Hallauer *et al.* (2010) supported the idea that significant improvement of maize cultivars can still be made by exploiting this phenomenon.

2.4. Combining ability

Combining ability refers to the capacity of an individual to contribute superior fitness related traits to hybrid progeny. It is very useful in mating designs to investigate the performance of lines in hybrid combinations (Griffing, 1956). In 1941 Sprague and Tatum introduced the concepts of general combining ability (GCA) and specific combining ability (SCA) (Hallauer *et al.*, 2010). They defined the two terms respectively as "the average performance of a line in hybrid combinations" and "the cases where certain combinations do relatively better or worse than would be expected on the basis of the average performance of the lines involved" (Griffing, 1956). The concepts of GCA and SCA are very useful in plant breeding and have particular significance to the diallel mating design (Hallauer *et al.*, 2010). They have been extensively used by breeders in determining heterotic patterns in maize germplasms.

2.5. Heterotic groups and heterotic patterns

Heterotic groups and patterns are two fundamental concepts exploited in maize hybrid breeding theory and practice (Reif *et al.*, 2005). The concept of heterotic group was defined by Melchinger and Gumber (1998) "as a group of related or unrelated genotypes from the same or different populations, which display similar combining ability and heterotic response when crossed with genotypes from other genetically distinct germplasm groups". On the other hand, the concept of heterotic patterns designates "a specific pair of two heterotic groups which express high heterosis and consequently high hybrid performance in their crosses" (Melchinger and Gumber, 1998). The identification of heterotic groups and patterns is of utmost importance for any hybrid breeding program. Sprague (cited in Reif *et al.*, 2005) stated that: "*the single most important element of a breeding program is the recognition and utilization of heterotic patterns. This recognition both simplifies and increases the efficiency of all subsequent operations*". Experimental results reviewed by Melchinger and Gumber (1998) revealed the superiority of inter-group over intra-group hybrids and hence demonstrated the necessity of the development of distinct heterotic groups in a breeding program.

2.6. Development of heterotic groups and heterotic patterns in maize

Maize heterotic patterns were developed by breeders and are not the result of historical or geographical contingencies (Tracy and Chandler, 2004). The fundamental principle underlying the development of heterotic patterns is to cross in a diallel or testcross fashion a large number of inbreds and identify those showing the highest hybrid performance (Melchinger and Gumber, 1998). Further improvement of the heterotic pattern is done by the adoption of a breeding and selection technique designated as reciprocal recurrent selection (Reif *et al.*, 2005). In the U.S. the first attempt at the identification of maize heterotic patterns was made when maize populations

from the Reid Yellow Dent group were found to combine well with the Lancaster Sure Crop group. The Dent x Flint heterotic patterns has since then been extensively exploited to generate outstanding maize hybrids in the U.S., in Central and Western Europe, in Japan (Reif *et al.*, 2005; Fan *et al.*, 2009) in China, in Argentina, and in South Africa.

Several approaches have been used to assign germplasms into distinct heterotic groups. The classical SCA method relates the heterosis observed in crosses with the origin of the parents involved in the crosses and/or the hybrid yield information (Melchinger and Gumber, 1998; Fan *et al.*, 2009). Another method employs various molecular markers to compute genetic similarity or genetic distance to assign maize lines to different heterotic groups (Menkir *et al.*, 2004; Aguiar *et al.*, 2008; Fan *et al.*, 2009; Badu-Apraku *et al.*, 2013a; Akinwale *et al.*, 2014). Results were not always consistent with the ones of the classical approach which therefore is still used as a major method for maize heterotic group classification. Fan *et al.*, (2009) proposed another alternative method that uses both GCA and SCA to assign inbred lines to known maize heterotic groups. The method designated as heterotic group's specific and general combining ability (HSGCA) is reported to explain more variation in maize hybrid yield and produce more predictable yield than the previous two methods (Fan *et al.*, 2009; Akinwale *et al.*, 2014). Badu-Apraku *et al.*, (2013) proposed another method designated as heterotic grouping based on GCA of multiple traits (HGCAMT) which could be more effective in classifying inbred lines into appropriate heterotic groups. The advantage of the HGCAMT method particularly in breeding for stress environments is that it uses GCA of multiple traits rather than GCA of yield alone which has low heritability in those environments.

2.7. Estimates of variance components

The type of gene action involved in the expression of quantitative traits has been under investigation since the era of earlier geneticists (Hallauer and Miranda, 1981). Knowledge of the mode of gene action is fundamental in making solid inferences on breeding populations. It informs breeders of the appropriate selection method to adopt for rapid progress in their breeding programs. Several approaches have been proposed for estimating variance components (Reif *et al.*, 2005). These include:

2.7.1. Approaches using first and second degree statistics

Various mating designs based on first and second-degree statistics have been used to estimate variance components mostly attributable to additive and dominance effects (Reif *et al.*, 2005). Most of these designs assume a normal Mendelian diploid inheritance, no maternal effects, linkage equilibrium, non-inbred relatives, randomly selected parents and relatives, arbitrary allelic frequencies, and no epistasis. Hallauer *et al.*, (2010) reviewed in detail the following designs that are extensively used to produce progenies for evaluation:

- **Bi-parental Progenies:** It is one of the simplest mating designs for estimation of genetic variance in a reference population. Pairs of individual plants randomly taken from a population are crossed and progenies are evaluated in replicated trials. The information provided by bi-parental progenies gives an indication as to whether indeed sufficient genetic variability is present in the population to allow significant gains from the selection program.
- **Parent–Offspring Regressions:** this method regresses offspring or selfed progeny measurements on those of one parent or both parents (mid parent-offspring regression). The simplest method consists of making measurements on individual plants in a reference population.

The same traits are measured on the offspring derived from each parent to determine the degree of association between the traits measured in the parents and in their respective offspring. This method allows a quick estimate of additive genetic component and the heritability of the trait of interest.

- **North Carolina design I:** It is adequate only for estimating genetic components of variance for a reference non inbred population. Male and female individuals are randomly selected in the reference population. Each male is crossed to a different set of females to produce progenies for evaluation in replicated trials. It is cost effective in producing a large number of progenies. This design provides estimates of additive genetic variance. It does not give a direct estimate of dominance variance. Since the males used for crossing are non-inbreds, specific combining ability (SCA) effects cannot be worked out.

- **North Carolina design II:** From a reference non inbred population males and females individuals are randomly selected and each male is crossed to each female to produce progenies for evaluation in replicated trials. Design II offers the following advantages over diallel designs: (i) more parents can be included, (ii) two independent estimates of additive variance are available, and (iii) an estimate of dominance variance is determined directly from the mean squares. However it is more difficult to apply in open-pollinated species with only one inflorescence since multiple crosses on female plants are not possible.

- **North Carolina design III:** Randomly selected F₂ individuals derived from crosses between two inbreds are backcrossed to the inbred parents. Design III provides good estimates of additive variance and dominance variance for F₂ populations assuming absence of linkage and epistasis. This design has an advantage over the design II because it can measure levels of dominance and the estimation of dominance is not subjected to any assumption regarding allele

frequencies. It can also determine the effects of linkages on the estimates of additive variance and dominance variance, and average level of dominance.

- **Diallel designs:** They are the most extensively used designs in maize breeding particularly in the public sector. Diallel cross refers to all possible crosses among n parents ranging from inbred lines (Kempthorne, 1955) to broad genetic base varieties (for Gardner and Eberhart's analysis) (Hallauer *et al.*, 2010). It is very powerful if correctly analyzed and interpreted. Griffing (1956) described four diallel methods depending on whether or not parental inbreds or the reciprocals or both are included: (i) method 1: full diallel in which parents and reciprocal crosses are involved along with F₁, (ii) method 2: half diallel with parents and without reciprocal crosses, (iii) method 3: full diallel without inclusion of parents, and (iv) method 4: half diallel without parents and reciprocal crosses. The diallel analysis takes into consideration two models i.e. fixed model (model 1) and random model (model 2). The fixed model suggests that parents of the progenies are the genotypes for which the inference will be drawn. On the other hand the random model suggests that parents are a sample of genotypes representing a reference population. In the fixed model estimation of GCA and SCA is more appropriate and more informative than estimation of components of variance while for the random model analysis, estimation of the components of variance is of prime interest. One major disadvantage of diallel methods is the limitation of the number of parents to be included due to the large number of crosses needed as the number of parents increases.

- **Line x tester:** The concept of line x tester analysis was developed by Kempthorne in 1957 (Sharma, 2006). It is an extension of the topcross design in the sense that in the case of top crosses only one tester is used, while in the case of line x tester crosses several testers are used (Nduwumuremyi *et al.*, 2013). Each tester is mated to each of the lines which usually are more in

number. The potential of the lines in hybrid combination could therefore be assessed from the evaluation of the F1 progeny. Line x tester is the simplest mating design that provides both full-sibs and half-sibs simultaneously as opposed to top cross which provides only half-sibs (Nduwumuremyi *et al.*, 2013). It provides SCA of crosses and better estimates of GCA of testers than of lines (Nduwumuremyi *et al.*, 2013). Additive and dominance variance components can also be obtained. An important advantage of line x tester design over diallel methods is that it allows the evaluation of a much higher number of lines.

2.7.2. Molecular approaches

The advent of molecular markers in the late 1980's offers another alternative way of determining the type of gene action involved in the expression of quantitative traits (Reif *et al.*, 2005). QTL studies have been extensively conducted to decipher the genetic basis of heterosis. Evidence from modern molecular studies of heterosis suggested an important contribution of dominance (Charlesworth and Willis, 2009). However the proportion of overdominance, dominance, epistasis effects as well as their interactions greatly depends on the genetic materials used in the study, the number and types of molecular markers, and the model used for the analysis (Reif *et al.*, 2005; Swanson-Wagner *et al.*, 2006; Ma *et al.*, 2007; Melchinger *et al.*, 2007a; Li *et al.*, 2008; Tang *et al.*, 2010).

2.8. Drought and maize production

Drought is a meteorological term commonly defined as a period without significant rainfall (Jaleel *et al.*, 2009). It is the most important threat to maize production in both temperate and tropical environments (Edmeades, 2008; Ribaut *et al.*, 2009). Yield losses due to drought average 15 percent annually in sub-Saharan Africa (Badu-Apraku and Lum, 2010; Badu-Apraku

et al., 2011a) even in areas where total rainfall is reasonably high (Fischer *et al.*, 1982). Grain yield losses could be higher if drought occurs at the flowering and grain filling periods (Denmead and Shaw, 1960; NeSmith and Ritchie, 1992). Total yield losses may even be observed when severe drought occurs at the reproductive stages. Furthermore, in drought prone environments, the high probability of drought occurrence dissuades farmers from applying adequate levels of fertilizers and other inputs. Drought is therefore probably responsible for a much higher economic loss than indicated (Fischer *et al.*, 1982). Drought may occur at the beginning, the middle, or the end of the rainy season. In addition, drought duration and intensity are also totally unpredictable (Ribaut *et al.*, 2009). In the tropics, periodic drought caused by irregular rainfall distribution and accentuated by low water-holding capacity of the soils is the major cause of significant reductions in maize yields (Wolf *et al.*, 1974).

2.9. Breeding maize for drought prone environments

Several strategies have been proposed to mitigate drought damage on crop production in drought-prone environments. These include (i) drought escape, primarily by avoiding the coincidence of stress with crops sensitive stages (ii) increasing the crop's water use efficiency and (iii) increasing the drought tolerance *per se* in plants (Ribaut *et al.*, 2009). Earliness is the drought escape mechanism mostly preferred by farmers especially those dealing with frequent late season drought (Defoer *et al.*, 1997; Abebe *et al.*, 2005; Obaa *et al.*, 2005; Ouma *et al.*, 2010; Sibiya *et al.*, 2013). However, when the occurrence and the severity of drought stress are completely unpredictable, drought avoidance by earliness alone or by planting date is not an appropriate solution (Fischer *et al.*, 1982). Therefore any maize genotypes to be deployed in drought prone environments should carry drought tolerance genes that will confer the ability to survive and to produce acceptable levels of grain yield under water limiting conditions.

2.10. Strategies for successful improvement of drought tolerance in maize

Fischer *et al.* (1982) reported two hypotheses described by Blum (1979) as the first attempts for improving drought tolerance in maize: (i) a superior variety with high yield potential under optimum growing conditions will also perform relatively well under sub-potential levels, (ii) breeding for yield performance under stress environments maintains that potential yield. Neither of these approaches succeeded in substantially improving drought tolerance in maize. Indeed many reports confirm that selection for yield in non-stressed environments is generally less effective in identifying individuals which will perform well in low-yielding stressed environments (Fischer *et al.*, 1982; Bolaños *et al.*, 1993; Bänziger *et al.*, 2000; Ribaut *et al.*, 2009). The alternative approach to breeding maize for drought tolerance is to develop selection methods that can increase or at least maintain potential yield and at the same time improve drought tolerance traits (Fischer *et al.*, 1982). This approach relies on (i) the development of efficient stress management methods that will effectively discriminate and elicit true differences among individuals screened for drought tolerance, (ii) the identification of useful secondary traits that have high correlation with yield under drought stress, (iii) the careful selection of evaluation sites representative of the most prevalent drought type in the target area, and (iv) the appropriate choice of germplasm and breeding schemes (Bänziger *et al.*, 2000; Badu-Apraku *et al.*, 2004; Ribaut *et al.*, 2009).

2.10.1. Drought management methods

The unpredictability of drought occurrence and severity coupled with soil variability and high genotype x environment interactions inhibits a reliable detection of treatment differences in drought experiments conducted under natural conditions. Therefore the use of uniform soils and appropriate stress management methods along with rigorous experimental designs and

appropriate statistical analyses are the alternative to guaranteeing good selection progress (Ribaut *et al.*, 2009). CIMMYT and IITA maize breeding programs have developed and extensively used stress management methods that simulate a clearly defined stress that is relevant in farmers' fields (Bänziger *et al.*, 2000; Badu-Apraku *et al.*, 2004). For the drought stress, the method consists of conducting experiments partly or entirely during the dry season and managing the stress through irrigation while taking into consideration the timing, intensity, and uniformity of the stress (Bänziger *et al.*, 2000). Experiment blocks are managed with one stress level only and are far enough apart to prevent border effects. Irrigation is stopped so that drought stress is sufficiently intense at the targeted critical growth stage (Bänziger *et al.*, 2000).

2.10.2. Type of drought tolerance to breed for in maize

With respect to drought tolerance *per se* in maize, three primary breeding targets can be distinguished i.e. drought tolerance at flowering time, drought tolerance during grain filling, and yield stability across a range of environments (Ribaut *et al.*, 2009). Greenhouse experiments, field trials and historical analysis of on-farm data revealed that drought occurring around flowering time has a major effect on maize grain yield while stress during the grain filling and the vegetative stages may have less effect on yield (Fischer *et al.*, 1982; Bänziger *et al.*, 2000; Kamara *et al.*, 2003; Ribaut *et al.*, 2009; Badu-Apraku *et al.*, 2010). Therefore Breeding for drought tolerance during flowering and/or post-flowering has the best chance of affecting maize production, provided those types of drought stress are the most relevant in the target environments (Bänziger *et al.*, 2000). For drought stress at flowering stage, irrigation is designed so that drought at flowering is severe enough to delay silking and cause ear abortion while in the case of drought stress during grain filling, irrigation is designed so that drought develops directly after flowering and accelerates leaf senescence (Bänziger *et al.*, 2000).

2.10.3. Selection based on yield and secondary traits under drought

Secondary traits are plant characters other than grain yield that provide additional information on how the plant performs under a given environment (Lafitte *et al.*, 2003). The low heritability of maize grain yield under drought necessitates their use. An ideal secondary trait should be genetically variable, genetically correlated with grain yield in the target environment, should have a high level of heritability, be simple and cheap, non-destructive and fast to assay, be stable throughout the measurement period, and not associated with any yield penalty under non-stress conditions (Edmeades *et al.*, 1997; Lafitte *et al.*, 2003; Badu-Apraku *et al.*, 2012). In maize breeding for drought tolerance, the secondary traits that have been used include anthesis-silking interval (ASI), number of ears per plant (EPP), the number of kernels per ear, plant and ear height, leaf area, extent of leaf rolling, osmotic adjustment, leaf chlorophyll concentration, stomatal conductance, canopy temperature, hydraulic conductivity, abscissic acid concentration, ear growth and barrenness, stay-green characteristic, erect upper leaves, tassel size, and root architecture (Edmeades *et al.*, 1997; Bänziger *et al.*, 2000; Ribaut *et al.*, 2009; Badu-Apraku *et al.*, 2012). ASI and EPP were identified by Edmeades *et al.* (1997) as the most reliable secondary traits among a number of secondary traits ranked on the basis of heritability, association with grain yield, cost, genetic variability, and time required for recording.

2.10.4. Selection of germplasm for drought tolerance improvement in maize

Breeding for drought tolerance is very challenging because of the complex nature of the stress tolerance due to factors including the largely polygenic nature of the tolerance, the typically low frequency of tolerance alleles in most maize germplasm, and the difficulties commonly encountered in field evaluation (Bänziger *et al.*, 2000). The selection of appropriate germplasm and efficient breeding methods is critical to improving the drought tolerance of maize

populations and hybrids (Bänziger *et al.*, 2000; Ribaut *et al.*, 2009). CIMMYT evaluated a wide range of landraces and adapted elite germplasm for drought tolerance and found that improving the latter ones is probably nearly always better than working with landraces (Bänziger *et al.*, 2000). However, there are other alternatives such as (i) creation of synthetic populations from local landraces and improved adapted varieties, (ii) improvement of non-adapted but drought tolerant populations for local adaptation, (iii) development of new breeding population by introgressing locally adapted germplasm with drought tolerant germplasm (Bänziger *et al.*, 2000).

2.10.5. Selection of breeding schemes

Some important factors that might be taken into consideration when designing a breeding program for drought tolerance are (i) the type of genotypes to produce e.g. OPVs, synthetics, hybrids, (ii) the most important traits to be preserved in the new product e.g. early maturity, grain characteristics, and (iii) strategy for developing and deploying the products (Bänziger *et al.*, 2000). Maize plants offer a wide array of options with respect to breeding methodologies. Among the various selection methods, recurrent selection remains the breeding procedure extensively used by CIMMYT and IITA to improve populations' performance under drought stress and maintain genetic variability to ensure continued progress from selection (Bolaños and Edmeades, 1993; Bolaños *et al.*, 1993; Bänziger *et al.*, 2000; Monneveux *et al.*, 2008; Ribaut *et al.*, 2009; Badu-Apraku *et al.*, 2013b). The resultant populations improved for drought tolerance are also useful sources for extracting drought tolerant inbred lines for hybrid development. However, in hybrid development for drought-prone environments, the relationship between the performance of inbred lines and their hybrids is an important issue to consider (Bänziger *et al.*, 2000). Many reports have found significant dosage effect under drought suggesting the need for

including drought tolerant parents on both sides of the hybrid to achieve acceptable drought tolerance where the stress is severe (Bänziger *et al.*, 2000; Betrán *et al.*, 2003a; Ribaut *et al.*, 2009; Badu-Apraku *et al.*, 2011b).

2.11. Characteristics of an ideal drought tolerant genotype

Drought tolerance in an agricultural sense refers to the ability of a crop plant to produce its economic product with limited available water; thus, the mere survival with no grain yield is of little importance (Fischer *et al.*, 1982; Bänziger *et al.*, 2000; Cattivelli *et al.*, 2008; Ribaut *et al.*, 2009). The expression of tolerance depends greatly on both the developmental stage during which water stress is imposed and the intensity and duration of the stress (Ribaut *et al.*, 2009). Ideal drought tolerant cultivars are characterized by increased production under drought (Bänziger *et al.*, 2000) and should display no yield penalty in non stress environments. These genotypes are expected to display reduced ear and kernel abortion, shorter anthesis-silking interval, greater ear growth rate at flowering, increased harvest index, reduced leaf area (especially in the upper part of the plant), short and thick stems, small tassels, erect leaves and delayed senescence (Bänziger *et al.*, 2000; Ribaut *et al.*, 2009). Other traits difficult to measure include root biomass, root system depth and root lateral ramifications (Jaleel *et al.*, 2009).

2.12. Molecular approaches for drought tolerance improvement in maize

Extensive studies of drought tolerance traits have been carried out in maize over the last decade, yielding a large number of QTLs involved in the determination of morphological traits, yield components, flowering traits and plant height (Bänziger *et al.*, 2000; Messmer *et al.*, 2009; Ribaut *et al.*, 2009; Tsonev *et al.*, 2009; Setter *et al.*, 2011). Several microarray-based studies, with inconsistent results however, have also been carried out on drought stressed maize leading

to the putative identification of multiple genes, including transcription factors and regulatory proteins as being part of the drought response network (Ribaut *et al.*, 2009). The candidate gene approaches have also been used revealing many drought tolerance candidate genes. However, few of them have been validated either via reverse genetics or transgenic approaches (Ribaut *et al.*, 2009). Despite the documentation of numerous QTLs involved in the expression of drought tolerance in maize, their exploitation in public breeding programs has to date been limited, although it is not the case in the private sector (Ribaut *et al.*, 2009). A better understanding of the genetic basis of maize response to drought brought about by molecular approaches, together with accurate phenotyping methods will probably play an important role in the identification, the transfer and the selection of key genes and alleles to build genotypes with much improved tolerance to drought.

2.13. Genotypes by environment interactions in drought experiments

Genotype by environment ($G \times E$) interactions are common under drought and make breeding progress difficult (Bänziger *et al.*, 2004). $G \times E$ refers to changes in order, ranking, and relative values among genotypes evaluated in multi-locational and multi-year trials (Hallauer *et al.*, 2010). In such trials, $G \times E$ are often found to account for a greater degree of variance than G alone (Chapman *et al.*, 1997). $G \times E$ has been a research focus among biometricians, quantitative geneticists and breeders with the notion that they are undesirable or confounding factors in the sense that they complicate the selection and/or recommendation of materials (Annicchiarico, 1997; Yan and Tinker, 2006). $G \times E$ are due mostly to macroenvironmental effects (Hallauer *et al.*, 2010) particularly the variation in weather conditions between and within seasons and soil properties (Derera, 2005). However, $G \times E$ study is of special interest for breeding programs since it may lead to the subdivision of a target region into different sub-

regions, relatively uniform with respect to genotypic responses and alternatively provide guidelines for the choice of crucial test sites (Annicchiarico, 1997). Better approaches to analyze G x E data are now available such as the GGE biplot method (Yan and Tinker, 2006) and the AMMI analysis (Annicchiarico, 1997). These methods can help breeders to identify environments that are similar in the way in which they discriminate among genotypes and also determine genotypes that have similar patterns of response across a range of environments (Yan and Tinker, 2006).

2.14. Participatory plant breeding

The ultimate aim of any breeding program is the high adoption of the cultivars developed for farmers; otherwise all the intensive research work and research funds invested are a waste. In the developing countries many attempts to develop the agriculture through research projects failed to increase the adoption rate of the research technologies by the target populations. A likely explanation for this low level of technology adoption is that stakeholders (e.g. farmers, consumers) were not involved enough in the research to adopt the findings or the findings were not within the capacity of their implementation (Njoku, 2012). Participatory approaches in plant breeding have been proposed as an alternative to address these issues. When participatory techniques are appropriately employed in plant breeding they can have an impact by quickly and cost-effectively producing much improved crop varieties and by accelerating their dissemination and their rate of adoption by farmers (Abebe *et al.*, 2005; Witcombe *et al.*, 2005). Therefore, it is of fundamental importance that farmers be involved in the variety selection and testing process, and that researchers pay careful attention to maize traits that are of most importance to farmers (Bänziger *et al.*, 2000).

2.15. The use of participatory methods to assess farmers' knowledge on crop production

Information gathering is a necessary prerequisite for designing successful programs and project activities to help rural communities (Freudenberger, 1999). Participatory and qualitative methods such as RRA (Rapid Rural Appraisal) and PRA (Participatory Rural Appraisal) have proven to be very useful tools in gathering information in rural areas (Bhandari, 2003). This information enables breeders to customize their varieties and refine their approaches according to the needs and circumstances of the farmers (Freudenberger, 1999). PRA is a continuous process and a more participatory approach that actively involves the communities' members, facilitates their analytical capabilities and empowers them to plan and undertake sustainable action (Freudenberger, 1999). On the other hand RRA is rather more extractive (Campbell, 2001) and less participatory (Freudenberger, 1999). RRA is relevant when information is needed quickly and decisions are preempted by the passage of time (Chambers, 1981). It is a short time study conducted in a limited number of representative sites to collect rough but accurate baseline information (Campbell, 2001). RRA is most important in the very early phases of project planning where basic information is needed to define project's priorities and project's approaches to be adopted to address the target population's concerns.

CHAPTER THREE

3.0. Maize production in Niger: crop management practices and production constraints

3.1. Introduction

Maize production in Niger has not been well documented compared to millet or sorghum production. Data on maize production in Niger is not exhaustive and has not been regularly updated. The data available is mostly on basic crop statistics e.g. area cultivated, grain yield, price and quantity imported. According to the National Statistics Institute (INS-Niger, 2013) the area devoted to maize cultivation in the country averages 7,400 hectares annually. The grain yield per hectare is around 0.8 ton, being the lowest in West Africa. The national production of maize remains low and averages 4,000 tons annually. However, it should be noted that the data on the national production does not take into consideration all the maize produced for green consumption, yet the green maize probably represents the most important part of the national production.

Recently the government of Niger decided to boost the national agricultural production through a new policy called “3N Initiative: Nigerien feed Nigerien” which basically aims at developing irrigation facilities and facilitating access to agricultural inputs and other modern farming technologies to farmers (HCI-3N, 2012). Maize was identified as a strategic crop in this new initiative particularly in areas where irrigation facilities are available. The national demand of high quality seeds of improved maize varieties is increasing and the agronomic research institutions are expected to play an important role in this new initiative through the development of new improved maize cultivars.

In order to accomplish this important task and meet expectations, maize breeders in the country need to understand the maize production system. This includes gathering information on

the types and characteristics of maize varieties that farmers prefer, the major factors limiting maize production, and the farming practices used by maize growers e.g. fertilizer application, crop association, pesticide usage, level of adoption of new cultivars and new farming technologies. The present study is a rapid rural appraisal conducted in eight maize production sites located in three different agro-ecological zones in Niger as an attempt at accessing to such important information on maize production in the country.

The main objectif of the study was to develop a better understanding of the maize production system in the country. The specific objectives were to (i) assess the importance of maize among the different crops produced in Niger, (ii) determine the different uses of maize crop in the country, (iii) assess the efficiency of farming practices used by maize growers in Niger, (iv) identify maize varietal preferences of farmers, (v) identify major factors that limit maize production in Niger, and (vi) determine the production facilities that could allow enhancing maize production in the visited sites.

3.2. Research methodology

3.2.1. Sites of the study

The RRA study was conducted in three districts (Figure 1) corresponding to three different agro-ecological zones and two different types of maize production systems:

- District of **Tchirozérine (region of Agadez)**. It is located in the **Saharan zone** which represents about 77% of the country. This zone has an annual precipitation hardly reaching 150 mm. Maize is produced under irrigation.

- District of **Madarounfa (Region of Maradi)**. It is located in the *Sahelian zone* which covers about 10% of Niger's total area. This zone has an annual precipitation of 400 to 500 mm. Maize is mostly produced under irrigation but also under rain-fed conditions.

- District of **Gaya (region of Dosso)**. It is located in the *Sahelo-Sudanian zone* which covers about 1% of Niger's total surface area and receives 700 to 900 mm of precipitation annually. Maize production is carried out under rain-fed conditions.

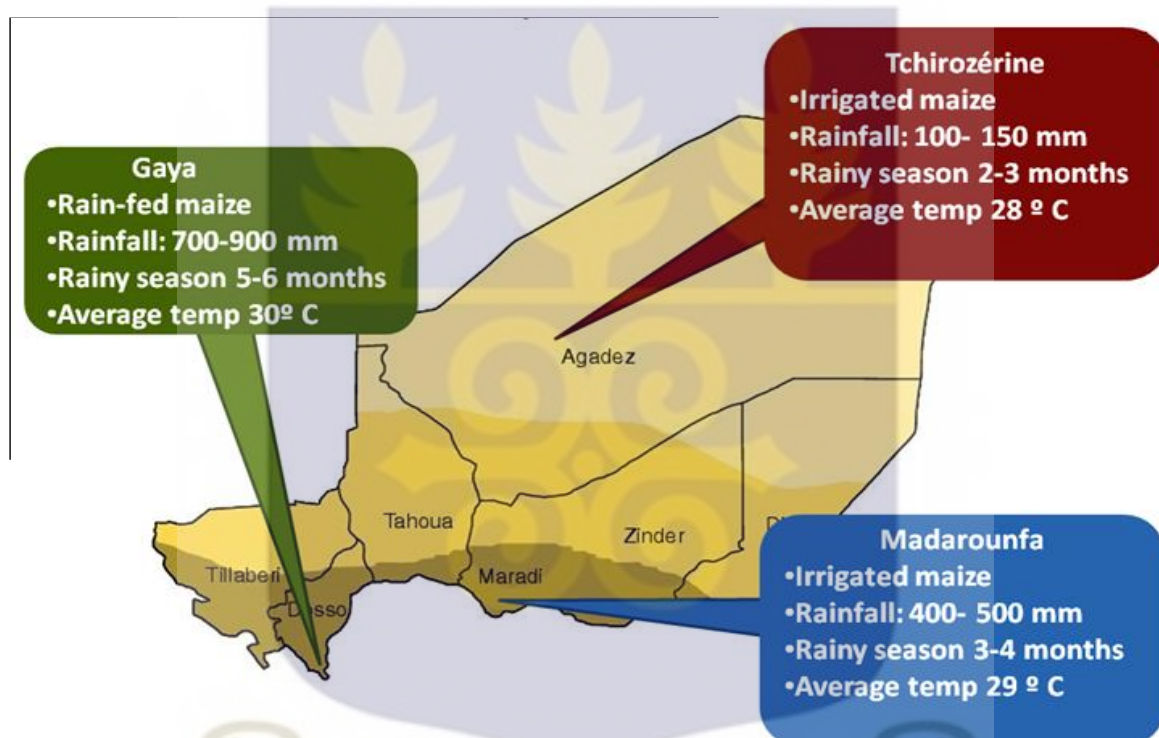


Figure 3.1. Sites of the rapid rural appraisal study on maize production in Niger

In each of the districts of Madarounfa and Gaya three villages that are maize production sites were chosen for the study. Initially, the district of Tchirozerine was not among the proposed sites to visit during the study. An opportunity offered by a mission conducted by the sorghum breeding unit of INRAN in the district was seized to carry out the RRA study in two villages of the Bagzan Mountain located in that district. However some of the RRA tools (e.g. simulation of

field activities by farmers) could not be applied in these two villages for lack of time. In total eight villages were used for the study (Table 3.1.).

Table 3.1. Characteristics of the sites used for the RRA study.

Districts	Villages	GPS Coordinates	Average rainfall (mm)	Length of the rainy season (months)	Type of land	Altitude (m)	Type of production
Tchirozérine	Emaléoulé	N 17°42' E 8° 46'	100-150	2-3	high land	1500	irrigated maize
	Bagzan n'Amass	N 17°42' E 8° 45'	100-150	2-3	high land	1500	irrigated maize
Madarounfa	Djiratawa	N 13°24' E 7°8'	400 -500	3-4	Valley land	350	irrigated maize
	Riadi	N 13°25' E 7° 8'21'	400 -500	3-4	Valley land	350	irrigated maize
	Koderawa	N 13° 22' E 7° 9'	400 -500	3-4	Valley land	350	irrigated maize
Gaya	Yelou	N 12° 15' E 3° 34'	600 -800	5-6	Valley land	185	rainfed maize
	Guidan Gaba	N 12° 10' E 3° 27'	500 -700	5-6	Valley land	190	rainfed maize
	Bengou	N 11° 59' E 3° 35'	600 -800	5-6	Valley land	185	rainfed maize

3.2.2. RRA team and farmers' selection

The RRA team was composed of the PhD Student (myself), a female agronomist, an agricultural development technician, the agricultural extension officer in charge of the village and a representative of farmers' organization in the village. In each of the eight villages a stratified random sampling procedure was used to select a group of 15 to 20 farmers that were representatives of the maize farmers' population in the village. The local authorities, the farmers' association and the agricultural extension officer were involved in the process of selection of participating farmers. The strata considered were gender, age, social status, and maize production capacity. The selection was done in such a way that elements of all the strata were represented in

the group. However, for social consideration and also to avoid gender bias, female groups and male groups were kept separated.

3.2.3. Data collection

Local authorities and agricultural extension officers were actively involved to facilitate the creation of good rapport with farmers and to sensitize them to be committed to the survey. Different RRA tools including (1) focus group discussion (FGD), (2) matrix ranking, (3) transect walks for field observations, and (4) simulation of field activities by farmers were used to obtain information (Figure 3.2.). The group discussion was guided by a checklist (Appendix 3.1.). The agricultural extension officer intervened as a facilitator and ensured that each farmer participated in the discussion and brought his own opinion on the matter. The topics for the discussions were the importance of maize among the crops produced by farmers, the different uses of maize, the type of production, the level of the production, and the different challenges facing maize growers. The farmers were asked to list and rank the major constraints to maize production and the key traits they pay attention to in adopting new maize cultivars. At the end of the discussion, except in the district of Tchirozérine, farmers were asked to simulate field operations such as planting and fertilizer application as practised in their own fields. The purpose was to have an idea of the plant density and the quantity of fertilizers used by farmers. After the group discussions a transect walk was carried out for field observations with some of the farmers. The objectives of the group discussions and the different RRA tools used to achieve them are presented in Table 3.2.



Figure 3.2. Simulation of planting at Koderawa (left) and fertilizer application at Jiratawa (right)

Table 3.2. Objectives of the RRA study and RRA tools used to achieve them

Objectives	PRA tools			
	FGD with Checklist	Matrix ranking	Transect walk	Simulation of field activities
Assess the importance of maize among the different crops produced in Niger	✓		✓	
Determine the different uses of maize crop in the country	✓			
Assess the efficiency of the farming practices used by the maize growers in Niger	✓		✓	✓
Identify farmer preferences for maize cultivars	✓	✓		
Identify major factors limiting maize production in Niger	✓	✓	✓	
Determine the production facilities that could allow enhancing maize production in the visited sites	✓		✓	

3.2.4. Data analysis

It should be noted that unlike quantitative methods (e.g. formal questionnaire) which generate information that can be captured numerically, qualitative methods such as RRA and PRA generally do not generate numbers for statistical analysis (Freudenberger, 1999). Their main focus is to explore meanings, processes, reasons and explanations. This is then captured in text or diagrams, but generally not in numbers (Freudenberger, 1999). Therefore most of the results of this study are narrative reports and not supported with statistically analyzed data. They are however worth reporting as an attempt to provide roughly accurate and useful information on the maize production system in Niger.

Data on plant population densities and amount of mineral fertilizers applied by farmers obtained from the simulation of field activities is analyzed using Microsoft Excel 2007. Means and standard deviations are computed for a rough comparison of field management practices among farmers from different sites.

3.3. Results

3.3.1. Importance of maize among the cereal crops produced in Niger

The RRA study revealed that maize production under rain-fed conditions has significantly reduced in the district of Madarounfa and even in the district of Gaya. In the district of Tchirozerine maize is produced solely under irrigation. Production under rain-fed conditions in the first two districts was supplanted by crops such as pearl millet, cowpea, sorghum and rice. However, maize is the first cereal crop grown under irrigation in all the three districts even though it is competing for the first place with wheat under irrigation in the district of Tchirozerine. The average land holding per farmer hardly exceeds a hectare. Maize is mostly

associated with legume crops for the production under irrigation in the district of Madarounfa. Maize sole crop production is found in the district of Gaya under rain-fed conditions and in the district of Tchirozerine under irrigation during the hot period (June to September).

3.3.2. Utilization of maize produced in Niger

Maize produced in Niger cannot meet the total national demand; it is therefore used for internal consumption. Maize grain is basically used for preparing traditional dishes such as the famous *Tuwo* with okra sauce. A large part of the national production is consumed as green maize either roasted or boiled while the green stalks are used as fodder for cattle and sheep. Apart from the two villages of the district of Tchirozerine where maize is produced for farmers' consumption, the majority of farmers interviewed were producing maize as a cash crop. In the villages of the district of Madarounfa, farmers reported that the beginning of the rainy season coincides with the period when farmers are the most vulnerable and when they also need to buy inputs for the new season. The green maize ears produced are therefore sold in the neighboring cities in order to raise cash to buy inputs and to meet other family needs. In the case of the majority of female farmers of the two districts of Madarounfa and Gaya, maize is not sold as green ears but kept until complete maturity. The production is then conserved for use during special traditional celebrations or in cases of family emergency.

3.3.3. Farming practices used by maize growers in Niger

The RRA findings revealed that crop management practices tend to be similar among farmers from the same locality. However, the ability to cultivate and manage a maize field according to what is recommended by the agronomic research depends on the awareness of farmers, the training they had received, and their financial resources. Few of the farmers

interviewed were aware of good crop management practices but could not adopt them for lack of financial resources. The RRA study also established that farmers from the eight villages practice land preparation with animal drawn ploughs before sowing but only a few of them apply manure because of lack of availability. Plants are inappropriately thinned to three per hill in all the villages. In Yelou and Bengou the plants were even thinned to four plants per hill. The weeding was done manually three or four times during plant growth and development depending on weed infestation and the ability of farmers to afford more weed control. Despite the thinning of plants to three or four per stand, the final plant population density used by farmers remains low (around 44,000 plants/ha). Results from the simulation of planting by farmers showed that 75% of them used plant population density below the recommended level (62,500 plants/ha) (Figure 3.3).

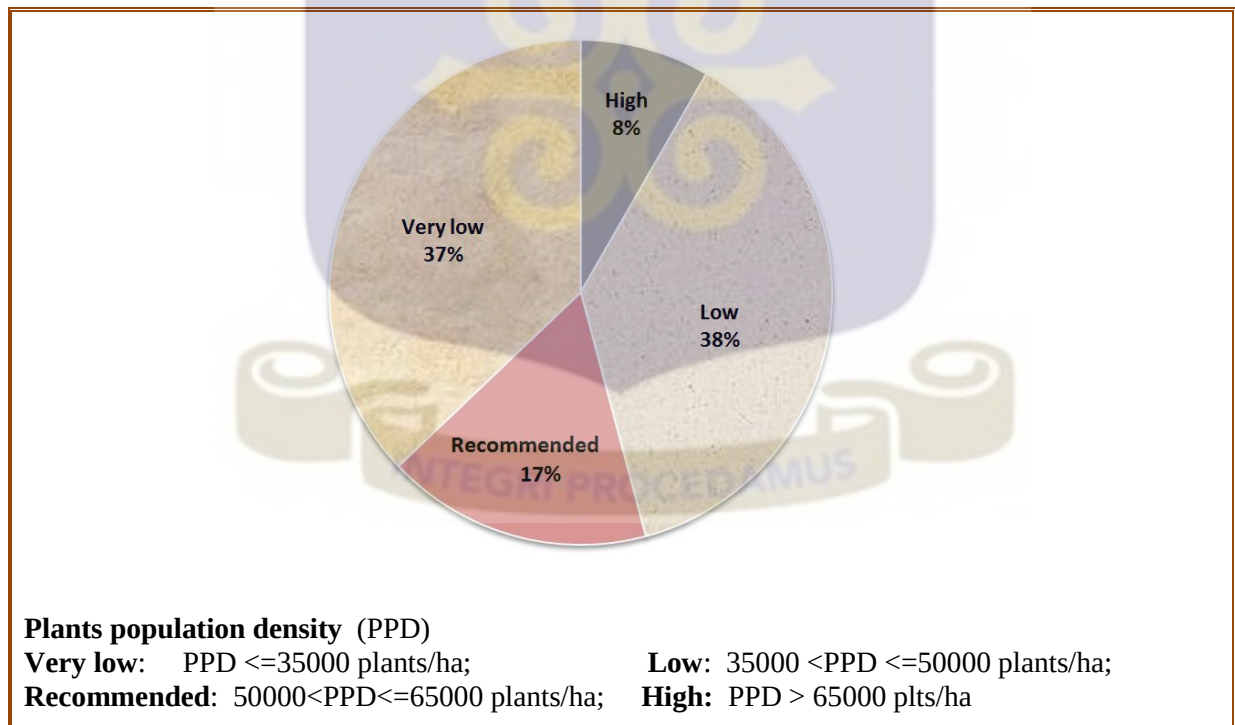


Figure 3. 3. Percentage of farmers applying different plants population densities across study sites

Results of the survey in the districts of Madarounfa and Gaya showed that farmers from the villages of Jiratawa and Yelou tended to use plant densities close to the recommended level. The lowest plant densities were observed at Guidan Gaba and Bengou (Figure 3.4).

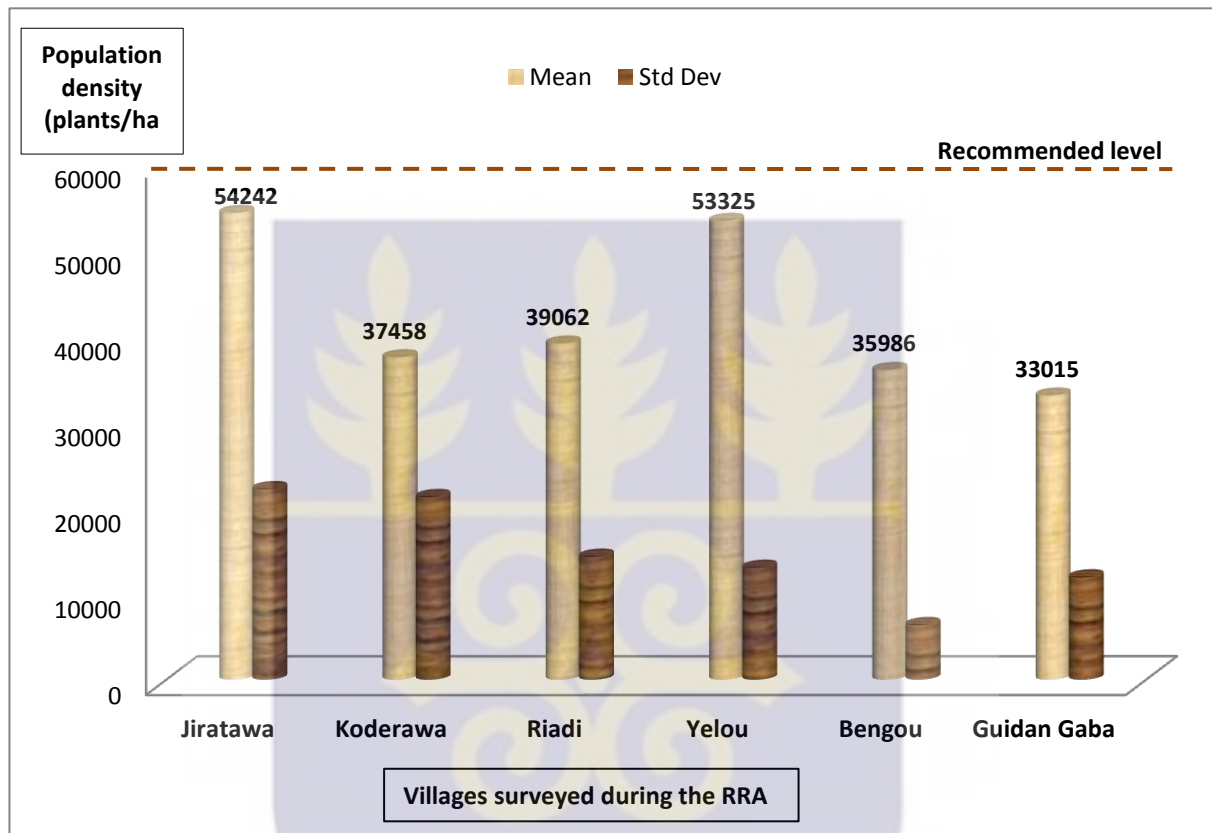


Figure 3.4. Plant population density adopted by farmers in the villages surveyed

The majority of farmers interviewed were aware of the right type of mineral fertilizers to apply. However, few of them were aware of the quantity of fertilizer recommended per hectare, the right time to apply the fertilizer and the appropriate method to use for the application. The common practice used by farmers is the placement of the dose of fertilizer on the ground at the base of the maize stalks. Results across the visited sites revealed a low application of mineral fertilizers by farmers particularly the compound fertilizers NPK. Ninety percent and 65% of farmers across the villages applied NPK and Urea fertilizers respectively far below the recommended rates (Figure 3.5).

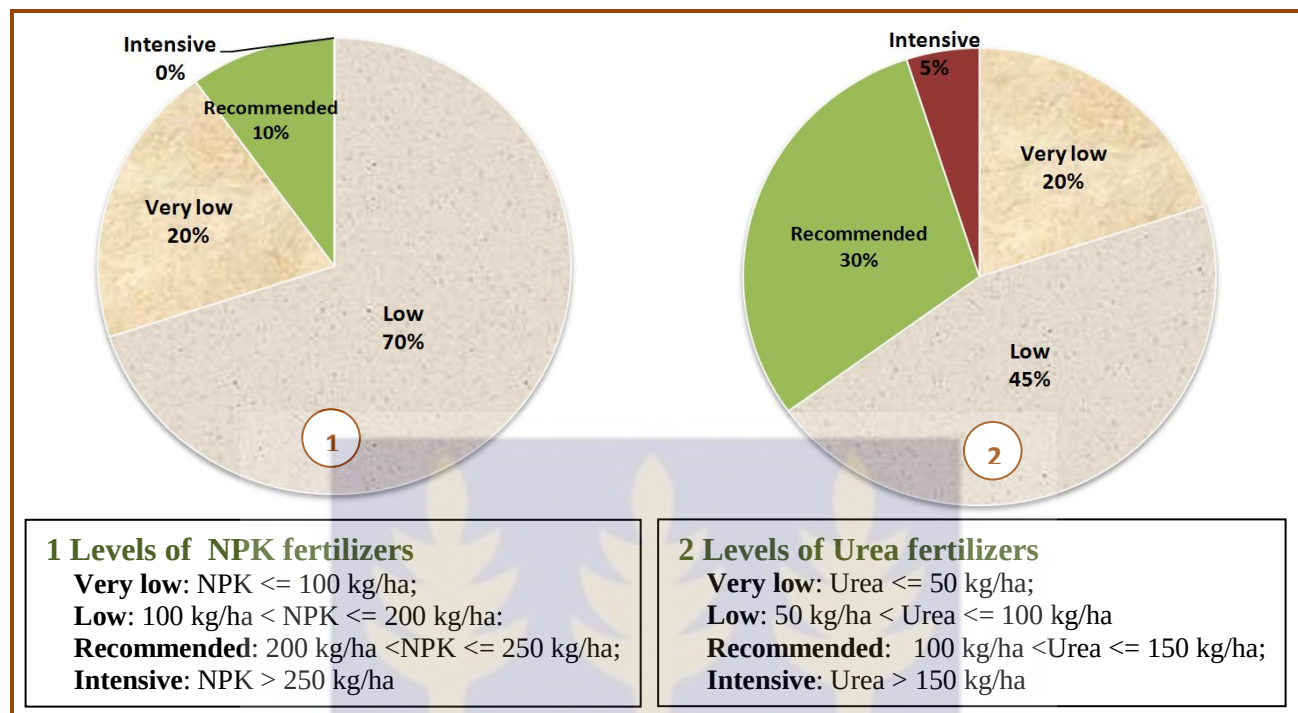


Figure 3.5. Percentage of farmers applying different level of mineral fertilizers across the sites of the study

Like for plant population densities, farmers from Jiratawa and Yelou also tended to apply the highest levels of mineral fertilizers (Figure 3.6.)

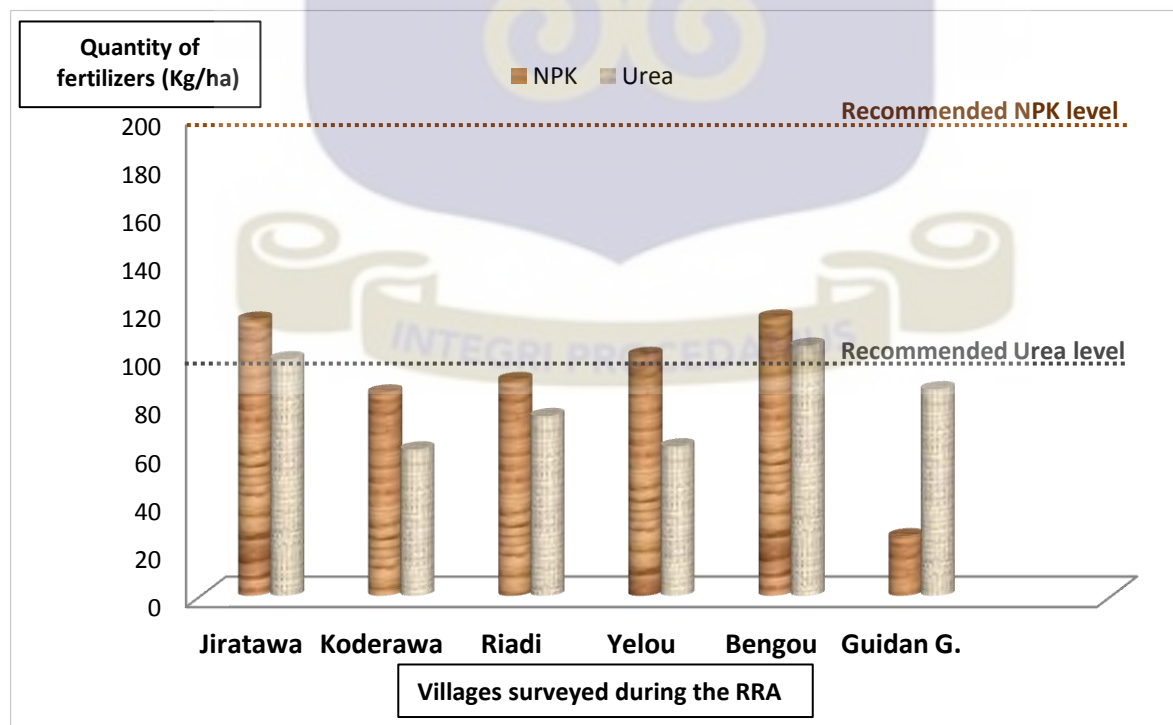


Figure 3.6. Quantity of mineral fertilizers applied by farmers in the villages surveyed

3.3.4. Maize traits preferred by farmers

There was a common agreement among the farmers interviewed that earliness and yield are the most important traits considered in the adoption of new maize cultivars. The second most important criterion used in varietal selection is the grain color. The yellow endosperm is preferred by the majority of the farmers. The maize yellow endosperm grain is believed to be more delicious than the white endosperm grain type. Farmers also indicated that the yellow grain endosperm provides more flour for preparing the popular local meal "tuwo massara" than the white grain type. However, in the district of Tchirozérine, farmers preferred the white endosperm. It seemed that farmers did not believe much in traits conferring tolerance to abiotic stresses. Apart from the earliness, none of these traits was ranked among the criteria used in varietal selection.

3.3.5. Major factors limiting maize production in Niger

Low soil fertility and the lack of availability of fertilizers at affordable prices constituted the most important constraints to the production of maize under irrigation as well as under rain-fed conditions. The second most important constraint is the lack of availability of good quality seeds of improved varieties. Farmers reported that seed saving and seed exchanges among farmers remain the major sources of maize seeds each growing season. In the district of Madarounfa farmers mentioned the African stem borer (*Sesamia calamistis*) (Figure 3.7) attack during the dry and cold seasons and bird damage as another major production constraint. Since 2008, the ring-necked parakeet (*Psittacula krameri*) (Figure 3.8) is reported by farmers to have become a serious constraint to green maize production. In the village of Bengou farmers added that maize production was also challenged by flood and field devastation by grazing animals. Drought was not identified among the constraints to maize production listed by farmers. However, when the

issue of drought was discussed by farmers, it came out that the significant changes observed in the rainfall distribution pattern represents the most important cause of the reduction of maize cultivation under rain-fed conditions in Niger. When drought became frequent, farmers preferred to grow other crops which are more tolerant to drought such as pearl millet, cowpea and sorghum. Only very few of them still grow extra-early maize cultivars on very limited areas.



Figure 3.7. Maize stem borer (*Sesamia calamistis*) (left) attack in maize field at Jiratawa (right)



Figure 3.8 The ring-necked parakeet (*Psittacula krameri*) (left) attack on maize cob at Jiratawa (right)
P. krameri image source: (Sevcik, 2014)

3.3.6. Availability of production facilities for increasing maize production in the visited sites

The transect walk carried out in the study sites and the group discussion with farmers revealed that maize grain yield and maize productivity are significantly higher in areas where irrigation facilities are available than in areas where farmers rely only on the rainfall for maize production. This suggest that the expansion of maize production in Niger will depend largely on the development of irrigation facilities. The Republic of Niger has an important potential of underground water and the authorities are currently investing in irrigation development. The irrigation facilities developed vary from the classic animal drawn water at Emaléoulé in the district of Tchirozerine, to artesian boreholes connected with water reservoir for flood or drip irrigation at Yélou in the district of Gaya, and to electric powered boreholes at Jiratawa in the district of Madarounfa.

3.4. Discussion

The RRA study findings suggest that maize production in Niger is carried out under poor crop management practices. This is certainly one important reason for the low grain yield recorded in the country. These findings should be taken into consideration by the policy-makers whose ambition is to boost the national production by facilitating farmers' access to seeds of improved varieties and other agricultural inputs. This approach should be accompanied by the creation of awareness and training of farmers on appropriate and effective crop management practices. The incredible increase in maize grain yield recorded in the USA from 1930 to date is not only due to the wide adoption of maize hybrids but also to changes in crop management practices such as increased nitrogen fertilizer application and higher plant densities (Russell, 1991; Duvick, 1999; Duvick, 2005b).

Despite farmers' knowledge of the importance of organic and mineral fertilizers in maize production, the quantity of fertilizers applied by farmers remains very low. This is essentially due to the inability of the majority of farmers to afford enough fertilizers particularly at the beginning of the rainy season which coincides with the period where farmers' food stock is low and, thus, are the most vulnerable. Mineral fertilizer prices on the market at that period in Niger are even higher than the main staple food crops such as millet, maize and sorghum. The issue of low application of mineral fertilizers because of their high prices by farmers has been reported by many authors as one of the major factors contributing to low crop productivity in Africa (Heisey and Mwangi, 1996; Gruhn *et al.*, 2000; Morris *et al.*, 2007; Denning, 2009; FARA, 2009; Druilhe and Barreiro-Hurlé, 2012). In addition to the low use of mineral fertilizers, inappropriate application consisting of placing the fertilizer dose on the ground near the plant stalks contributes to an inefficient nutrient uptake by plants. A study on nitrogen fertilizers conducted in Niger revealed that only 20 percent of the applied nitrogen is found in the harvested crop (Christianson and Vlek, 1991). However the low amount of mineral fertilizers used by farmers is justified where soil moisture is a limiting factor. In environments exposed to frequent drought, high nitrogen application may actually diminish yield (Christianson and Vlek, 1991; Morris *et al.*, 2007).

The study revealed the use of plant densities below the level of 62,500 plants/ha recommended by the National Agronomic Research Institute (INRAN). Optimum plant densities for maximum maize grain yield depends on water availability, soil fertility, maturity period, planting date and row spacing (Sangoi, 2000). Given the low soil fertility and harsh climatic conditions in Niger, the adoption by farmers of low population densities under rain-fed conditions may be a reasonable practice. Maize grain yield has been reported to be dramatically

reduced under high plant densities when water and nitrogen supply are limiting factors (Keating and Wafula, 1990; Sangoi, 2000; Fasoula and Tollenaar, 2005). However, there is no single recommendation for plant population densities for all conditions (Sangoi, 2000). It is likely that early maturing genotypes (which are the types grown in Niger) may require higher plant densities for maximum yield than the late maturing genotypes (Tollenaar, 1992; Sangoi *et al.*, 2002). A study in pearl millet conducted in Niger revealed that under drought conditions and four different levels of N fertilizer, yield reduction under relatively high planting density i.e. 60,000 plants/ha was not significantly different from that at the low planting density i.e. 10,000 plants/ha (Christianson and Vlek, 1991) suggesting that low plant density does not guarantee a better yield in water limiting environments. The higher plant densities observed in the villages of Jiratawa and Yelou may be explained by the collaboration and the training received by farmers from the two main agronomic research institutions in the country i.e. INRAN and ICRISAT.

Low soil fertility is a serious concern to maize production at all the study sites as to any crop production in the whole country. Many reports indicate that lack of moisture is a major constraint to crop production in West Africa but that poor soil fertility is a more serious concern in the long run (Bationo and Mokwunye, 1991; Gruhn *et al.*, 2000). In general, soils in Niger have low organic matter content and are naturally deficient in phosphorus and nitrogen. In addition to these, continuous cropping over decades with no measures in place to regenerate the soil productivity has worsened the soil fertility status and the level of crop production in the country as in many African countries (Keating and Wafula, 1990; Smithson and Giller, 2002; FARA, 2009).

Another important challenge to maize production in the country is the lack of availability of improved varieties. Maize has not been considered as a priority crop in the breeding programs

of INRAN. Up to now very few early maturing yellow-grained OPVs (P₃Kollo, CET) have been released by the institute. Some OPVs (e.g. MAKKA, EV 84-22 RS) have been introduced in the country through research collaboration with regional and international research institutions (MA-Niger, 2012). However P₃ Kollo is still the most widely grown maize variety because of its shorter cycle (75 to 85 days) even though its yield potential rarely exceeds 4 tons/ ha under optimal growing conditions.

Stemborer attack and bird damage were also reported by farmers to be a big threat to maize production particularly in the villages of the district of Madarounfa. The African stemborer *Sesamina calamistis* attack is widely reported at these sites. A similar stemborer species *Busseola fusca* has not been reported in Niger but it is present in almost all the neighboring countries as well as in Central, Eastern and Southern Africa (Harris and Nwanze, 1992). *Sesamina* infestation is observed on maize mostly during the dry and cold seasons i.e. from October to February. Signs of the attack appear 2-3 weeks after planting and increase in severity until the harvest; plant growth is therefore highly affected (Kouamé, 1995; Kalule *et al.*, 1997; Oigiangbe *et al.*, 1997). However the stemborer populations and the degree of infestation vary over seasons and from one site to another (VandenBerg, 2012). Bird damage is mostly caused by the ring-necked parakeet *Psittacula krameri krameri* whose populations are found from Senegal to Uganda and in South Sudan (Butler, 2003; Ahmad *et al.*, 2011). The Asian sub species *P.k. parvirostris* was reported to reduce maize crop yields by up to 81% (Reddy and Long cited in Butler, 2003). In Niger *P.k. krameri* damage was observed on forest trees but was recently reported on mango, guava, and maize. Ahmad *et al.* (2011) reported that the damage on maize caused by *P. krameri* is highest at the maturity stage (23.8%) and minimum (7.60%) at the germination stage.

Niger is one of the Sahelian countries whose agriculture is frequently challenged by drought. Yet farmers at the study sites did not rank drought among the major constraints to maize production. Farmers mentioned problems for which they think there may be a solution. They believe that drought is not among such problems. It is a phenomenon that cannot be under the control of men. Farmers don't believe much in drought and low nitrogen tolerance in maize particularly for the type of severe drought they are experiencing in Niger. Their perception is that maize is an exigent crop that should be grown only when well-watered conditions and good level of soil fertility are guaranteed. Therefore, when moisture becomes a limiting factor farmers prefer to grow crops that are more tolerant to drought like pearl millet, sorghum or cowpea. However, considering the harsh climatic conditions of maize growing areas in Niger, there is no doubt that drought tolerant maize genotypes are more appropriate even where irrigation facilities are available. Indeed water availability for irrigation varies even in those areas. For instance the frequency of irrigation in the large public irrigation schemes of Konni and Jiratawa depends on the water level in the dam of Cerasa for Konni and on the availability of electricity for running the boreholes at Jiratawa.

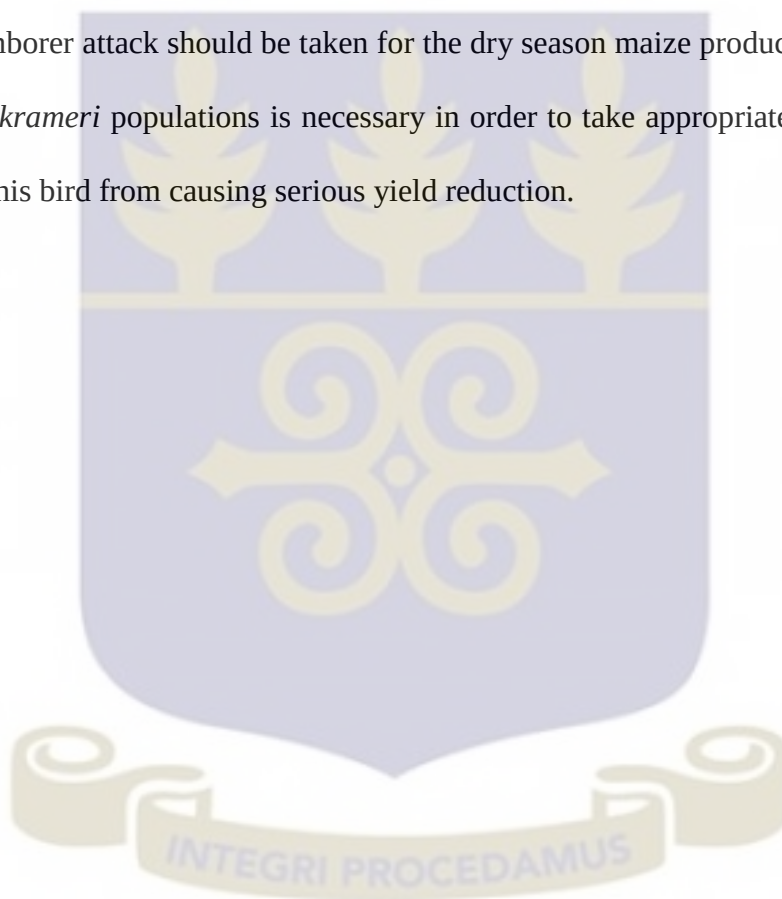
Earliness and yield are the most important traits in farmers' criteria for the selection of maize cultivars at all the visited sites. The two negatively correlated traits are reported to be of major importance to farmers by many authors (Defoer *et al.*, 1997; Abebe *et al.*, 2005; Obaa *et al.*, 2005; Ouma *et al.*, 2010; Sibiya *et al.*, 2013). Early maturing varieties are needed by farmers for different reasons. Obaa *et al.* (2005) reported that varieties with shorter cycle can escape drought and ensure early and quick provision of cash and food to households for hunger alleviation. They may also be planted twice in environments where rainfall has a bimodal distribution. The next important trait mentioned by farmers is the endosperm color. Yellow-

grained maize is desired by farmers for green consumption. It is also reported to have a better taste in local meals whereas white endosperm maize is reported to be preferred in many sub Saharan countries (Sibiya *et al.*, 2013). Traits conferring tolerance to biotic stresses (pests and diseases) and abiotic stresses were not mentioned by farmers probably because genotypes carrying such traits are not available for them to see the difference. Taking into consideration farmers' preferred traits in a breeding program may increase the chance of adoption of newly released varieties. However, it is difficult to predict farmers' decisions on whether to adopt or not to adopt a new variety (Doss *et al.*, 2003). The best option is to give farmers choice and let them test the new materials. In the villages of Emaléoulé and Bagzan n'Amass farmers grow a recently introduced white grained and intermediate maturing variety. They preferred it over their local extra-early yellow grained variety for its higher grain yield. A similar case showing farmers' decision to tolerate late maturing variety when it is associated with higher grain yield and other desirable traits was reported by Tiwari *et al.* (2009).

3.5. Conclusions and breeding implications

The study was conducted to understand maize crop management practices in Niger, identify maize characteristics desired by farmers and the major constraints to maize production in the country. Some important findings that can have practical implications for the national breeding program and policy were revealed by the study. Maize production in Niger is carried out under poor crop management practices particularly low fertilizer application and low plant population densities. This suggests that more effort is needed in training and creating awareness among farmers on appropriate and effective maize field management practices. This also calls for the government of Niger to implement a national input subsidy program to help farmers increase the rates of fertilizer application for a better response of their crops. Early maturing yellow-grained

cultivars with acceptable grain yield are generally preferred by farmers. This suggests that the national breeding program should take into consideration those traits in the development of new maize varieties. Maize production in Niger is challenged mainly by low soil fertility and water limiting conditions suggesting that new maize cultivars should carry low nitrogen and drought tolerance genes. Biotic stresses such as stemborer (*Sesamia calamistis*) and bird (*Psittacula krameri*) damage are also serious concerns in some areas. Therefore appropriate control measures for stemborer attack should be taken for the dry season maize production. Also, careful monitoring of *P. krameri* populations is necessary in order to take appropriate control measures that can prevent this bird from causing serious yield reduction.



CHAPTER FOUR

4.0. Combining ability for grain yield and other agronomic traits of early maturing maize inbreds under drought and well-watered conditions

4.1. Introduction

Maize is a cereal crop that underpins the household and national food security in many African countries (Gibbon *et al.*, 2007). Its production is frequently challenged by drought. Significant yield losses in maize due to drought are expected to increase with global climate change as temperature rises and rainfall becomes uncertain in key traditional production areas (Campos *et al.*, 2004; Ribaut *et al.*, 2009). In the savannah agro-ecology of West and Central Africa (WCA), all the countries experience drought during the growth cycle of maize (Badu-Apraku *et al.*, 2004). Yield losses due to drought average 15 percent annually in the sub-region (Badu-Apraku and Lum, 2010; Badu-Apraku *et al.*, 2011a) even in areas where total rainfall is reasonably high (Fischer *et al.*, 1982). Drought is probably responsible for a much higher economic loss than indicated because in drought-prone environments, the high probability of drought occurrence dissuades farmers from applying adequate levels of fertilizers and using high planting densities (Fischer *et al.*, 1982; Pswarayi and Vivek, 2008).

Adapting crop phenology to rainfall patterns through drought escape mechanisms is one strategy adopted to achieve yield stability in drought-prone environments (Fischer *et al.*, 1982; Bänziger *et al.*, 2004). Fischer *et al.* (1981) indicated that the most effective means of reducing the effects of drought on maize would be to escape periods of low moisture availability through the manipulation of genotype maturity and planting date. It is obvious that early maturing genotypes are more suited to areas with a short growing period and those facing recurrent terminal drought as they can complete their growing cycle before the occurrence of the drought.

They are also preferred by farmers as they provide an early harvest to bridge the "hunger period" before the harvest of full-season crops. They provide flexibility in planting dates which enables multiple plantings in a season to spread risk of losing a single crop due to drought. Lastly, they are suitable for late plantings when there is a delay in the onset of rainfall (Pswarayi and Vivek, 2008; Badu-Apraku *et al.*, 2013b).

However, unlike low soil fertility or mineral toxicity, drought stress is strongly dependent upon random weather conditions (Campos *et al.*, 2004). Therefore, the manipulation of the maturity cycle or the planting dates of maize cultivars alone is not an appropriate solution in such environments. The use of genes that confer drought tolerance to improve early and extra-early maturing maize cultivars is the most appropriate alternative to improve productivity and ensure stable production of maize crop in WCA (Campos *et al.*, 2004; Badu-Apraku *et al.*, 2013a).

The previous Rapid Rural Appraisal study conducted in eight maize production sites in Niger revealed that the low maize production observed in the country is due to multiple factors such as drought and lack of availability of high yielding and stable maize genotypes. It also revealed that early maturing maize genotypes of yellow type are preferred by farmers. It is therefore important to firstly develop high yielding and stable maize varieties of yellow type that could also display less yield reduction under drought and, secondly, facilitate their accessibility to Nigerien farmers. The present study is an attempt at achieving the first objective and consists of (i) introducing early maturing and drought tolerant yellow maize inbreds in the country, (ii) developing an efficient method for screening maize genotypes under drought, (iii) developing maize single cross hybrids from the introduced inbreds and evaluating their performance under drought and optimum growing conditions, and (i) exploring the combining ability and heterotic pattern of these inbreds for future studies.

The international centers for maize improvement IITA and CIMMYT have developed a large number of early maturing maize inbreds that are adapted to the climatic conditions of sub-Saharan African countries. However, information on the combining abilities and the heterotic patterns of these lines is limited (Pswarayi and Vivek, 2008; Badu-Apraku *et al.*, 2011c; Badu-Apraku *et al.*, 2013a; Akinwale *et al.*, 2014). Knowledge and understanding of the heterotic patterns of these inbreds will be very useful in developing high yielding and stable hybrids (Badu-Apraku *et al.*, 2011c).

The efficiency of inbred classification into distinct heterotic group depends greatly on the classification method used (Fan *et al.*, 2009). A good heterotic group classification method identifies heterotic groups for which inter-heterotic group crosses produce hybrids superior to the within-group crosses (Fan *et al.*, 2009). Different methods have been utilized for classifying inbreds into heterotic groups. The most widely used classification method is the SCA_PY method which uses specific combining ability with some line-pedigree information and/or field hybrid-yield information to assign a maize line to a heterotic group (Menkir *et al.*, 2004; Fan *et al.*, 2009; Badu-Apraku *et al.*, 2013c). Another method employs various molecular markers to compute genetic similarity or genetic distance to assign maize lines to different heterotic groups (Menkir *et al.*, 2004; Aguiar *et al.*, 2008; Fan *et al.*, 2009; Badu-Apraku *et al.*, 2013a; Akinwale *et al.*, 2014). Fan *et al.* (2009) introduced the HSGCA method defined as heterotic group's specific and general combining ability that combines both GCA and SCA to assign inbred lines to known heterotic groups. Recently another method designated as heterotic grouping based on GCA of multiple traits (HGCAMT) has been proposed by Badu-Apraku *et al.* (2013c) to classify extra-early inbreds into heterotic groups.

The objectives of the present study are to (i) test the efficiency of CIMMYT/IITA screening method (with some modifications) for drought tolerance in Niger, (ii) examine the combining ability and the mode of gene action modulating drought tolerance in 15 early maturing yellow-grained inbreds, (iii) classify the inbreds into heterotic groups using the SCA_PY and HSGCA methods, and (iv) assess the yield performance and stability of the inbreds and hybrids under contrasting environments.

4.2. Materials and methods

4.2.1. Germplasm and mating design

Fifteen early maturing tropical yellow-grained maize inbred lines from IITA and CIMMYT were used in this study. Most of these inbreds were developed under environmental stresses such as drought, low N and *Striga* but information about their combining ability is limited. The characteristics of these inbreds are given in Table 4.1. The fifteen inbred lines were crossed in a 15 x 15 diallel at the National Agronomic Research Institute (INRAN) of Maradi (Niger) to generate 105 single cross hybrids. The diallel crosses and the reciprocals were bulked to obtain enough seed for the field evaluations. It was assumed that no maternal effects on drought tolerance in maize occur. Four early maturing single crosses from IITA (TZEI 9 x TZEI 16, TZEQI 82 x TZEQI 93, TZEI 16 x TZEI 8, and TZEI 23 x TZEI 13) and an open-pollinated variety (OPV) P₃ Kollo from INRAN, Niger were used as checks for the evaluations.

Table 4.1. Origin, pedigree and reaction to abiotic stresses of 15 inbred lines used in the diallel study

No	Entries	Origin	Pedigree	Reaction to :	
				<i>Striga</i>	Drought
1	ENT 4	CIMMYT	[[KILIMA ST94A]-30/MSV-03-2-10-B-1-B-B-xP84c1 F26-2-2-6-B-3-B] F17-1-2-1-1 x P43C9-1-1-1-1-1-BBBB-1-xP	Resistant	Tolerant
2	ENT 13	CIMMYT	[M37W/ZM607#bF37sr-2-3sr-6-...1-B x CML486]-1-1	Susceptible	Tolerant
3	ENT 15	CIMMYT	CLA149	Tolerant	Tolerant
4	ENT 17	CIMMYT	[(87036/87923)-X-800-3-1-X-1-B-B-1-1-1	Susceptible	Tolerant
5	TZEI 14	IITA	TZE Comp5-Y C6 S6 Inbred 21	Tolerant	Tolerant
6	TZEI 16	IITA	TZE Comp5-Y C6 S6 Inbred 31	Resistant	Tolerant
7	TZEI 129	IITA	TZE-Y Pop STR Co S6 Inbred 16-1-3	Tolerant	Susceptible
8	TZEI 23	IITA	TZE-Y Pop STR Co S6 Inbred 62-2-3	Tolerant	Tolerant
9	TZEI 124	IITA	TZE-Y Pop STR Co S6 Inbred 3-1-3	Resistant	Susceptible
10	TZEI 135	IITA	TZE-Y Pop STR Co S6 Inbred 17-2-3	Tolerant	Tolerant
11	TZEI 157	IITA	TZE-Y Pop STR Co S6 Inbred 102-1-2	Tolerant	Tolerant
12	TZEI 161	IITA	TZE-Y Pop STR Co S6 Inbred 103-2-3	Resistant	Tolerant
13	TZEI 167	IITA	TZE Comp5-Y C6 S6 Inbred 13	Resistant	Susceptible
14	TZEI 160	IITA	TZE-Y Pop STR Co S6 Inbred 102-2-3	Resistant	Tolerant
15	TZEI 182	IITA	TZE-Y Pop STR Co S6 Inbred 152-2-2	Susceptible	Tolerant

4.2.2. Stress management

To determine the right time to apply the last irrigation in drought trials in Niger, the drought screening method described by Bänziger et al., (2000) and Badu-Apraku et al. (2004) was used in an experiment conducted during the dry season 2011/2012 at SEHA (the hydro-agricultural experimental station of INRAN Maradi). The local OPV check P3 Kollo and a bulk of F2 seeds from an IITA DT hybrid (TZEE 95 x TZEE 82) were used in the experiment. The two genotypes were sown at five planting dates at five days intervals. For each planting date a block of 10 rows was established for each genotype. An adjacent block of 10 rows of each

genotype was also established with plants grown under well-watered conditions until maturity. All five blocks were irrigated twice a week at the same time. The last irrigation for all five blocks was carried out when plants in the first block were at about one week to anthesis; that is when 50% of plants in that block had hard and swollen flag leaves, an indication of an imminent tassel emergence. A “rescue irrigation” was applied to all the blocks 10 days later. The normal irrigation was resumed 10 days after the “rescue irrigation” until the maturity of plants. The right time to stop irrigation was determined as the one for which about 80 to 85% of yield reduction was observed compared to the yield of the adjacent well-watered block.

4.2.3. Experimental design and evaluation sites

The 105 single crosses and the 5 checks were evaluated under managed drought and well-watered conditions using a 10 x 11 alpha lattice design with 2 replications at the INRAN Research Stations at Maradi (N 13°26' E 7°06'; 350 m altitude; 490 mm average annual rainfall), Konni (N 13°47' E 5°14'; 260 m altitude; 530 mm average annual rainfall), and at FESA Seed Company (N 13° 39' E 7° 04'; 382 m altitude; 500 mm average annual rainfall). The evaluation was done under managed drought and well-watered conditions during the dry season 2012/2013 (October, 2012 to March, 2013) at INRAN Stations at Maradi and Konni. During the rainy season of 2013, the evaluation was done under well-watered conditions at FESA and INRAN Maradi. The second evaluation under managed drought was done during the dry season 2013/2014 (October, 2013 to March, 2014) at INRAN Maradi. In summary, the evaluation was done at the following seven environments (four well-watered environments and three stressed environments):

1. MDS12WWC: Maradi (M), cold and dry season 2012/2013 i.e. October, 2012 to March, 2013 (DS12), under well-watered conditions (WWC);
2. KDS12WWC: Konni (K), cold and dry season 2012/2013 i.e. October, 2012 to March, 2013 (DS12), under well-watered conditions (WWC);
3. MRS13WWC: Maradi (M), rainy season 2013 (RS13), under well-watered conditions (WWC);
4. FRS13WWC: FESA Seed Co (F), rainy season 2013 (RS13), under well-watered conditions (WWC);
5. MDS12WSC: Maradi (M), cold and dry season 2012/2013 i.e. October, 2012 to March, 2013 (DS12), under water stress conditions (WSC);
6. KDS12WSC: Konni (K), cold and dry season 2012/2013 i.e. October, 2012 to March, 2013 (DS12), under water stress conditions (WSC);
7. MDS13WSC: Maradi (M), cold and dry season 2013/2014 i.e. October, 2013 to March, 2014 (DS13), under water stress conditions (WSC);

It is important to note that during the first part of the dry season in Niger (November - January) the cold weather conditions prolong the maturity cycle of maize plants by about 20 days compared to the maturity cycle of the rainy season.

4.2.4. Field practices and stress management

Except for the water treatment, all the field management practices were similar in both the stressed and the well-watered blocks. Each entry was planted in a single row of 5m length with spacing of 40 cm within rows and 75 cm between rows. Three seeds were sown per hill at

planting and the seedlings thinned to two plants per hill about two weeks after emergence to give a final population density of 66 000 plants ha⁻¹. A compound fertilizer (NPK-15-15-15) was applied at the rate of 52 kg N ha⁻¹, 52 kg P ha⁻¹, and 52 kg K ha⁻¹ as follows: at planting 2 grams of NPK fertilizer was placed in each hill with the seeds; the remaining NPK fertilizer (9 grams of NPK /hill) was applied two weeks after planting. Urea was top-dressed at the rate of 46 kg of N ha⁻¹ 20 days later. Weed control was done manually.

The time to impose water stress was determined from the drought screening experiment described above. From planting to water stress imposition plants were irrigated twice a week in all the blocks. Irrigation continued in the well-watered blocks until crop maturity. In the stressed blocks, the water stress was imposed by stopping the irrigation two weeks before flowering. It is important to note that in Niger, during the dry season (October to May) the weather conditions are so harsh that plants could not have survived if the stress had been maintained until the end of the experiment, particularly at Maradi. Therefore the stress intensity was monitored and a “rescue irrigation” was applied when plants started showing signs of severe stress very early in the morning. In 2012, the water stress was imposed at 48 days after planting at Maradi. A “rescue irrigation” was applied 12 days later and the normal irrigation was resumed 10 days after the “rescue irrigation”. In 2012 the stress was imposed at Konni 44 days after planting. A “rescue irrigation” was applied 17 days later and the normal irrigation resumed 11 days after the “rescue irrigation”. In 2014 the stress was imposed at Maradi 50 days after planting. A “rescue irrigation” was applied 17 days later and the normal irrigation resumed 10 days after the “rescue irrigation”.

4.2.5. Data collection

Data for grain yield and other agronomic traits were recorded as follows:

DYA (days to anthesis) is the number of days from planting to when 50% of the plants had shed pollen;

DYS (days to silking) is the number of days from planting to when 50% of the plants had emerged silks;

ASI (anthesis-silking interval) is the number of days between **DYA** and **DYS**;

PLTH (Plant height) measured as the distance from the base of the plant to the first tassel branch was computed as the average height of 10 plants randomly chosen in the row;

EHT (ear height) measured as the distance from the base of the plant to the node bearing the upper ear and was computed as the average ear height of 10 plants randomly chosen in the row;

PASP (plant aspect) estimated based on the overall plant appeal on a scale of 1 to 5, where 1 = excellent plant type and 5 = poor plant type;

HUSK (husk cover) rated on a scale of 1 to 5, where 1 = husks tightly arranged and extended beyond the ear tip and 5 = open tip cover.

NPHARV (number of plants harvested) the number of plants harvested per plot

EHARV (number of ears harvested) the number of ears bearing at least one developed kernel in the plot;

EPP (number of ears per plant) estimated by dividing the total number of ears per plot by the number of plants harvested;

EASP (ear aspect) estimated based on absence of disease and insect damage, ear size, uniformity of ears, and grain filling. It was scored on a scale of 1 to 5, where 1 = clean, uniform, large, and well-filled ears and 5 = ears with undesirable features.

ADJGRY: grain yield adjusted to 15% moisture content. It was computed using the formula: $W_f = W_i * ((100-MC_i)/(100-MC_f))$ where W_f is the final grain weight; W_i is the initial grain weight; MC_i is the initial moisture content and MC_f is the final moisture content (15%);

YLD_HA (grain yield adjusted to 15% moisture and converted to kg ha^{-1}). This was computed from the shelled grain weight and grain moisture at harvest.

SGREEN1 (stay-green characteristic) scored for the water stressed blocks at 90 days after planting on a scale of 1 to 9, where 1 = almost all leaves green and 9 = virtually all leaves dead;

SGREEN2 (stay-green characteristic) scored for the water stressed blocks at 100 days after planting on a scale of 1 to 9, where 1 = almost all leaves green and 9 = virtually all leaves dead.

4.2.6. Statistical analysis

Analysis of variance (ANOVA) was performed on plot means for grain yield and other agronomic characters for each and across environments using PROC GLM procedure of SAS software, version 9.2 TS2M0 (SAS Institute, 2002). In the combined ANOVA, the combination of location, cropping-season, and water treatment was considered as an environment. The entries (105 single-cross hybrids and 5 checks) were considered as fixed factors while environments, replications and blocks were considered as random factors.

The statistical model used for the combined analysis is as follows:

$$Y_{ijkl} = \mu + \alpha_l + b_{kl} + v_{ij} + (\alpha v)_{ijl} + e_{ijkl}$$

Y_{ijkl} = observed trait value from each experimental unit

(i and j = parents; k = replication, l = location);

μ = population mean;

α_l = environment effect;

b_{kl} = block or replication within environment effect;

v_{ij} = F_1 hybrid effect;

$(\alpha v)_{ijl}$ = interaction between F_1 hybrids and environments;

e_{ijkl} = residual effect (Zhang and Kang, 1997).

To identify productive single-cross hybrids under stress conditions, a correlation matrix displaying relationship between grain yield and secondary traits was computed. Then a selection index similar to that used by Badu-Apraku *et al.* (2011d) was computed using standardized data for selected variables that were highly and significantly correlated to grain yield:

$$I = [(2 \times \text{Yield}) + \text{PLTH} - \text{ASI} - \text{PASP} - \text{EASP} - \text{SG2}]$$

PLTH = plant height,

ASI = anthesis-silking interval;

EASP = ear aspect;

PASP = plant aspect;

SG2 = stay green characteristic 2

Genetic analysis of the GCA effects of the parents and SCA effects of the crosses in each environment and across environments was performed using the Griffing's method 4 and model 1 (Griffing, 1956) and the DIALLE-SAS05 program (Zhang *et al.*, 2005). Only the crosses (excluding the checks) were used in the diallel analysis.

The statistical model used for the combined diallel analysis across environments is the following:

$$Y_{ijk} = \mu + E_e + g_i + g_j + s_{ij} + gE_{eg} + sE_{es} + \varepsilon_{ijk}$$

-**Y_{ijk}** : the observed measurement for the ijth cross grown in the kth environment

-**μ**: grand mean

-**E_e**: effect of environment

-**g_i & g_j**: GCA effects; (i and j = parents; i=1...15; j=1...15; k =replications)

-**s_{ij}**: SCA effects;

-**gE_{eg}**: interaction effect between GCA and the environment;

-**sE_{es}**: interaction effect between SCA and the environment,

-**ε_{ijk}**: error term associated with the ijth cross evaluated in the kth replication and the Ee environment.

GCA and SCA effects for the measured traits were computed from the mean values adjusted for the block effects for each environment and across environments:

$$\text{GCA} = \text{Line mean } (X_{.j}) - \text{Overall mean } (X_{..})$$

$$\text{SCA} = \text{Cross mean } (X_{ij}) - \text{Line mean } (X_{.j}) - \text{Tester mean } (X_{i.}) + \text{Overall mean } (X_{..})$$

i and j = parents, i= 1 to15; j= 1 to 15 (Fan *et al.*, 2009)

The relative importance of general combining ability and specific combining ability on the performance of the F_1 hybrids was estimated as the ratio:

$$= \frac{2\sigma^2_{GCA}}{(2\sigma^2_{GCA} + \sigma^2_{SCA})}$$

where σ^2_{GCA} is the quadratic form (analogous to a variance component but referring to a fixed effect) derived from the mean square of GCA effect and σ^2_{SCA} is the quadratic form of SCA effects since the total genetic variation among single-cross progeny is equal to twice the GCA component plus the SCA component (Hung and Holland, 2012).

Two different classification methods i.e. **SCA_PY method** and **HSGCA method** were used to assign the 15 early maturing inbred lines used in the diallel study. The grouping efficiencies of the two classification methods were also compared.

- **SCA_PY method:** the classical method based on the use of specific combining ability with some line-pedigree information and/or field hybrid-yield information (Fan *et al.*, 2009). The procedure used is the one described by Menkir *et al.*, (2004).
- **HSGCA method:** the heterotic group's specific and general combining ability proposed by Fan *et al.*, (2009) and computed as follows:

$$\text{HSGCA} = \text{Cross mean } X_{ij} - \text{Tester mean } (X_{i.}) = \text{GCA} + \text{SCA}$$

- where X_{ij} is the mean yield of the cross between i th tester and j th line;
- $X_{i.}$ is the mean yield of the i th tester;
- $X_{.j}$ is the mean yield of j th line.

The computed HSGCA values were subjected to the three classification steps described by Fan et al., (2009).

The GGE biplot analysis (Yan and Tinker, 2006) was used on the grain yield means adjusted for block effects to obtain information on yield performance and stability of the single-cross hybrids across test environments. It was also applied to the estimated GCA effects of the inbred parents across environments for stability analysis.

The GGE biplot model used is:

$$Y_{ij} - \beta_j = \lambda_1 \xi_{i1} \eta_{j1} + \lambda_2 \xi_{i2} \eta_{j2} + \varepsilon_{ij}$$

- Y_{ij} is the genetic value (yield) of the combination (hybrid) between Entry i (hybrid) and Tester j (environment) for the trait of interest;
- β_j is the mean of all combinations involving Tester j ;
- λ_1 , and λ_2 are the singular values for PC1 and PC2;
- ξ_{i1} and ξ_{i2} are the PC1 and PC2 eigenvectors, respectively, for Entry i ;
- η_{j1} and η_{j2} are the PC1 and PC2 eigenvectors, respectively, for Tester j ;
- ε_{ij} is the residual of the model associated with the combination of Entry i and Tester j .

4.3. Results

4.3.1. Identification of the time to impose water stress in maize drought studies in Niger

In the drought experiment conducted to identify the right time to impose water stress for maize genotypes evaluated under managed drought in Niger, data from two blocks corresponding to the 4th and the 5th planting dates for P₃ Kollo was discarded because of high soil heterogeneity observed in the field and termite damage. Data for the number of days to anthesis was not recorded because more than 50 percent of plants had tassel blast and did not shed pollen. Therefore it was not possible to compute the anthesis - silking interval.

The highest grain yields i.e. 3,627 Kg ha⁻¹ and 2,369 Kg ha⁻¹ displayed respectively by P₃ Kollo and the F2 of the cross TZEEI 95 x TZEEI 82 were obtained from the well-watered blocks. The lowest grain yields were observed in the first and second planting dates for which irrigation was stopped 7 and 12 days before flowering, respectively (Table 4.2 and Figure 4.1).

Table 4.2. Grain yield of the drought experiment conducted to identify the right time to impose moisture stress in maize drought trials in Niger.

Genotypes	Grain Yield in Kg ha ⁻¹ adjusted to 15% moisture content					
	WWC*	WSC* 1	WSC 2	WSC 3	WSC 4	WSC 5
(TZEEI 95 x TZEEI 82) F2	2,369	322	397	800	753	1097
P ₃ Kollo	3,627	462	587	922	-	-

*WWC: Well-Watered Conditions;

WSC 1: water stress imposed 1week before anthesis;

WSC 3: water stress imposed 17 days before anthesis;

WSC 5: water stress imposed 27 days before anthesis

*WSC: Water Stress Conditions;

WSC 2: water stress imposed 12 days before anthesis;

WSC 4: water stress imposed 22 days before anthesis;



Figure 4.1. Variation in grain yield depending on the water stress intensity in the drought experiment conducted to identify the right time to impose water stress in maize drought trials in Niger. **WWC:** well-watered conditions; **WSC:** water stress conditions; **PD:** planting date; **1st PD:** water stress imposed 1 week before anthesis; **2nd PD:** water stress imposed 12 days before anthesis; **3rd PD:** water stress imposed 17 days before anthesis; **4th PD:** water stress imposed 22 days before anthesis; **5th PD:** water stress imposed 27 days before anthesis

CIMMYT recommends to impose water stress by stopping irrigation when one can predict that the stress will be severe enough to bring the yield level of the stressed blocks to about 15-20% of the yield of the well-watered blocks (Bänziger *et al.*, 2000). Such stress level was observed in this experiment in the case of the first and the second planting dates for which irrigation was stopped 7 and 12 days before anthesis respectively (Figure 4.2). However for the first and the second planting dates, the stress intensity observed in the field was too severe and a large number of plants collapsed even before the anthesis. It is therefore advisable to target a moderate stress level for future maize drought trials in Niger. This could be obtained if water stress is imposed 3 to 2 weeks before anthesis. A “rescue irrigation” should be applied 13 to 15 days later. Then the normal irrigation should be resumed 10 to 12 days after the “rescue irrigation” and continued until plant maturity.

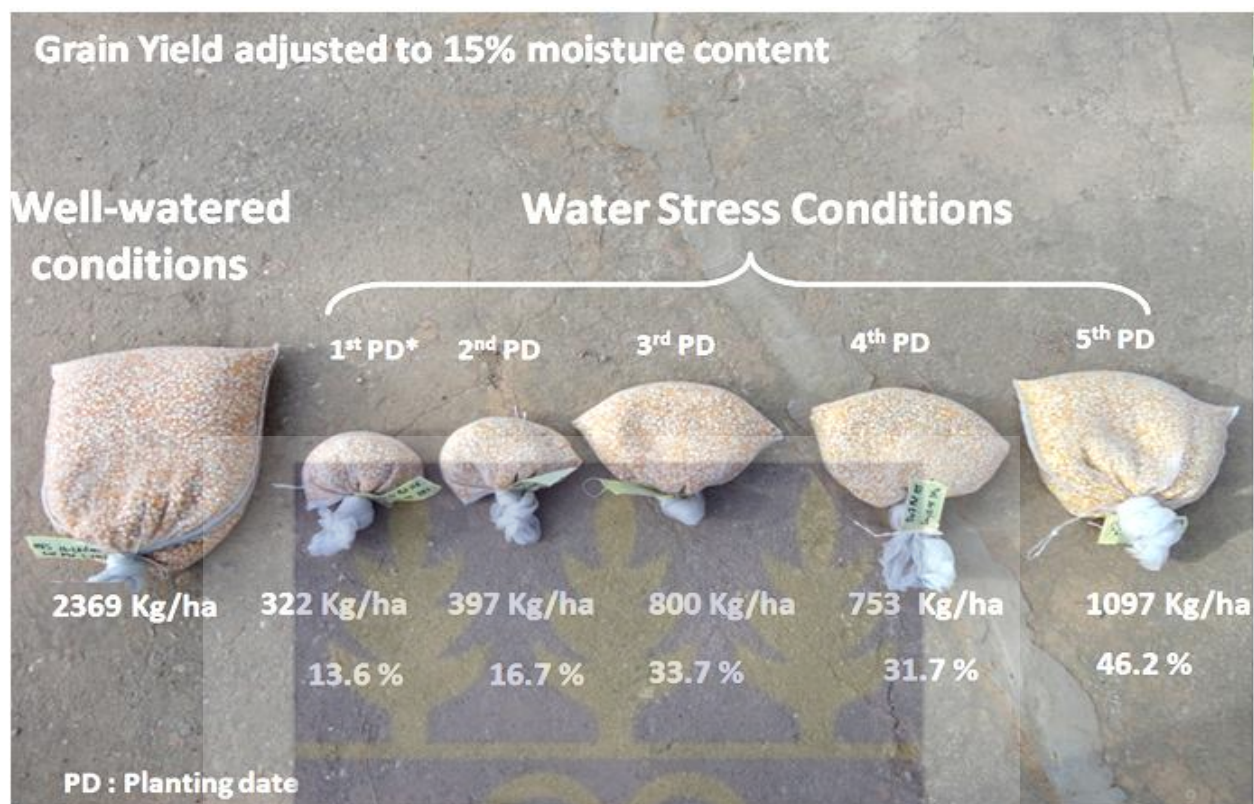


Figure 4.2. Grain yield reduction depending on the stress intensity from the drought experiment conducted to identify the right time to impose water stress in maize drought trials in Niger. **PD:** planting date; **1st PD:** water stress imposed 1week before anthesis; **2nd PD:** water stress imposed 12 days before anthesis; **3rd PD:** water stress imposed 17 days before anthesis; **4th PD:** water stress imposed 22 days before anthesis; **5th PD:** water stress imposed 27 days before anthesis.

4.3.2. Performance of single cross hybrids, inbred parents and checks under drought and well-watered conditions

The analysis of variance of hybrids evaluated under drought stress showed significant genotype (G), environments (E), and genotype x environment interaction (GEI) mean squares for all the measured traits except the E for ear aspect and the GEI for the number of days to silking, plant and ear height, plant aspect, and number of ears per plant (Appendix 4.1). The ANOVA across the well-watered environments also revealed significant mean squares for all the traits measured for genotypes, environments, and GEI (Appendix 4.1). Similarly the combined analysis of variance across the seven environments revealed that genotypes, environments and GE interactions were significantly different for all the traits measured (Table 4.3). The test

environments contributed to about 65.6% of the total variation in grain yield; while the genotypes accounted for about 9.5% and GE sources of variation, about 13.6 % (Table 4.4).

Mean grain yield of the single crosses under drought stress was 1684 kg ha^{-1} representing 36.84% of the well-watered yield which was 4571 kg ha^{-1} (Appendix 4.1). Under drought stress, grain yield ranged from 594 kg ha^{-1} for ENT 15 x ENT 4 to 2753 kg ha^{-1} for TZEI 182 x ENT 13 (Table 4.5). Under drought, eight single-cross hybrids out-yielded the best check, TZEI 82 x TZEI 93 (2309 kg ha^{-1}) (Appendix 4.1). The top five hybrids in terms of grain yield under drought stress, TZEI 182 x ENT 13 (2753 kg ha^{-1}), TZEI 160 x TZEI 157 (2570 kg ha^{-1}), ENT 13 x TZEI 157 (2560 kg ha^{-1}), TZEI 182 x TZEI 161 (2401 kg ha^{-1}), and TZEI 129 x ENT 17 (2399 kg ha^{-1}) out-yielded the best drought-tolerant single cross check by 19.22%, 11.30%, 10.83%, 3.95% and 3.87%, respectively (Table 4.5).

Across well-watered conditions, grain yield ranged from 1995 kg ha^{-1} for TZEI 14 x TZEI 16 to 6584 kg ha^{-1} for TZEI 124 x ENT 13 (Table 4.5). The four highest yielding hybrids were TZEI 124 x ENT 13 (6584 kg ha^{-1}), TZEI 124 x TZEI 23 (5806 kg ha^{-1}), TZEI 167 x ENT 13 (5711 kg ha^{-1}), and TZEI 160 x TZEI 157 (5708 kg ha^{-1}). The highest yielding hybrid, TZEI 124 x ENT 13 out-yielded the 5 checks by 23 to 42% (Table 4.5). The intensity of the induced water stress estimated as the ratio of the average grain yield from the water stress environments to that of the well-watered environments was 36.84% falling outside the limits of 15-20% or 20-30% proposed by Bänziger et al. (2000) and Bolaños and Edmeades (1996), respectively.

Table 4.3. Mean squares from the combined analysis of variance of grain yield and other agronomic traits across environments

Source of variation	DF	Yield (kg ha ⁻¹)	DYA	DYS	ASI	PLTH (cm)	EHT (cm)	PASP (1-5)	EASP (1-5)	EPP	HUSK (1-5)
ENV	6	601167066**	25443**	34902**	2002.94**	81785**	38742**	23.18**	92.03**	6.59**	11.52**
Rep(ENV)	7	7324402**	22.92**	54.74**	58.23**	1312.90**	762.23**	1.32**	3.34**	0.08*	0.77**
Block(Rep*env)	140	1849399**	6.66**	14.52**	6.64 ^{ns}	351.00**	129.53*	1.15**	0.67**	0.03 ^{ns}	0.21 ^{ns}
Entry	109	4783030**	67.64**	91.98**	15.59**	1791.62**	720.26**	2.21**	1.79**	0.07**	1.32**
ENV*Entry	654	1145913**	5.30**	9.67**	7.00**	209.95**	86.00*	0.58**	0.41**	0.04**	0.21**
Residual	623	664552	3.41	6.79	4.51	161.42	72.71	0.44	0.26	0.03	0.15

YIELD: Grain yield; **DYA:** days to anthesis; **DYS:** days to silk; **ASI:** anthesis silking interval; **PLTH:** plant height; **EHTH:** ear height; **PASP:** plant aspect; **EASP:** ear aspect; **EPP:** ears per plant; **HUSK:** husk cover; **ENV:** environment; **Rep:** replication; **DF:** degree of freedom;
 *Significant at the 0.05 probability level
 **Significant at the 0.01 probability level
 ns: not significant

Table 4.4. Proportions of the total variance attributable to the sources of variation for grain yield of maize hybrids evaluated in 7 contrasting environments in Niger from 2012 to 2014

Source of variation	DF	SS	MS	% of total variation
Total	1539	5494758680		
ENV	6	3607002393	601167066**	65.64%
Rep(ENV)	7	43946412	7324402**	
Block(Rep*env)	140	36987971	1849399**	
Entry	109	521350315	4783030**	9.49%
ENV*Entry	654	749427354	1145913**	13.64%
Residual	623	493762429	664552	
Model	916	5000996250	6282659	

ENV: environment; Rep: replication; DF: degree of freedom; SS: sum of squares; MS: mean squares

**Significant at the 0.01 probability level

Table 4.5 Grain yield and other agronomic traits of the 5 highest yielding hybrids, the 5 lowest yielding hybrids and the 5 checks evaluated under drought stress and well-watered environments in Niger from 2012 to 2014 (see complete table in Appendix 4.1)

Single cross hybrids	Yield Kg ha ⁻¹		DYS		ASI		PLTH		PASP		SGC2
	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WSC
TZEI 124 x ENT 13 	6584	1993	58	77	1	9	194	164	1.1	2.7	6.2
TZEI 124 x TZEI 23 	5806	1897	56	70	1	6	170	151	2.5	3.2	7.5
TZEI 167 x ENT 13 	5711	2297	61	77	2	5	181	141	2.4	2.8	6.2
TZEI 160 x TZEI 157  	5708	2570	57	72	1	5	182	157	2.8	3.0	6.7
TZEI 16 x TZEI 161 	5652	2125	59	76	1	7	175	142	2.9	2.7	6.7
ENT 13 x TZEI 157 	5454	2560	60	75	1	6	195	161	2.1	2.7	5.5
TZEI 182 x ENT 13 	5416	2753	58	72	1	5	189	158	2.6	2.7	6.0
ENT 15 x TZEI 124 	5290	736	61	83	3	12	189	156	2.5	4.2	7.7
TZEI 129 x ENT 17 	5141	2399	60	75	1	4	191	156	3.0	3.0	6.2
TZEI 124 x ENT 4 	5097	649	60	82	2	14	182	154	2.5	4.2	7.3
TZEI 23 x TZEI 13 Check	5063	1992	59	76	1	4	168	134	2.9	3.3	6.5
TZEI 9 x TZEI 16 Check	4981	1835	59	76	1	7	164	144	2.5	3.5	7.0
ENT 17 x TZEI 124 	4859	721	60	84	1	10	190	142	2.8	4.5	7.8
P3 Kollo Check	4690	1439	55	70	1	6	172	156	3.0	3.8	6.8
TZEI 16 x TZEI 8 Check	4423	2008	59	76	1	7	156	135	2.8	3.2	7.3
TZEI 182 x TZEI 161 	4045	2401	58	71	2	4	166	145	3.4	3.2	4.7
TZEI 82 x TZEI 93 Check	3792	2309	65	78	2	4	175	147	2.9	2.3	5.2
TZEI 160 x TZEI 161 	2533	1043	58	77	-1	6	131	111	4.0	4.2	7.3
TZEI 182 x TZEI 157 	2397	1298	59	74	1	7	150	141	4.5	4.5	5.5
TZEI 167 x TZEI 14 	2248	1183	66	80	2	4	151	131	3.8	4.2	5.7
ENT 15 x ENT 4  	2021	594	66	84	2	7	167	131	4.4	4.3	7.2
TZEI 14 x TZEI 16  	1995	819	67	85	2	4	150	119	4.1	4.2	6.2
Overall mean	4571	1684	60	76	1	7	174	145	3.0	3.5	6.5
Lsd	865	775	1.7	3.9	1.3	3.2	12	15	0.5	0.9	1.1
Genotypes	**	**	**	**	**	**	**	**	**	**	**
Environments	**	**	**	**	**	**	**	**	**	*	**
G x E	**	*	**	ns	**	**	*	ns	**	ns	*

: top yielding hybrids under WWC; : lowest yielding hybrids under WWC; **WWC**: well-watered conditions; **WSC**: water stress conditions;
: top yielding hybrids under WSC; : lowest yielding hybrids under WSC; **YIELD**: Grain yield; **DYS**: days to silk; **ASI**: anthesis silking interval;
PLTH: plant height; **PASP**: plant aspect; **SGC2**: stay-green 2; *Significant at the 0.05 probability level; **Significant at the 0.01 probability level

The evaluation of the parental inbred lines under water stress and well watered conditions at Konni during the dry season 2013/2014 was lost due to a failure of the irrigation system. Therefore, only the results from the evaluation at Maradi were considered for the analysis. The analysis of variance of the grain yield and other agronomic traits revealed significant differences among the inbreds for grain yield and all the measured traits except for ear aspect under drought and the number of ears per plant under well watered conditions (Table 4.6). The average grain yield of the inbreds under drought stress was 670 kg ha^{-1} representing 36.88% of the well watered yield which was $1,818 \text{ kg ha}^{-1}$. Under drought stress, grain yield ranged from 27 kg ha^{-1} to 1605 kg ha^{-1} (Table 4.6). The five top yielding inbreds under drought stress were ENT 13, ENT 17, TZEI 167, TZEI 161 and TZEI 135 (Table 4.6). Inbreds TZEI 124 and TZEI 16 were the most sensitive to the water stress. They yielded less than 100 kg ha^{-1} under drought. Under well-watered conditions, the grain yield ranged from 748 kg ha^{-1} for TZEI 157 to $3,723 \text{ kg ha}^{-1}$ for TZEI 167. Inbreds TZEI 167, TZEI 135, ENT 13, ENT 15 and ENT 17 were the highest yielding with grain yields of 3723 kg ha^{-1} ; 3161 kg ha^{-1} ; 2191 kg ha^{-1} ; 2130 kg ha^{-1} ; and 2102 kg ha^{-1} respectively (Table 4.6). Across water regimes, TZEI 167, TZEI 135 and ENT 13 were the three top yielding inbreds while TZEI 16 and TZEI 157 were the poorest.

Table 4.6 Grain yield and other agronomic traits of the 15 inbreds evaluated under drought stress and well-watered conditions at Maradi during the dry season of 2013/2014

Entry	YIELD Kg ha ⁻¹			DYA		DYS		ASI		PLHT		EHT		PASP		EASP		EPP	
	WWC	WSC	AWR	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC
TZEI 160	1588	475	1031	73	76	71	80	-1.5	4	105	107	58	69	3.5	3.5	4.2	4.3	1.3	0.5
TZEI 129	1781	303	1042	75	76	73	82	-1.5	5.5	168	154	90	99	2.5	3.5	3.6	4.4	1.1	0.4
ENT 15	2130	329	1230	76	76	78	89	2.5	13	145	122	70	78	2.5	4.5	3.3	3.8	1.0	0.4
ENT 17	2102	1265	1683	78	79	78	81	-0.5	2	128	123	73	76	2.5	3	3.6	3.9	1.0	0.6
TZEI 182	1036	637	836	71	71	72	79	1	8.5	108	112	55	61	4.5	3.5	4.6	4.6	1.1	0.5
TZEI 167	3723	1243	2483	72	74	71	76	-1	2.5	155	143	80	93	1.0	2	2.7	4.1	1.0	0.7
TZEI 14	1355	862	1109	80	82	82	88	2	5.5	103	116	50	70	3.0	1.5	4.2	4.6	1.0	0.8
TZEI 124	1513	76	794	72	72	75	89	2.5	17	145	140	60	74	3.0	4.5	3.3	3.3	0.9	0.3
TZEI 16	1292	27	659	76	78	79	85	2.5	7.5	145	133	80	82	3.0	3	4.3	2.5	1.1	0.1
TZEI 23	1565	714	1140	70	71	69	72	-0.5	1.5	100	115	53	64	3.5	3	3.8	3.9	1.0	0.6
ENT 4	1522	341	931	77	78	80	92	3	13.5	135	121	70	76	3.0	4.5	3.5	3.0	1.4	0.3
TZEI 161	1564	1009	1287	73	72	72	74	-1	2	123	139	68	88	3.0	2.5	3.8	4.2	1.0	0.8
TZEI 135	3161	868	2015	70	71	72	80	1.5	8.5	165	138	85	83	1.5	2.5	2.6	3.3	1.1	0.5
ENT 13	2191	1605	1898	78	78	79	80	1.5	2.5	150	144	80	92	2.0	2	3.4	3.7	1.1	0.9
TZEI 157	748	302	525	76	75	79	81	3	6.5	130	134	68	87	4.0	3.5	4.8	5.0	1.0	0.6
mean	1818	670	1244	74	75	75	82	0.9	7	134	129	69	80	2.8	3.1	3.7	3.9	1.1	0.5
lsd	1070	768	1198	1.6	4.7	2.6	4.8	2.2	4.2	21	21	18	12	1.1	1.7	1.1	1.6	0.5	0.3
Rep	ns	ns	ns	ns	ns	ns	ns	ns	ns	**	ns	**	*	ns	ns	ns	ns	ns	ns
Entry	**	*	**	**	**	**	**	**	**	**	**	**	**	**	*	*	ns	ns	**

WWC: well-watered conditions; **WSC:** water stress conditions; **AWR:** across water regimes; **Rep:** replication; **lsd:** least significant difference;

YIELD: Grain yield; **DYA:** days to anthesis; **DYS:** days to silk; **ASI:** anthesis silking interval; **PLTH:** plant height; **EHT:** ear height;

PASP: plant aspect; **EASP:** ear aspect; **EPP:** number of ears per plant;

*Significant at the 0.05 probability level; **Significant at the 0.01 probability level ; ns: not significant

4.3.3. Correlations, selection indices and identification of productive single-cross hybrids for production under drought stress conditions

The Pearson correlation analysis revealed significant correlations between the measured traits and the grain yield of the hybrids under drought and well-watered conditions except for ear height and husk cover under well-watered conditions (Table 4.7). Positive correlations were found between plant height, number of ears per plant and grain yield under the two water treatments. In contrast, plant and ear aspects were strongly and negatively correlated to grain yield under the two water regimes. Under drought stress, negative and relatively strong correlations were found between the grain yield and the number of days to anthesis, the number of days to silk, anthesis to silking interval, plant and ear aspects, and stay-green characteristic 2 (Table 4.7). However traits such as the stay- green characteristic 1 and husk cover showed negative but weak associations with grain yield under drought (Table 4.7).

Grain yield and other traits displaying strong correlation with yield under drought such as ASI, ear aspect, plant aspect, stay- green characteristic 2 and number of ears per plant were used to compute the selection indices to identify outstanding hybrids under drought conditions. Based on the selection indices under drought stress, significant differences were detected among the single cross hybrids (Appendix 4.1). Three single crosses TZEI 182 x ENT 13, ENT 13 x TZEI 157 and TZEI 182 x TZEI 161 out- performed the best check TZEQI 82 x TZEQI 93 based on the selection index. The best five hybrids under stress based on the selection index (Appendix 4.1) were TZEI 182 x ENT 13 (2753 kg ha⁻¹), ENT 13 x TZEI 157 (2560 kg ha⁻¹), TZEI 182 x TZEI 161 (2401 kg ha⁻¹), TZEQI 82 x TZEQI 93 Check (2309 kg ha⁻¹), and TZEI 160 x TZEI 157 (2570 kg ha⁻¹).

Table 4.7. Pearson correlation coefficients between pairs of traits across 105 single cross hybrids and 5 checks evaluated under drought stress (lower diagonal) and well-watered conditions (upper diagonal) in Niger from 2012 to 2014

	YIELD	DYA	DYS	ASI	PLTH	EHT	PASP	EPP	EASP	HUSK	SG1	SG2
YIELD		-0.26**	-0.30**	-0.24**	0.29**	-0.03 ^{ns}	-0.69**	0.48**	-0.78**	-0.03 ^{ns}	-	-
DYA	-0.49**		0.99**	-0.15**	0.52**	0.72**	0.18**	-0.17**	0.04 ^{ns}	0.02 ^{ns}	-	-
DYS	-0.67**	0.77**		0.01 ^{ns}	0.52**	0.73**	0.20**	-0.20**	0.08**	0.03 ^{ns}	-	-
ASI	-0.50**	0.08*	0.69**		-0.06 ^{ns}	-0.03 ^{ns}	0.14**	-0.21**	0.22**	0.07*	-	-
PLTH	0.45**	-0.33**	-0.37**	-0.21**		0.82**	-0.29**	-0.04 ^{ns}	-0.48**	0.00 ^{ns}	-	-
EHT	0.29**	-0.09*	-0.10*	-0.04 ^{ns}	0.77**		-0.03 ^{ns}	-0.27**	-0.15**	0.14**	-	-
PASP	-0.70**	0.29**	0.47**	0.41**	-0.43**	-0.26**		-0.23**	0.62**	0.07*	-	-
EPP	0.25**	-0.01 ^{ns}	-0.05 ^{ns}	-0.07 ^{ns}	-0.06 ^{ns}	0.00 ^{ns}	-0.18**		-0.30**	-0.19**	-	-
EASP	-0.72**	0.31**	0.47**	0.38**	-0.57**	-0.38**	0.69**	-0.14**		0.04 ^{ns}	-	-
HUSK	-0.10**	0.17**	0.15**	0.04 ^{ns}	0.04 ^{ns}	0.17**	0.08 ^{ns}	-0.17**	-0.06 ^{ns}		-	-
SG1	-0.29**	0.11**	0.26**	0.28**	-0.16**	0.04 ^{ns}	0.26**	-0.08*	0.29**	0.09*		-
SG2	-0.43**	0.25**	0.35**	0.26**	-0.08*	0.06 ^{ns}	0.36**	-0.22**	0.32**	0.17**	0.44**	
YIELD: Grain yield; ASI: anthesis-silking interval; PASP: plant aspect; HUSK: husk cover; SG1: stay-green 1; DYA: days to anthesis; PLTH: plant height; EPP: ear per plant; SG2: stay-green 2; DYS: days to silk EHT: ear height EASP: ear aspect												

4.3.4. Genetic analysis of the diallel crosses evaluated under drought and well-watered conditions

The analysis of variance of the single crosses revealed significant mean squares for genotypes (G), environments (E) and genotypes by environments interactions (GEI) for all the traits under well-watered conditions and across contrasting environments (Tables 4.8 and 4.10) except ear height for GEI across environments. Significant mean squares were also found for G and E under drought conditions except ear aspect for environments (Table 4.9). However the GEI mean squares under drought were not significant for grain yield, number of days to silking, plant and ear heights, and plant aspect (Table 4.9).

Partitioning of the entries into components revealed that GCA and SCA mean squares were significant for all measured traits under drought, well-watered conditions and across research environments except the SCA for EPP under drought (Tables 4.8, 4.9 and 4.10). Similarly GCA by environment interactions were significant for all the traits under drought, well-watered conditions and across research environments except for plant aspect under drought. SCA by environment interactions were not significant for all measured traits under drought stress (Table 4.9) and for DYA, EHT, PASP and husk cover under well-watered conditions (Table 4.8). The proportions of GCA effects were larger than those of SCA effects across test environments.

Table 4.8 Combined analysis of variance for grain yield and other traits of the early maturing single crosses evaluated across well-watered environments in Niger from 2012 to 2014

Source of variation	DF	Yield	DYA	DYS	ASI	PLTH	EHT	PASP	EASP	EPP	HUSK
ENV	3	120650005**	31206**	29741**	77**	49811**	74953**	8.2**	20.4**	6.26**	9.2**
Rep(ENV)	4	7391247**	25**	34**	3 ^{ns}	1325**	674**	0.7 ^{ns}	1.4**	0.07*	0.4*
Entry	104	5555332**	28**	41**	5**	1571**	490**	1.7**	1.6**	0.07**	0.9**
ENV*Entry	312	1296562**	4**	6**	3**	183**	95**	0.5**	0.3**	0.04**	0.2**
GCA	14	16217668**	149**	241**	28**	9041**	2379**	6.1**	6.6**	5.25**	3.2**
SCA	90	3896747**	9**	10**	2**	408**	196**	1.0**	0.9**	0.06**	0.5**
ENV*GCA	42	3049903**	11**	18**	8**	273**	254**	1.1**	0.6**	0.04**	0.5**
ENV*SCA	270	1023820*	3 ^{ns}	4*	2*	169*	70 ^{ns}	0.4 ^{ns}	0.2*	0.02**	0.1 ^{ns}
Residual	416	804728	3	3	1.7	139	64	0.3	0.2	0.01	0.1

YIELD: Grain yield

ASI: anthesis-silking interval

PLTH: plant height

PASP: plant aspect

HUSK: husk cover

DYA: days to anthesis

DYS: days to silk

EHT: ear height

EASP: ear aspect

EPP: ear per plant

*Significant at the 0.05 probability level;

**Significant at the 0.01 probability level;

ns: not significant.

Table 4.9 Combined analysis of variance for grain yield and other traits of the early maturing single crosses evaluated across stress environments in Niger from 2012 to 2014

Source of variation	DF	Yield	DYA	DYS	ASI	PLTH	EHT	PASP	EASP	EPP	SGREEN2
ENV	2	33974256**	1732**	4017**	676**	4418**	376*	2.5*	0.7 ^{ns}	4.8**	106**
Rep(ENV)	3	6374226**	17*	154**	170**	1633**	591**	3.8**	6.8**	0.1 ^{ns}	4**
Entry	104	1388241**	46**	65**	22**	594**	352**	1.4**	0.9**	0.1**	3**
ENV*Entry	208	620636 ^{ns}	7**	14 ^{ns}	11*	207 ^{ns}	87 ^{ns}	0.7 ^{ns}	0.5*	0.1*	1*
GCA	14	4439140**	246**	342**	79**	2192**	1262**	2.7**	2.5**	0.3**	11**
SCA	90	913656**	15**	22**	13**	346**	210**	1.2**	0.6**	0.1 ^{ns}	1*
ENV*GCA	28	1456065**	13**	27**	23**	323*	160*	0.9 ^{ns}	0.9**	0.1**	2**
ENV*SCA	180	490680 ^{ns}	6 ^{ns}	12 ^{ns}	9 ^{ns}	189 ^{ns}	76 ^{ns}	0.6 ^{ns}	0.4 ^{ns}	0.1 ^{ns}	1 ^{ns}
Residual	312	531587	5	13	9	206	91	0.6	0.4	0.1	1

YIELD: Grain yield

ASI: anthesis-silking interval

PLTH: plant height

PASP: plant aspect

SGREEN2: stay-green characteristic 2

DYA: days to anthesis

DYS: days to silk

EHT: ear height

EASP: ear aspect

EPP: ear per plant

*Significant at the 0.05 probability level

**Significant at the 0.01 probability level

ns: not significant

Table 4.10 Combined analysis of variance for grain yield and other traits of the early maturing single crosses evaluated across the seven test environments in Niger from 2012 to 2014

Source of variation	DF	Yield	DYA	DYS	ASI	PLTH	EHT	PASP	EASP	EPP	HUSK
ENV	6	575606929**	24342**	33463**	1945**	79606**	37725**	22**	89.5**	6.3**	10.7**
Rep(ENV)	7	6955381**	21**	85**	75**	1457**	639**	2**	3.7**	0.1*	0.6**
Entry	104	5009929**	67**	93**	16**	1853**	773**	2**	1.9**	0.1**	1.3**
ENV*Entry	624	1177434**	5*	9*	7**	213**	88 ^{ns}	1**	0.4**	0.0**	0.2**
GCA	14	13026012**	375**	549**	74**	9911**	3500**	6**	5.9**	0.23**	5.9**
SCA	90	3762982**	20**	22**	7**	599**	349**	2**	1.2**	0.05**	0.6**
ENV*GCA	84	3282106**	13**	23**	17**	465**	204**	1**	1.1**	0.08**	0.5**
ENV*SCA	540	850040*	4*	8 ^{ns}	6*	174 ^{ns}	70 ^{ns}	0.5 ^{ns}	0.3 ^{ns}	0.04**	0.2*
Residual	728	687668	4	7	5	168	75	0.5	0.3	0.03	0.2

YIELD: Grain yield ASI: anthesis-silking interval PLTH: plant height PASP: plant aspect HUSK: husk cover
 DY A: days to anthesis DYS: days to silk EHT: ear height EASP: ear aspect EPP: ear per plant

*Significant at the 0.05 probability level
 **Significant at the 0.01 probability level
 ns: not significant

4.3.5. Combining ability effects of measured traits

Significant GCA effects for grain yield and other traits were observed for the early maturing yellow grained inbreds under drought, well-watered conditions and across test environments (Table 4.11). Under drought stress, GCA for grain yield ranged from -320 kg ha^{-1} for TZEI 124 to 472 kg ha^{-1} for ENT 13. Of the 15 inbreds, only ENT13, TZEI 182, and TZEI 161 showed significant positive GCA effects for grain yield under drought conditions (Table 4.11). In contrast, TZEI 124, ENT15, ENT4, TZEI 14, and TZEI 16 showed significant negative GCA effects for grain yield under stress conditions. Under well-watered conditions, GCA of grain yield ranged from -830 kg ha^{-1} for TZEI 14 to 693 kg ha^{-1} for ENT13. The highest significant positive GCA effects were observed for ENT 13, TZEI 124, and TZEI 129 (Table 4.11) while TZEI 14, TZEI 182 and TZEI 167 displayed the lowest significant negative GCA in well-watered environments. Only ENT13 and TZEI 129 had significant and positive GCA effects for grain yield across test environments. In addition, across test environments, four inbreds (TZEI 160, TZEI 182, TZEI 161 and TZEI 23) displayed significant negative GCA for the number of days to silking, four inbreds (TZEI 129, TZEI 124, ENT 13 and TZEI 135) showed significant positive GCA for plant height, while three inbreds (ENT 13, TZEI 124 and TZEI 157) had significant negative GCA for plant aspect (Table 4.11).

Table 4.11. GCA effects of grain yield and other agronomic traits of early maturing maize inbred lines from the evaluation of the single crosses under drought and well-watered conditions in Niger from 2012 to 2014

Inbred Lines	Grain yield kg ha ⁻¹			DYS			PLTH			PASP			EPP			SGC2
	WWC	WSC	Across	WWC	WSC	Across	WWC	WSC	Across	WWC	WSC	Across	WWC	WSC	Across	WSC
TZEI 160	-49 ^{ns}	114 ^{ns}	21 ^{ns}	-1.9 ^{ns}	-2.4 ^{**}	-2.1 ^{**}	-12 ^{**}	-4.4 ^{**}	-8.6 ^{**}	0.2 [*]	-0.07 ^{ns}	0.05 ^{ns}	0.04 ^{ns}	0.04 ^{ns}	0.04 [*]	-0.05 ^{ns}
TZEI 129	517 ^{**}	30 ^{ns}	308 [*]	-0.4 ^{ns}	-0.1 ^{ns}	-0.3 ^{ns}	14 ^{**}	7.5 ^{**}	11 ^{**}	-0.1 [*]	0.03 ^{ns}	-0.06 ^{ns}	-0.01 ^{ns}	0.08 [*]	0.03 ^{ns}	-0.14 ^{ns}
ENT 15	-109 ^{ns}	-286 ^{**}	-185 ^{ns}	1.6 ^{ns}	2.2 ^{**}	1.9 [*]	5 [*]	0.1 ^{ns}	2.6 ^{ns}	0.1 ^{ns}	0.24 ^{**}	0.16 ^{**}	-0.03 ^{ns}	-0.07 [*]	-0.05 ^{**}	1.15 ^{**}
ENT 17	37 ^{ns}	-65 ^{ns}	-7 ^{ns}	0.7 ^{ns}	1.3 [*]	1 ^{ns}	4 ^{ns}	-2.5 ^{ns}	0.9 ^{ns}	0.1 ^{ns}	-0.02 ^{ns}	0.03 ^{ns}	0.06 ^{**}	-0.02 ^{ns}	0.02 ^{ns}	0.23 ^{ns}
TZEI 182	-446 ^{**}	333 ^{**}	-112 ^{ns}	-1.2 ^{ns}	-2.6 ^{**}	-1.8 [*]	-8 ^{**}	0.3 ^{ns}	-4.4 ^{**}	0.2 ^{**}	-0.20 [*]	0.05 ^{ns}	-0.01 ^{ns}	0.07 [*]	0.03 ^{ns}	-0.86 ^{**}
TZEI 167	-270 [*]	-122 ^{ns}	-206 ^{ns}	1.4 ^{ns}	1.3 [*]	1.3 ^{ns}	-5 ^{**}	-4.4 ^{**}	-4.9 ^{**}	-0.1 ^{ns}	0.06 ^{ns}	0.00 ^{ns}	-0.05 [*]	0.00 ^{ns}	-0.03 ^{ns}	0.03 ^{ns}
TZEI 14	-830 ^{**}	-210 [*]	-564 ^{**}	2.6 [*]	3.0 ^{**}	2.8 ^{**}	-9 ^{**}	-8.3 ^{**}	-8.6 ^{**}	0.2 ^{**}	0.16 ^{ns}	0.20 ^{**}	-0.02 ^{ns}	-0.06 [*]	-0.04 [*]	-0.15 ^{ns}
TZEI 124	612 ^{**}	-320 ^{**}	213 ^{ns}	-0.3 ^{ns}	1.4 [*]	0.5 ^{ns}	11 ^{**}	9.7 ^{**}	11 ^{**}	-0.6 ^{**}	0.04 ^{ns}	-0.33 ^{**}	-0.02 ^{ns}	-0.12 ^{**}	-0.07 ^{**}	0.92 ^{**}
TZEI 16	-121 ^{ns}	-202 [*]	-156 ^{ns}	2.0 ^{ns}	2.0 ^{**}	2 [*]	3 ^{ns}	-0.7 ^{ns}	1.1 ^{ns}	0.1 ^{ns}	-0.03 ^{ns}	0.01 ^{ns}	0.08 ^{**}	0.03 ^{ns}	0.06 ^{**}	-0.04 ^{ns}
ENT 4	-96 ^{ns}	-253 ^{**}	-163 ^{ns}	1.0 ^{ns}	2.1 ^{**}	1.5 ^{ns}	3 ^{ns}	-0.4 ^{ns}	1.3 ^{ns}	0.1 [*]	0.31 ^{**}	0.21 ^{**}	-0.01 ^{ns}	-0.04 ^{ns}	-0.02 ^{ns}	0.63 ^{**}
TZEI 161	59 ^{ns}	222 [*]	129 ^{ns}	-1.8 ^{ns}	-2.4 ^{**}	-2 [*]	-7 ^{**}	-0.4 ^{ns}	-4 [*]	0.1 [*]	-0.01 ^{ns}	0.08 ^{ns}	0.00 ^{ns}	-0.02 ^{ns}	-0.01 ^{ns}	-0.38 [*]
TZEI 23	-168 ^{ns}	151 ^{ns}	-32 ^{ns}	-2.5 [*]	-3.3 ^{**}	-2.9 ^{**}	-18 ^{**}	-8.4 ^{**}	-14 ^{**}	0.2 ^{**}	-0.06 ^{ns}	0.07 ^{ns}	0.01 ^{ns}	0.04 ^{ns}	0.02 ^{ns}	-0.26 ^{ns}
ENT 13	693 ^{**}	472 ^{**}	598 ^{**}	0.0 ^{ns}	-0.8 ^{ns}	-0.3 ^{ns}	13 ^{**}	6.2 ^{**}	10 ^{**}	-0.4 ^{**}	-0.47 ^{**}	-0.45 ^{**}	-0.01 ^{ns}	0.07 [*]	0.02 ^{ns}	-0.74 ^{**}
TZEI 135	-0.1 ^{ns}	-20 ^{ns}	-9 ^{ns}	-0.5 ^{ns}	0.1 ^{ns}	-0.2 ^{ns}	5 ^{**}	2.2 ^{ns}	4 [*]	0.1 ^{ns}	0.13 ^{ns}	0.10 ^{ns}	-0.01 ^{ns}	0.00 ^{ns}	-0.01 ^{ns}	-0.19 ^{ns}
TZEI 157	172 ^{ns}	157 ^{ns}	165 ^{ns}	-0.8 ^{ns}	-1.9 ^{**}	-1.3 ^{ns}	3 ^{ns}	3.7 [*]	3.3 ^{ns}	-0.2 [*]	-0.10 ^{ns}	-0.13 [*]	-0.02 ^{ns}	0.03 ^{ns}	0.00 ^{ns}	-0.14 ^{ns}
SE ±	43	34	49	0.4	0.3	0.3	0.7	0.6	0.6	0.02	0.03	0.02	0.03	0.01	0.01	0.06

PLTH: plant height; DYS: days to silk; EPP: ear per plant ; PASP: plant aspect; SGC2: stay-green 2
 WWC: well-watered conditions; WSC: water stress conditions; Across: across the seven contrasting environments

*Significant at the 0.05 probability level; **Significant at the 0.01 probability level; ns: not significant

4.3.6. Mode of gene action controlling measured traits

The relative importance of GCA and SCA effects was assessed by computing the ratio of GCA effects to the total genetic effects (twice the GCA effects plus the SCA effects). The closer the ratio to unity, the greater the predictability based on GCA alone (Baker, 1978). GCA effects were greater than the SCA effects for grain yield and all the measured traits under drought stress (Fig. 4.3), well-watered conditions (Fig. 4.4) and across test environments (Fig. 4.5). In all cases, GCA effects accounted for more than 80% of the genetic variation in the traits compared to SCA effects that accounted for less than 20%. This is an indication that additive gene action is more important in controlling the measured traits than non-additive gene action.

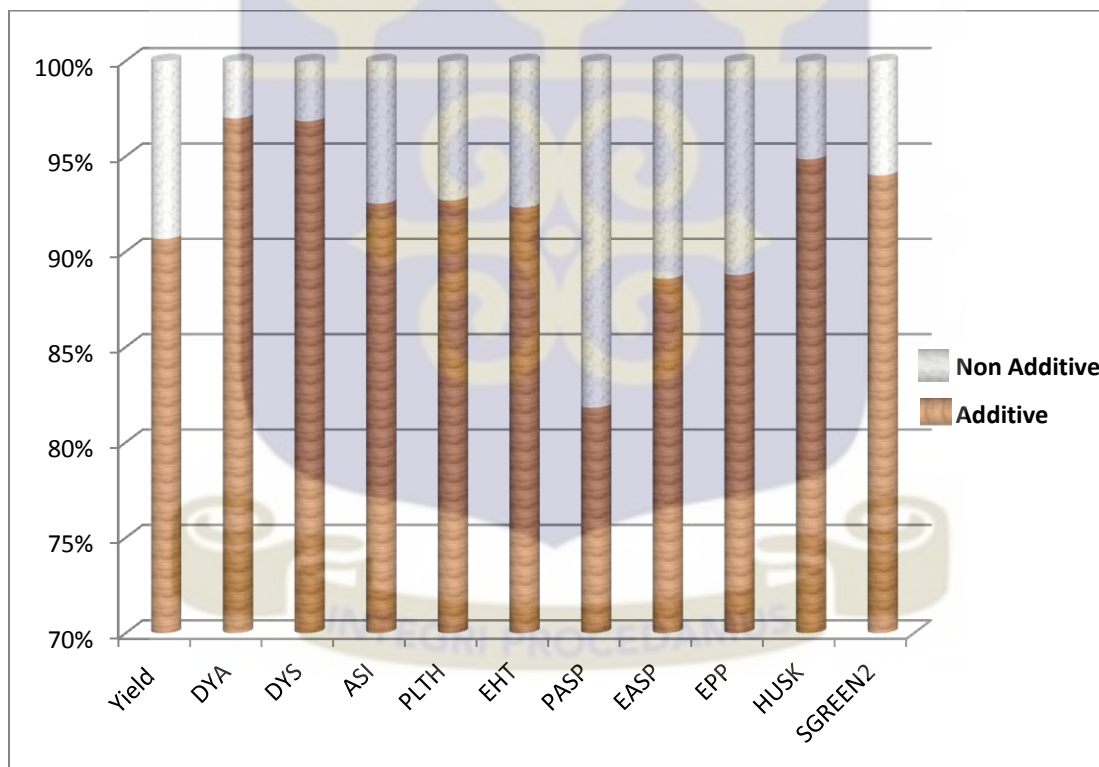


Figure 4.3. Proportion of additive (lower bar) and non-additive (upper bar) genetic variance for grain yield and other traits of 105 single cross hybrids derived from 15 × 15 diallel crosses among 15 early maturing maize inbred lines and evaluated at 3 water stress environments

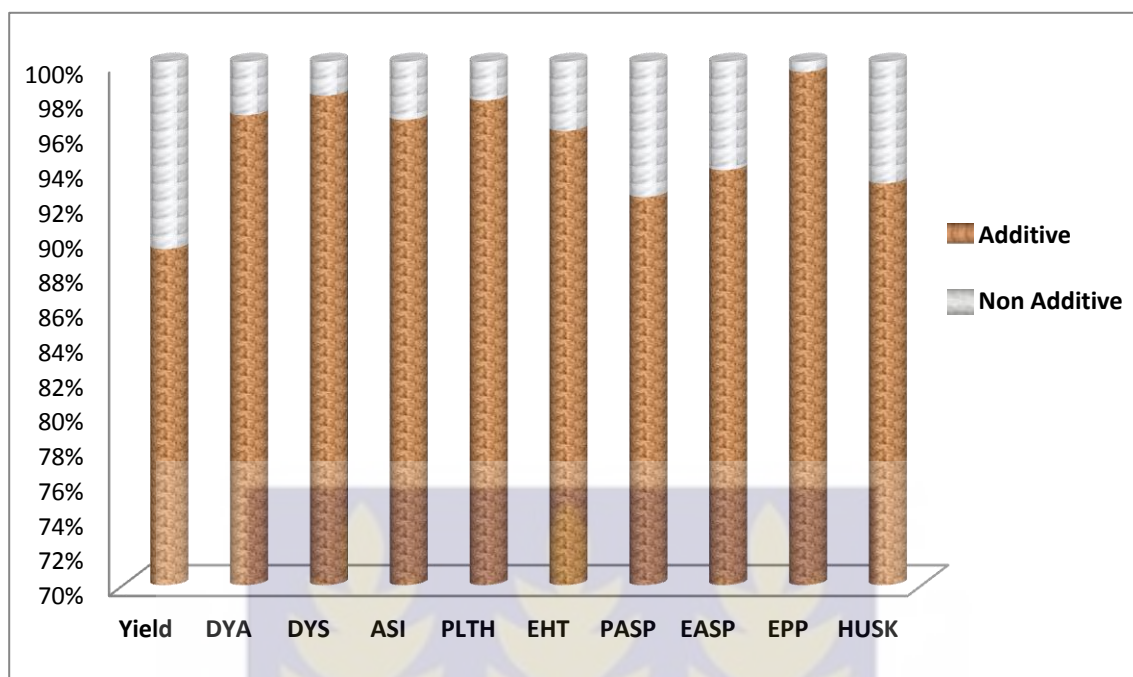


Figure 4.4 Proportion of additive (lower bar) and non-additive (upper bar) genetic variance for grain yield and other traits of 105 single cross hybrids derived from 15×15 diallel crosses among 15 early maturing yellow-grained maize inbred lines and evaluated at 4 well-watered environments

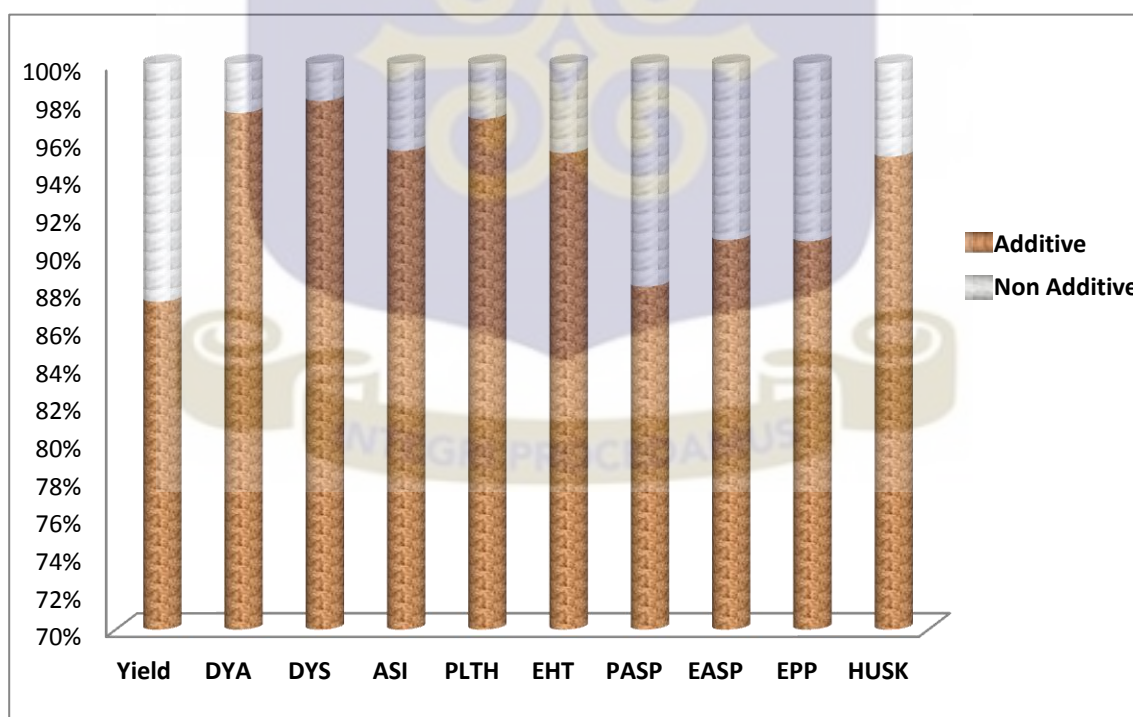


Figure 4.5 Proportion of additive (lower bar) and non-additive (upper bar) genetic variance for grain yield and other traits of 105 single cross hybrids derived from 15×15 diallel crosses among 15 early maturing yellow-grained maize inbred lines across test environments

4.3.7. Heterotic grouping of the early maturing inbreds using SCA_PY and HSGCA methods

In this study GCA effects for grain yield were largely predominant (more than 86%) over SCA effects. Under drought stress and across environments none of the positive SCA effects displayed by the single crosses was significant (tables not shown). Therefore no appropriate heterotic grouping of the inbreds could be expected from this data. However, under well-watered environments, 8 crosses exhibited positive and significant SCA effects for grain yield (Table 4.12). Therefore the classification of the inbreds into heterotic groups using the SCA_PY and the HSGCA methods was based on SCA values from the evaluation of the single crosses under well-watered environments.

- ***Heterotic grouping based on SCA_PY method***

The procedure described by Menkir *et al.* (2004) was adopted to classify inbreds into heterotic groups based on SCA effects under well-watered conditions (Table 4.12) and hybrid yield information under well-watered conditions (Appendix 4.1). According to this procedure, two testers e.g. tester 1 and tester 2 are considered. For an inbred to be classified into a heterotic group, it should have a positive SCA for grain yield with one tester, a negative SCA with the other tester and the testcross of the line with the opposite tester should have a yield equal or superior to the yield of tester1 x tester 2 hybrid. The ideal situation for an efficient heterotic grouping is when the SCA effects are significant. The yield of the best hybrid check under well-watered conditions TZEI 23 x TZEI 13 (5063 kg ha⁻¹) was considered as reference yield for the heterotic grouping of inbreds. Only hybrids showing a grain yield equal or superior to that of the check were used for the classification. The highest and significant SCA effect for grain yield

(1143 kg ha⁻¹) was displayed by the single cross TZEI 160 x TZEI 157 (table 4.12). The two inbreds TZEI 160 and TZEI 157 were considered as testers to classify the other inbreds.

Two inbreds ENT 13 and TZEI 161 showed positive SCA when crossed to TZEI 157 and negative SCA when crossed to TZEI 160. Their hybrids with TZEI 157 outyielded the best check by 8 % and 11% (Tables 4.12). ENT 13 and TZEI 161 are thus opposite to TZEI 157; they were therefore classified in the group with TZEI 160. Inbreds ENT 4, TZEI 124 and TZEI 129 showed positive SCA when crossed to TZEI 160 and negative SCA when crossed to TZEI 157. Their hybrids with TZEI 160 outyielded the best check by 0.1%, 8% and 11% (Tables 4.12). ENT 4, TZEI 124 and TZEI 129 are thus opposite to TZEI 160; they were therefore classified in the group with TZEI 157. The SCA_PY method could classify 7 out of the fifteen inbreds used in the diallel (Tables 4.13).

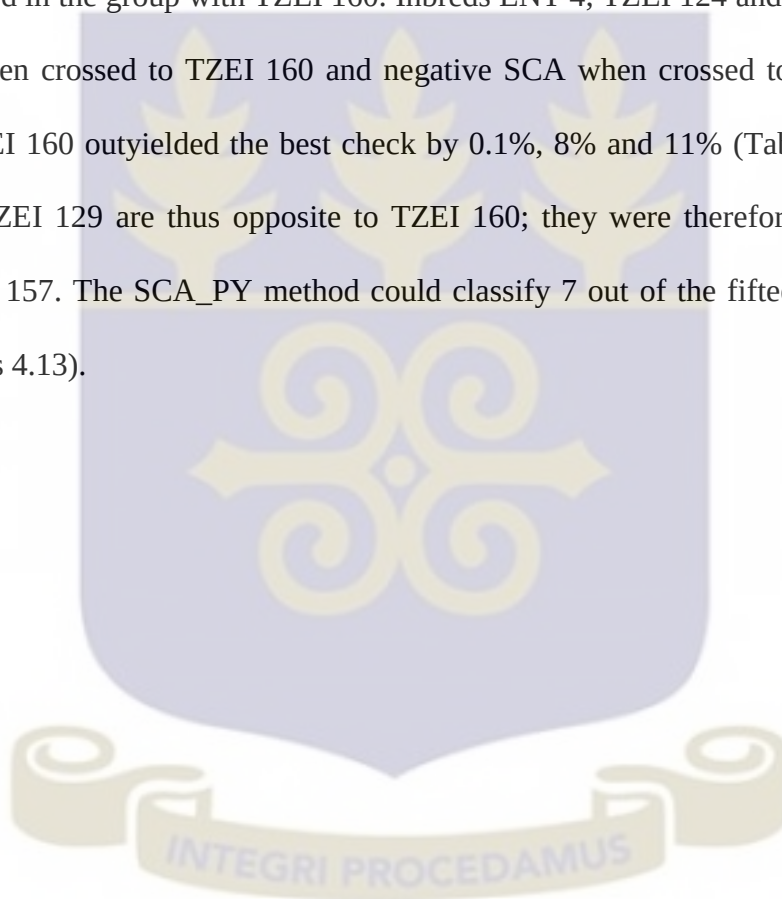


Table 4.12 SCA effects for grain yield (Kg ha⁻¹) of the 105 single-cross hybrids evaluated under WWC and standard heterosis for grain yield of testcrosses involving the inbreds and the two testers TZEI 160 and TZEI 157 over the best check under WWC (TZEI 23 x TZEI 13)

Inbreds	TZEI 160	TZEI 129	ENT 15	ENT 17	TZEI 182	TZEI 167	TZEI 14	TZEI 124	TZEI 16	ENT 4	TZEI 161	TZEI 23	ENT 13	TZEI 135	TZEI 157
TZEI 160		561 ^{ns}	322 ^{ns}	175 ^{ns}	-267 ^{ns}	-451 ^{ns}	173 ^{ns}	350 ^{ns}	484 ^{ns}	637 ^{ns}	-2048 ^{ns}	-1757 ^{ns}	-24 ^{ns}	829*	1143**
TZEI 129			-208 ^{ns}	17 ^{ns}	274 ^{ns}	710 ^{ns}	685 ^{ns}	-741 ^{ns}	-140 ^{ns}	616 ^{ns}	-91 ^{ns}	-116 ^{ns}	-525 ^{ns}	-670 ^{ns}	-369 ^{ns}
ENT 15				-455 ^{ns}	257 ^{ns}	163 ^{ns}	389 ^{ns}	217 ^{ns}	-176 ^{ns}	-2344 ^{ns}	305 ^{ns}	623 ^{ns}	-308 ^{ns}	316 ^{ns}	901*
ENT 17					266 ^{ns}	803*	170 ^{ns}	-361 ^{ns}	-537 ^{ns}	70 ^{ns}	297 ^{ns}	472 ^{ns}	-653 ^{ns}	-271 ^{ns}	8 ^{ns}
TZEI 182						324 ^{ns}	886*	-140 ^{ns}	173 ^{ns}	293 ^{ns}	-139 ^{ns}	-107 ^{ns}	599 ^{ns}	-521 ^{ns}	-1899 ^{ns}
TZEI 167							-1223**	236 ^{ns}	-715 ^{ns}	-209 ^{ns}	-261 ^{ns}	-254 ^{ns}	718 ^{ns}	-85 ^{ns}	243 ^{ns}
TZEI 14								261 ^{ns}	-1624 ^{ns}	-188 ^{ns}	486 ^{ns}	139 ^{ns}	424 ^{ns}	209 ^{ns}	-786 ^{ns}
TZEI 124									60 ^{ns}	9 ^{ns}	-37 ^{ns}	791 ^{ns}	709 ^{ns}	-549 ^{ns}	-804*
TZEI 16										72 ^{ns}	1015*	751 ^{ns}	-45 ^{ns}	52 ^{ns}	502 ^{ns}
ENT 4											754 ^{ns}	1038*	-100 ^{ns}	-373 ^{ns}	-275 ^{ns}
TZEI 161												-1119**	-469 ^{ns}	352 ^{ns}	824*
TZEI 23													-506 ^{ns}	-14 ^{ns}	59 ^{ns}
ENT 13														-163 ^{ns}	19 ^{ns}
TZEI 135															561 ^{ns}
TZEI 157															
SCA with TZEI 160		561	322	175	-267	-451	173	350	484	637	-2048	-1757	-24	829	1143
SCA with TZEI 157	1143	-369	901	8	-1899	243	-786	-804	502	-275	824	59	19	561	
SHGY * with TZEI 160		11%	-7%	-7%	-25%	-25%	-24%	8%	-4%	0.1%	-50%	-49%	3%	6%	13%
SHGY with TZEI 157	13%	-3%	9%	-5%	-53%	-7%	-38%	-10%	1%	-14%	11%	-8%	8%	5%	

*SHGY: standard heterosis for grain yield of testcrosses involving the inbreds and the two testers TZEI 160 and TZEI 157 over the best check under Well-Watered Conditions TZEI 23 x TZEI 13 (**5063 kg ha⁻¹**)

Table 4.13 Classification of the 15 inbreds into heterotic groups based on SCA effects and standard heterosis for grain yield of testcrosses involving the inbreds and the two testers TZEI 160 and TZEI 157 over the best check under well-watered conditions (TZEI 23 x TZEI 13)

Groupe A	Group B	Not classified	
TZEI 160	TZEI 157	ENT 15	TZEI 167
TZEI 161	TZEI 129	TZEI 135	TZEI 14
ENT 13	TZEI 124	TZEI 16	TZEI 23
	ENT 4	TZEI 182	ENT 17

- ***Heterotic grouping based on HSGCA method***

For the classification based on the HSGCA method, each of the 15 inbreds used for the diallel crosses was considered as a tester. The HSGCA values were computed based on the SCA effects of crosses (Table 4.12) and the GCA effects of inbreds (Table 4.11). The computed HSGCA values (Table 4.14) were subjected to the three classification steps described by Fan *et al.* (2009):

Step 1: Place all inbred lines with negative HSGCA effects into the same heterotic groups as their tester.

Step 2: If an inbred line was assigned to more than one heterotic group in Step 1, keep the line in the heterotic group if its HSGCA had the smallest value (or largest negative value) and remove it from other heterotic groups.

Step 3: If a line had a positive HSGCA effect with all the testers, do not assign that line to any heterotic group because the line might belong to a heterotic group different from the testers used.

The results showed four heterotic groups (Table 4.15). The first group was composed of TZEI 160, TZEI 161 and TZEI 23. The second group consisted of TZEI 157, TZEI 182, TZEI 124, TZEI 129 and TZEI 135. Inbreds TZEI 14, TZEI 16, and TZEI 167 constituted the third group and ENT 15 and ENT 4 composed the fourth. Inbreds ENT 17 and ENT 13 were not assigned to any of the four groups.

Table 4.14 HSGCA⁺ values for the 15 inbreds used in the diallel study computed based on the GCA effects for grain yield of inbreds and SCA effects of crosses under well-watered environments.

No	Inbred	HSGCA1	HSGCA2	HSGCA3	HSGCA4	HSGCA5	HSGCA6	HSGCA7	HSGCA8	HSGCA9	HSGCA10	HSGCA11	HSGCA12	HSGCA13	HSGCA14	HSGCA15
1	TZEI 160	-49	511	272	125	-316	-500	124	300	435	587	-2097	-1807	-73	779	966
2	TZEI 129	1078	517	309	534	791	1227	1202	-224	377	1133	426	401	-8	-153	148
3	ENT 15	213	-318	-109	-564	148	53	279	108	-285	-2453	195	514	-417	207	792
4	ENT 17	211	53	-418	37	303	840	207	-324	-501	107	334	508	-617	-234	45
5	TZEI 182	-713	-172	-189	-180	-446	-122	440	-586	-273	-153	-585	-553	153	-967	-2345
6	TZEI 167	-720	441	-107	533	54	-270	-1493	-34	-984	-479	-530	-524	448	-354	-27
7	TZEI 14	-656	-145	-441	-660	57	-2053	-830	-569	-2454	-1018	-343	-691	-406	-621	-1616
8	TZEI 124	962	-129	829	251	473	848	873	612	672	622	575	1404	1321	64	-192
9	TZEI 16	363	-262	-298	-659	51	-836	-1746	-62	-121	-49	1022	629	-167	-69	381
10	ENT 4	541	520	-2440	-25	197	-305	-284	-86	-23	-96	659	942	-196	-468	-370
11	TZEI 161	-1988	-31	364	357	-79	-201	546	22	1202	814	59	-1060	-409	412	883
12	TZEI 23	-1925	-284	455	303	-275	-422	-29	623	582	869	-1287	-168	-674	-182	-109
13	ENT 13	669	167	384	39	1292	1411	1117	1401	647	592	224	187	693	530	712
14	TZEI 135	829	-670	316	-271	-521	-85	209	-549	52	-373	352	-14	-163	0	561
15	TZEI 157	1187	-198	1073	180	-1727	414	-615	-632	674	-103	996	231	191	732	172

⁺ HSGCA1 through HSGCA15 were computed considering inbred 1 (TZEI 160) through inbred15 (TZEI 157) as testers.

Table 4.15 Classification of the 15 inbreds into heterotic groups based on HSGCA effects of grain yield under well-watered environments

Group 1	Group 2	Group 3	Group 4
TZEI 160	TZEI 157	TZEI 14	ENT 15
TZEI 161	TZEI 182	TZEI 16	ENT 4
TZEI 23	TZEI 124	TZEI 167	
	TZEI 129		
	TZEI 135		

Grouping efficiency

Grouping efficiency was defined by Fan *et al.* (2009) as the percentage of superior high-yielding hybrids obtained across the total number of inter-heterotic group crosses. However, it is still highly possible to observe superior hybrids from intra-group crosses (Fan *et al.*, 2009). To compare the grouping efficiency of the two methods, the procedure described by Fan *et al.* (2009) was applied to the results of the present study. Hybrids developed from inbreds that were effectively classified by each of the two methods were used for the comparison. The procedure consisted of dividing the total number of hybrids for each method into two major groups i.e. **inter-group** and **intra-group** crosses. These two groups were subsequently divided into high yielding hybrids (**Yield group 1**) with a mean grain yield superior to that of the best check i.e. 5063 kg.ha⁻¹; intermediate hybrids (**Yield group 2**) with a mean grain yield between 5063 and 3700 kg.ha⁻¹ and low yielding hybrids (**Yield group 3**) with a mean grain yield < 3700 kg.ha⁻¹. The best classification method is the one whose heterotic groups allowed inter-heterotic group crosses to produce more superior hybrids than the intra-group crosses (Fan *et al.*, 2009).

Of the 21 high yielding hybrids identified by the HSGCA method, **only one** hybrid was among the **intra-group** crosses. **Three** out of the 13 high yielding hybrids identified by the SCA_PY method were among the **intra-group** crosses (Table 4.16). The grouping efficiency of the HSGCA and the SCA_PY methods were therefore 95% and 77% respectively.

Table 4.16 Number of hybrids with mean grain yield greater than 5063 kg.ha⁻¹ (yield group 1), between 5063 and 3700 kg.ha⁻¹ (yield group 2), and inferior to 3700 kg.ha⁻¹ (yield group 3) out of the total number of hybrids identified by each of the two classification methods

Yield Group	Cross type	HSGCA	SCA_PY
1	Inter-group	20	10
	Intra-group	1	3
2	Inter-group	39	2
	Intra-group	7	5
3	Inter-group	2	0
	Intra-group	9	1
Total		78	21

Comparison of average grain yield heterosis exhibited by crosses between opposing heterotic groups for each of the two methods revealed that the HSGCA method tended to identify heterotic groups displaying higher heterosis for grain yield than the SCA_PY method (Tables 4.17 and 4.18). In contrast, the SCA_PY method identified inter-group crosses that showed higher average grain yield (5449 kg ha⁻¹) compared to the best average grain yield of inter-group crosses (5055 kg ha⁻¹) identified by the HSGCA method (Tables 4.17 and 4.18).

Table 4.17 Average Grain Yield (GY) (Kg.ha⁻¹) for intra-group and inter-group crosses and average GY heterosis (%) showed by crosses from opposing heterotic groups for the HSGCA method

Heterotic groups	Group1	Group2	Group3	Group4
Group1	2824	4956 (12%)	4357 (54%)	5028 (78%)
Group2		4427	4556 (3%)	5055 (14%)
Group3			2569	4069 (58%)
Group4				2021

Table 4.18 Average Grain Yield (GY) (Kg.ha^{-1}) for intra-group and inter-group crosses and average GY heterosis (%) showed by crosses from opposing heterotic groups for the the SCA_PY method

Heterotic groups	Group A	Group B
Group A	4192	5449 (11%)
Group B		4912

The SCA effects of crosses under well-watered conditions (Table 4.12) were also subjected to the three classification steps described by Fan et al., (2009). The results revealed a classification identical to that of the HSGCA method with additional information on the two inbreds (ENT 13 and ENT 17) that the HSGCA method failed to classify (Table 4.19). The SCA method here revealed that ENT 13 and ENT 17 belong to another heterotic group. The HSGCA method therefore has no advantage over the SCA method since the same classification could be obtained by either method.

Table 4.19 Heterotic grouping based on the application of the classification procedure described by Fan et al. (2009) on the SCA effects of crosses under well-watered conditions

Group 1	Group 2	Group 3	Group 4	Group 5
TZEI 160	TZEI 157	TZEI 14	ENT 15	ENT 13
TZEI 161	TZEI 182	TZEI 16	ENT 4	ENT 17
TZEI 23	TZEI 124	TZEI 167		
	TZEI 129			
	TZEI 135			

4.3.8. Stability analysis of GCA effects of early maturing inbreds across test environments

The GGE biplot of the GCA values of the grain yield of the fifteen early maturing yellow maize inbreds revealed that PC1 explained 50.9 % of the total variance while PC2 explained 26.4 %, thus both PCs accounted for 77.3 % of the total variation for the GCA effects of the inbreds across test environments (Figure 4.6). In the average-tester-coordination view of the GGE biplot (Figure 4.6), the average environment (represented by the small circle on the single-arrowed red horizontal line) has the average coordinates of all test environments, while the single-arrowed red line is the Average Tester coordinate Abscissa (or ATA) which points to higher GCA effect of grain yield across environments. The longer the absolute length of the projection of an inbred on to this line in the direction of the arrow, the higher is the GCA of the inbred. Therefore, inbreds ENT13, TZEI 129, TZEI 124 and TZEI 157 had the highest GCA values across test environments. The absolute length of the projection of an inbred on to the Average Tester coordinate Ordinate (ATO) (double-arrowed blue horizontal line passing through the origin of the biplot on the y-axis) is a measure of its stability. The shorter the projection, the more stable is the GCA of the inbred. Thus, the inbreds ENT 13, TZEI 157, TZEI 160, TZEI 167 and TZEI 14 were the most stable across test environments (Figure 4.6). Based on their high and stable GCA effects for grain yield across environments, inbreds ENT 13 and TZEI 157 are likely to contribute favorable alleles for grain yield to their progenies.

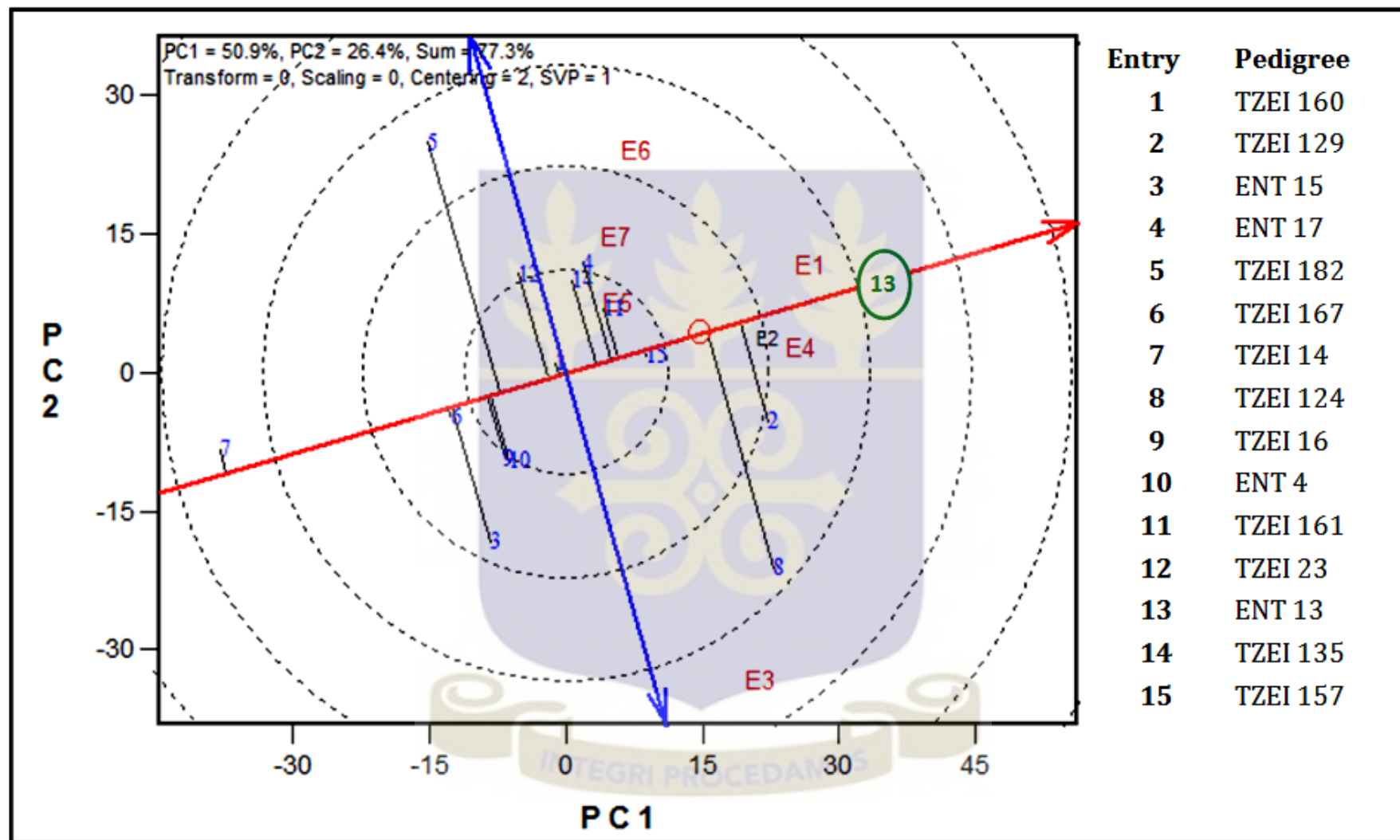
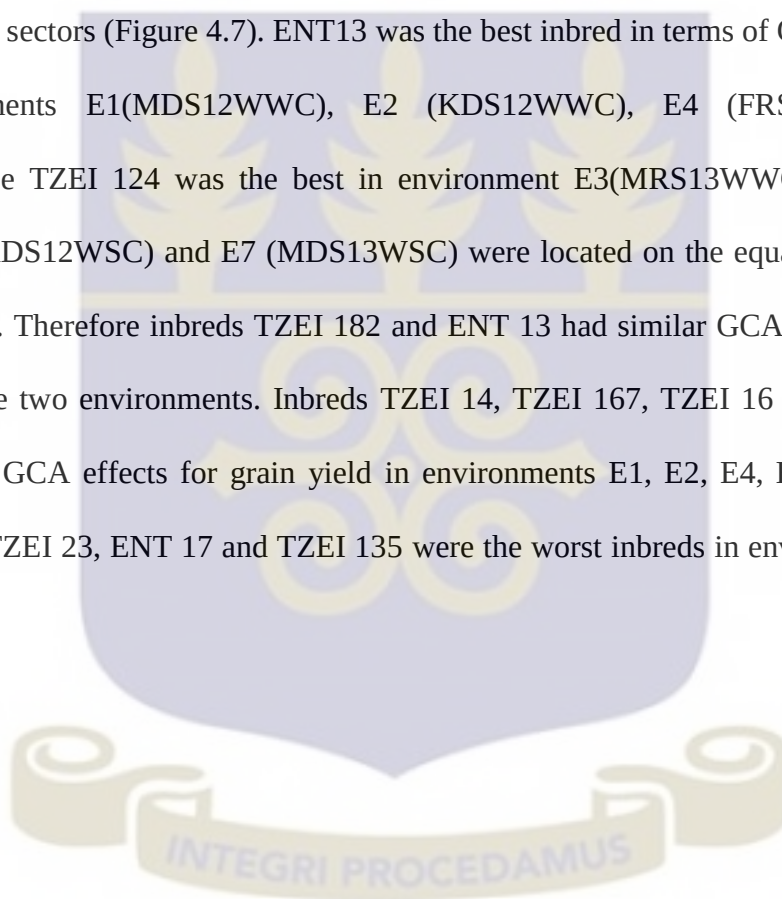


Figure 4.6. An entry/tester genotype main effect plus genotype by environment interaction biplot for GCA effects of grain yield of 15 early maturing yellow inbreds across test environments (E1 through E7)

The polygon view or the "which-won-where" view of a biplot provides an opportunity to visualize the interaction patterns between entries and environments. It allows easy identification of genotypes that were outstanding in each environment (Yan and Tinker, 2006). In the polygon view (Figure 4.7) the perpendicular lines dividing the biplot into sectors are called equality lines, they facilitate visual comparison among the inbreds (Yan and Tinker, 2006). The winning inbred for each sector in terms of GCA effects is the one located on the respective vertex. In the present study, the seven environments fell into two to three sectors (Figure 4.7). ENT13 was the best inbred in terms of GCA effects for grain yield in environments E1(MDS12WWC), E2 (KDS12WWC), E4 (FRS13WWC) and E5 (MDS12WSC) while TZEI 124 was the best in environment E3(MRS13WWC) (Figure 4.7). The environments E6 (KDS12WSC) and E7 (MDS13WSC) were located on the equality line 2, and thus, fell into two sectors. Therefore inbreds TZEI 182 and ENT 13 had similar GCA effects and were the best inbreds in these two environments. Inbreds TZEI 14, TZEI 167, TZEI 16 and ENT 4 were the poorest in terms of GCA effects for grain yield in environments E1, E2, E4, E5, E6 and E7 while inbreds TZEI 182, TZEI 23, ENT 17 and TZEI 135 were the worst inbreds in environment E3 (Figure 4.7).



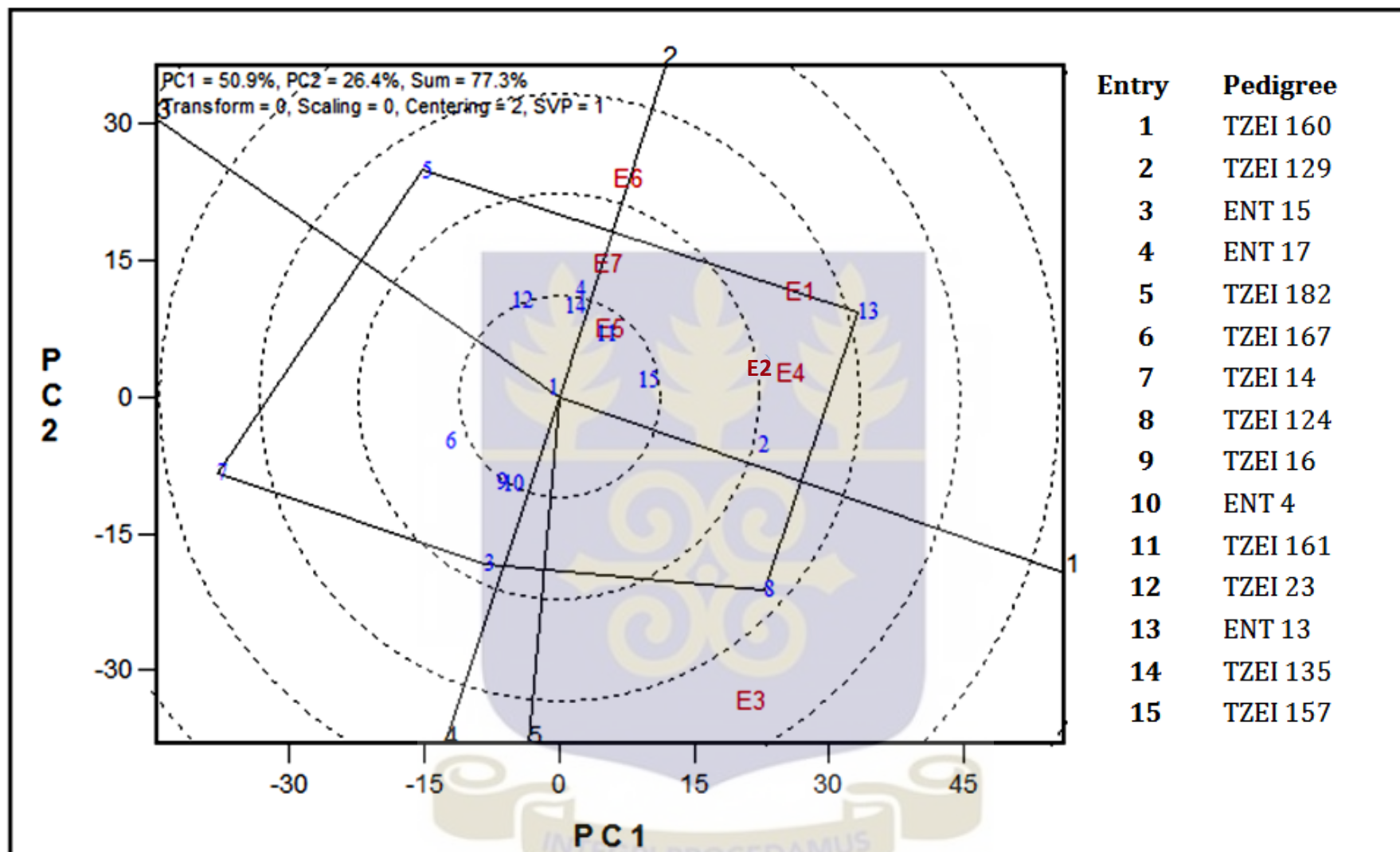


Figure 4.7. A “which won where” genotype plus genotype x environment interaction biplot of GCA effect for grain yield of the 15 early maturing maize inbreds across seven environments (E1 through E7)

4.3.9. GGE biplot analysis of grain yield performance and stability of early maturing single cross hybrids

The biplot analysis could not display all the 105 single crosses and five checks in a readable pattern. Therefore only 25 hybrids derived from a selection of two checks, the 18 top yielding hybrids and the five lowest yielding hybrids across environments were used for the GGE biplot analysis. The GGE biplot analysis revealed that PC1 and PC2 together accounted for 82.9% of the total variance for grain yield across test environments (Figure 4.8). PC1 explained 76.2 % of the total variance while PC2 explained 6.7 %. The GGE biplot was based on genotype-metric preserving (SVP=1) which is more appropriate for comparing genotypes. The red single-arrowed line is the average environment abscissa (AEA) that points to higher mean yield across environments. Therefore, the five top yielding hybrids across test environments were in descending order: TZEI 124 x ENT 13, TZEI 167 x ENT 13, TZEI 160 x TZEI 157, TZEI 124 x TZEI 23 and TZEI 161 x TZEI 157. The lowest yielding hybrids were ENT 15 x ENT 4, TZEI 14 x TZEI 16 and TZEI 167 x TZEI 14 (Figure 4.8). The double-arrowed blue line is the average environment ordinate pointing to greater variability or poorer stability in either direction. Thus, hybrids TZEI 161 x TZEI 157, TZEI 167 x ENT 13 and TZEI 124 x ENT 13 were the best hybrids in terms of stability and yield performance across test environments (Figure 4.8). TZEI 124 x ENT 13 was the highest yielding hybrid across test environments but it was less stable than TZEI 161 x TZEI 157 and TZEI 167 x ENT 13. The single crosses TZEI 16 x TZEI 161 and TZEI 124 x TZEI 23 were the most unstable genotypes of the selection (Figure 4.8).

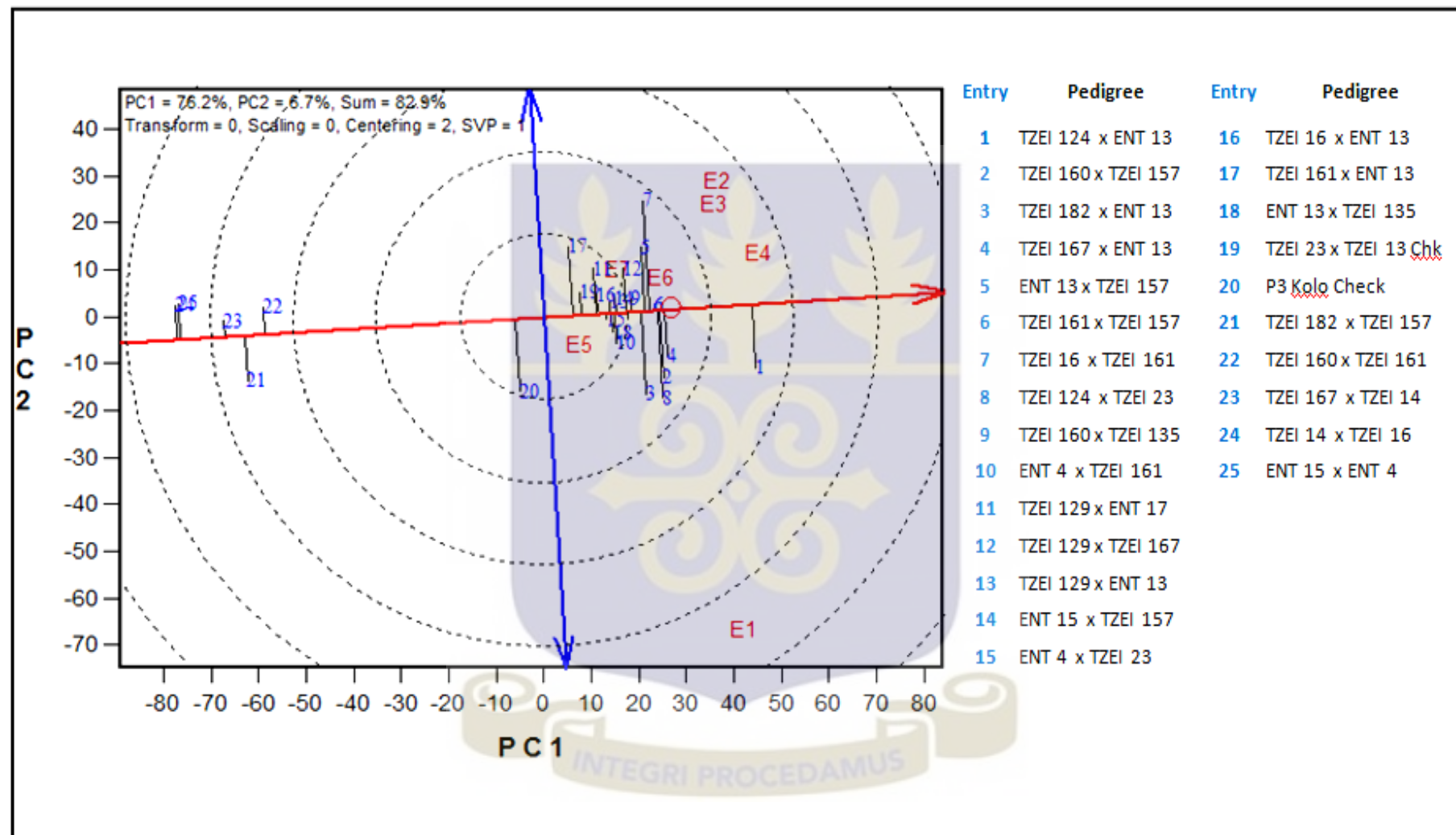
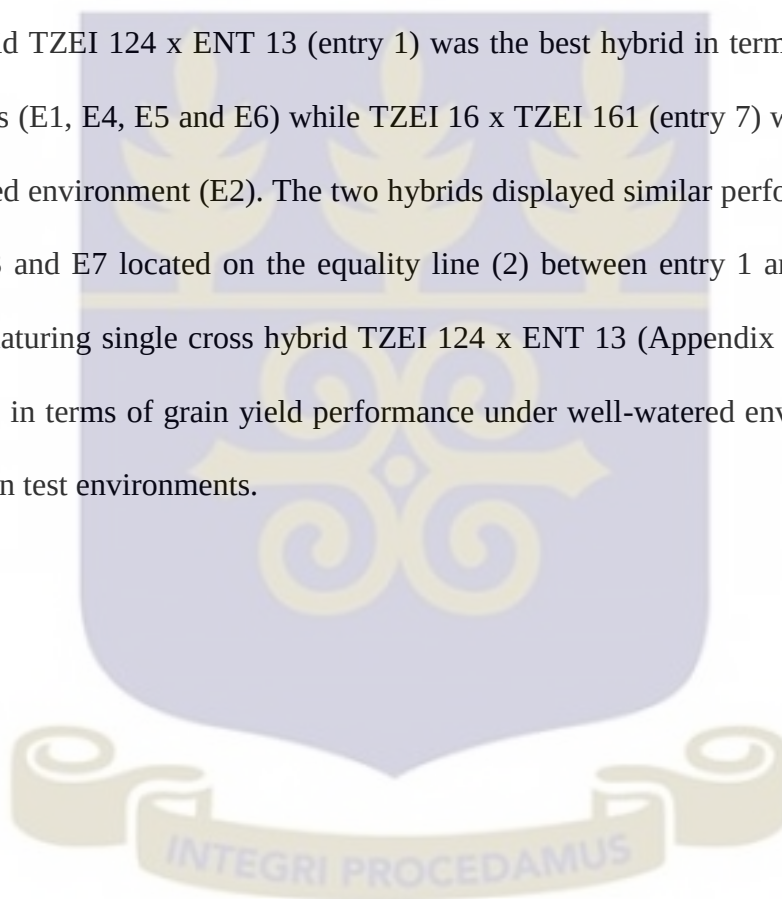


Figure 4.8. GGE biplot for grain yield performance and stability of 23 selected single cross hybrids and two checks across seven environments (E1 through E7)

The 23 hybrids and two checks were also compared using the “which-won-where” function of the GGE biplot which is very useful for determining the winning hybrids in one or more environments (Figure 4.9). The perpendicular lines to the sides of the polygon are equality lines between adjacent genotypes in the polygon; they facilitate visual comparison among the genotypes. The winning genotype for each sector of the polygon defined by the equality lines is the one located on the respective vertex. The seven environments lay between two sectors. The single cross hybrid TZEI 124 x ENT 13 (entry 1) was the best hybrid in terms of grain yield at four environments (E1, E4, E5 and E6) while TZEI 16 x TZEI 161 (entry 7) was the best hybrid at the well-watered environment (E2). The two hybrids displayed similar performance in the two environments, E3 and E7 located on the equality line (2) between entry 1 and entry 7 (Figure 4.9). The early maturing single cross hybrid TZEI 124 x ENT 13 (Appendix 6.1) was therefore the best genotype in terms of grain yield performance under well-watered environments as well as across the seven test environments.



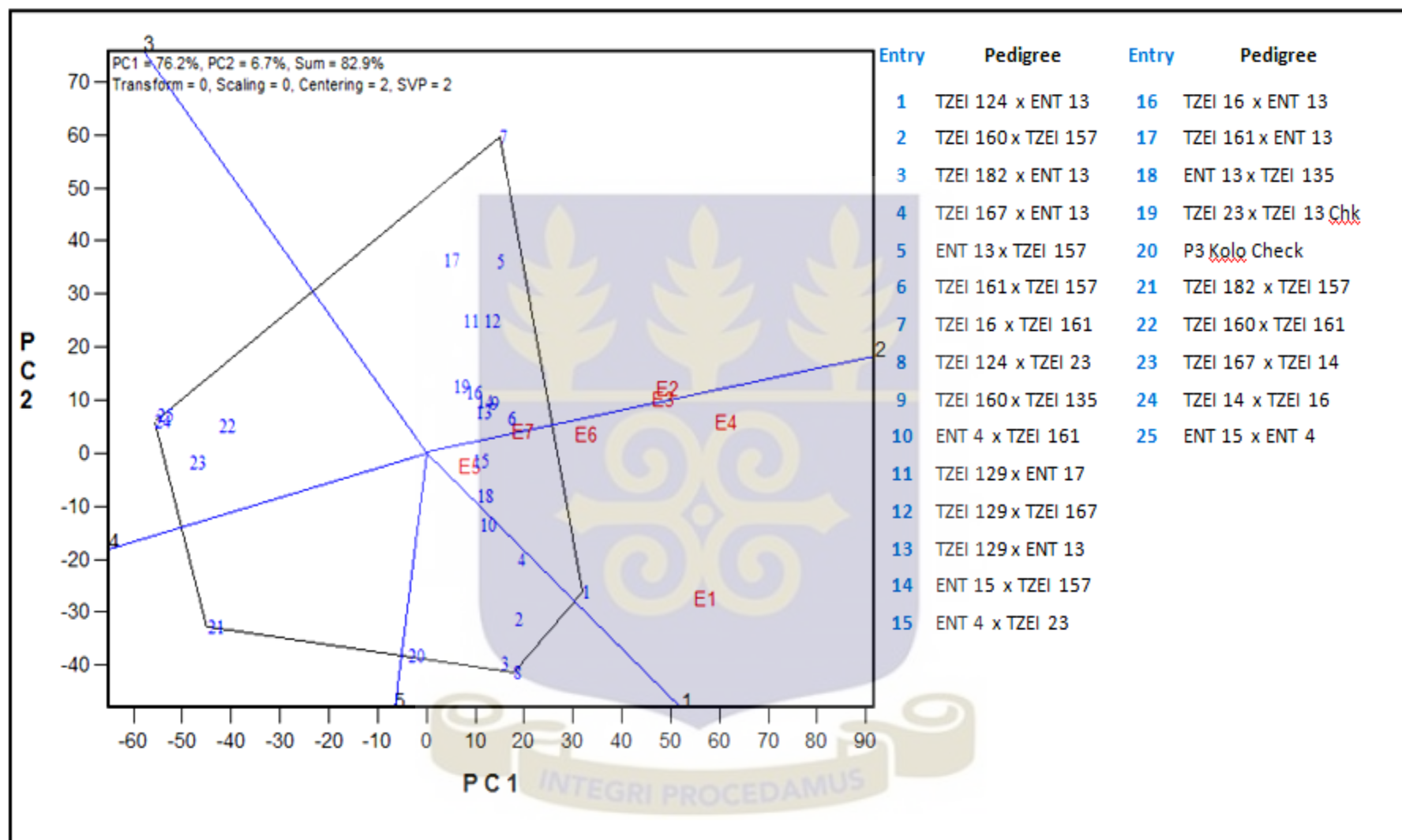


Figure 4.9. A “which won where” GGE biplot of grain yield of 23 selected early maturing single cross hybrids and two checks evaluated across seven environments (E1through E7)

4.4. Discussion

One of the strategies proposed by CIMMYT to identify the time to impose water stress in maize drought trials is to conduct an experiment in which a particular maize genotype is sown at different dates at five days intervals. All the blocks are irrigated at the same time. The last irrigation is applied before flowering when one can predict that it will result in an appropriate drought stress intensity for the 2nd planting date (Bänziger *et al.*, 2000). The intensity of the induced water stress in maize drought trial can be estimated by comparing the grain yield under stress with that under well-watered conditions. Bolaños and Edmeades (1996) proposed that average yield under drought and/or low-N should be 20 to 30% of the expected average yield in the same location under optimal management while Bänziger *et al.* (2000) proposed a much more severe stress that brings the grain yield from the stressed blocks to about 15 to 20% of well-watered yields. However, this study revealed that such a level of yield reduction should not be targeted under harsh climatic conditions. The study revealed that due to the low water holding capacity of the soils at Maradi and Konni coupled with the low relative humidity and frequent windy weather conditions, most of the plants in the stressed blocks would not survive if such a yield reduction was targeted. The study revealed therefore that a moderate yield reduction of about 30-40% of the well-watered yield was a more appropriate target for drought experiments in Niger. This could be achieved by stopping the irrigation 2 to 3 weeks before anthesis, and thereafter, applying one “rescue irrigation” 13 to 15 days after imposing the stress, then resuming the normal irrigation 10 to 12 days later. A similar experiment was conducted by Badu-Apraku *et al.*, (2004) at Soumis and Ferkessedougou in Côte d’Ivoire where they imposed the water stress about 2 weeks before flowering until maturity. Their results indicated that the stress intensity was too severe and they suggested that for such trials, a “rescue irrigation” should be applied

once every 10 days during the period of managed drought, or when plants started showing signs of temporary wilting early in the day.

The significant differences observed among genotypes for grain yield and the associated traits under water stress and well-watered environments indicated that adequate genetic variation existed among the hybrids which could allow good progress from selection under contrasting environments. The significant environmental variation for grain yield and most traits under water stress and well-watered environments indicated that the environments were different which is desirable for assessing the performance and stability of the single cross hybrids in contrasting environments. However, this calls for extensive evaluation of the hybrids in more environments over years in order to draw solid inferences about hybrids' performance and stability. The significant genotype x environment interactions for grain yield and associated traits under water stress and well-watered environments implied the need for extensive testing of cultivars in multiple environments over years before recommendations could be made. Similar findings have been reported for early maturing tropical maize genotypes by several researchers (Pswarayi and Vivek, 2008; Badu-Apraku *et al.*, 2010; Badu-Apraku *et al.*, 2011c; Badu-Apraku *et al.*, 2011d; Badu-Apraku *et al.*, 2013b; Badu-Apraku *et al.*, 2014).

An important objective of the present study was to examine the combining ability for grain yield of the fifteen early maturing inbreds under both drought stress and optimal growing conditions. The results revealed significant GCA and SCA effects for grain yield, flowering dates, ASI, and other agronomic traits under drought and well-watered conditions except the SCA for number of ears per plant under drought, indicating the importance of both additive and non-additive gene action in controlling these traits. The study revealed larger GCA mean squares compared to SCA mean squares for all measured traits under drought (> 80%) and under well-watered conditions (>90%).

The preponderance of GCA mean squares over SCA mean squares implied that additive gene action was more important than non-additive gene action for most traits and that GCA is the major component accounting for the differences among the single cross hybrids. This suggested a greater contribution of inbred parents with high GCA effects to the performance of the hybrids across environments (Baker, 1978). However the prediction of hybrid performance based on GCA effects of the parents alone might not be accurate since SCA effects are also significant. The results of this study corroborate the findings of Betràn *et al.* (2003) and Badu-Apraku *et al.* (2011b) who reported ratios of additive to non-additive variances for grain yield of 84% and 63% under drought and 60% and 80% under well-watered conditions, respectively. The results are also in agreement with the findings of other researchers (Melani and Carena, 2005; Derera *et al.*, 2008; Pswarayi and Vivek, 2008; Makumbi *et al.*, 2011; Badu-Apraku and Oyekunle, 2012). However, these results are in disagreement with those of Badu-Apraku *et al.* (2011c) who reported a minor importance of GCA effects for grain yield and overdominant SCA effects in a diallel study involving nine early maturing yellow inbreds. The difference in these results could be attributed to the differences in the germplasm used and probably the method used to assess the relative contribution of GCA effects versus SCA effects. In this study the relative importance of general and specific combining ability was assessed by the ratio given by Griffing (1956) while it was assessed based on the GGE Biplot analysis by Badu-Apraku *et al.* (2011c).

The significant $GCA \times Environment$ interaction mean squares for all traits under drought and well-watered environments indicated that GCA effects associated with parents were not consistent over environments. This justified the use of the GGE biplot analysis on the GCA estimates of the inbreds to identify those with high and stable GCA effect across environments. The lack of significant $SCA \times Environment$ interaction mean squares for grain yield and almost

all other traits indicated that the hybrids expressed the traits consistently in the test environments. Of the 15 inbreds, only ENT13, TZEI 182, and TZEI 161 showed significant and positive GCA effects for grain yield under drought conditions suggesting that these lines are likely to contribute favorable alleles in a recurrent selection program for drought tolerance improvement and such lines could be used as parents to form a synthetic population that could be improved for tolerance to drought. This also suggests that these inbreds are tolerant to drought as confirmed by the high grain yield *per se* of inbreds ENT 13 and TZEI 161 under drought. ENT 13 and TZEI 161 could therefore be considered as the best parents under drought conditions. In contrast, TZEI 124, ENT15, ENT4, TZEI 14, and TZEI 16 showed significant negative GCA for grain yield under stress conditions suggesting that hybrids derived from these inbreds would suffer severe yield reduction in presence of water deficit. Under well-watered conditions, the highest, positive and significant GCA effects for grain yield were displayed by inbreds ENT 13, TZEI 124 and TZEI 129 suggesting a greater contribution of these inbreds to the yield performance of their progeny under optimal growing conditions. The CIMMYT line ENT 13 had the highest and also highly significant and positive GCA effect for grain yield under drought, well-watered conditions and across test environments. It specifically combined well with TZEI 124, TZEI167 and TZEI 157. It was also identified as the best and most stable inbred in terms of GCA effects for grain yield by the biplot analysis. Furthermore this inbred produced an acceptable grain yield under drought (1,605 kg ha⁻¹) and well-watered environments (2,191 kg ha⁻¹) and hybrids developed from this line averaged a grain yield of 5,214 kg ha⁻¹ under well-watered conditions and 2,110 kg ha⁻¹ under drought conditions. The inbred line ENT 13 is therefore the most attractive general combiner. This inbred could be a desirable parent for the development of hybrids and synthetics as well as for population improvement, since it may contribute favorable alleles in the synthesis of new varieties (Legesse *et al.*, 2009).

Inbred ENT 13 was also ranked among inbreds with superior GCA effects for grain yield under low nitrogen and optimal growing environments by Ifie (2013). TZEI 124 and TZEI 129 are also good combiners under well-watered conditions based on their high positive GCA effects for grain and high grain yield performance of their hybrids ($> 5,000 \text{ kg ha}^{-1}$) in optimal growing environments. However, these two inbreds are very susceptible to drought as confirmed by their low stability across environments by the GGE biplot analysis. Across test environments inbreds TZEI 160, TZEI 182, TZEI 161 and TZEI 23 displayed significant negative GCA effects for the number of days to silking suggesting their use as parental lines in breeding for earliness.

Another important objective of the present study was to identify superior hybrids under drought stress, well-watered conditions and across environments. Relying on grain yield alone for the selection of the best hybrids under drought is not an appropriate solution as its heritability usually decreases under stressed condition, while the heritability of some secondary traits remains high and their genetic correlation with grain yield increases sharply under stress (Bolaños and Edmeades, 1996; Bänziger *et al.*, 2000). This study revealed high and significant correlations between grain yield under drought and secondary traits such as flowering dates (DYA and DYS), ASI, PASP and EASP PLTH and EHT, EPP and SG1 and SG2 indicating that some of these traits could be included in an index for reliable selection of the best hybrids under drought. Badu-Apraku *et al.* (2011a) identified PASP, EASP, ASI and EPP as the most reliable traits for selection for yield under drought in a study conducted in tropical early maturing maize cultivars. Similarly, numerous studies have reported secondary traits such as EPP, ASI and stay green characteristic to possess strong correlations with grain yield under drought conditions and have been used to select for higher levels of tolerance to drought and low-N in maize (Bolaños and Edmeades, 1996; Bänziger *et al.*, 2000; Betrán *et al.*, 2003b; Ribaut *et al.*, 2009). This justified the use of a base index that integrates grain yield under drought stress, ASI, EPP, stay

green characteristic, PASP and EASP in this study. A similar index has been extensively used by CIMMYT and IITA researchers (Badu-Apraku *et al.*, 2011a; Badu-Apraku *et al.*, 2011d).

Drought tolerant genotypes are expected to suffer less yield reduction under drought stress. They are expected to display better values for secondary traits that are strongly correlated to high grain yield under drought i.e. reduced ASI, increased EPP, excellent PASP and EASP and delayed leaf senescence (Bolaños and Edmeades, 1996; Bänziger *et al.*, 2000; Betrán *et al.*, 2003b; Ribaut *et al.*, 2009). In the present study, the single cross hybrids TZEI 182 x ENT 13, TZEI 160 x TZEI 157, ENT 13 x TZEI 157, TZEI 182 x TZEI 161 and TZEI 129 x ENT 17 were ranked as the top five yielding hybrids under drought stress. The performance of the top four hybrids was confirmed by the selection index. All the four hybrids were obtained from combinations involving two drought tolerant inbreds suggesting a dosage effect of drought tolerance genes in these hybrids. This is consistent with the findings of several authors who reported significant dosage effect under drought suggesting the need for including drought tolerant parents on both sides of a hybrid to achieve acceptable drought tolerance where the stress is severe (Bänziger *et al.*, 2000; Betrán *et al.*, 2003a; Ribaut *et al.*, 2009; Badu-Apraku *et al.*, 2011b). Under well-watered environments the best single cross hybrids identified were TZEI 124 x ENT 13; TZEI 124 x TZEI 23; TZEI 167 x ENT 13; TZEI 160 x TZEI 157 and TZEI 16 x TZEI 161. Only the single cross hybrid, TZEI 160 x TZEI 157 was identified among the five top yielding hybrids under drought as well as under well-watered conditions. Three single cross hybrids, TZEI 160 x TZEI 157; ENT 13 x TZEI 157 and TZEI 182 x ENT 13 out-yielded the checks and showed above-average grain yield $> 5,400 \text{ kg ha}^{-1}$ across well-watered environments and $> 2,500 \text{ kg ha}^{-1}$ under moderate drought stress suggesting that they should be extensively tested in on-farm trials under rainfed conditions in Niger. The two highest yielding hybrids under optimal growing conditions, TZEI124 x ENT13 and TZEI 124 x TZEI 23 were

ranked at the 33rd and 41st positions under drought probably because they had in common the drought susceptible inbred TZEI 124 as parent. This is confirmed by the results of the GGE biplot analysis (restricted to only 25 hybrids) that showed that the hybrid TZEI124 x ENT13 has low stability despite its overall high performance across test environments. Therefore the hybrids TZEI124 x ENT13 and TZEI 124 x TZEI 23 should be recommended for maize production under irrigation or under rainfed conditions in areas where complementary irrigation can be provided in case of drought.

The identification of heterotic groups and patterns is of fundamental importance in a maize hybrid breeding program (Melchinger and Gumber, 1998; Hede *et al.*, 1999). In the present study the efficiency of a recently introduced method (HGSCA) for classifying inbreds into heterotic groups was compared to the classical SCA_PY method which combined line pedigree or hybrid yield information. The development of the HGSCA was justified by the fact that SCA effects are greatly influenced by the interaction between two inbred lines and by the interaction between hybrids and environments, thus, different studies might assign the same inbred line to different heterotic groups (Fan *et al.*, 2009). The classification based on the two methods revealed different trends in assigning inbreds into heterotic groups. The SCA_PY is a highly selective method and, because of that, many inbreds are not classified. For an inbred to be classified by the SCA_PY method, it must display a negative SCA with one tester, a positive SCA with the other tester and the testcross of this line with the opposite tester should yield equal to or better than the yield of the best hybrid check. The HSGCA method tends to classify all the inbreds, however, when applied to diallel data where no tester is included; it tends to define a large number of heterotic groups which are of no practical use in the breeding program.

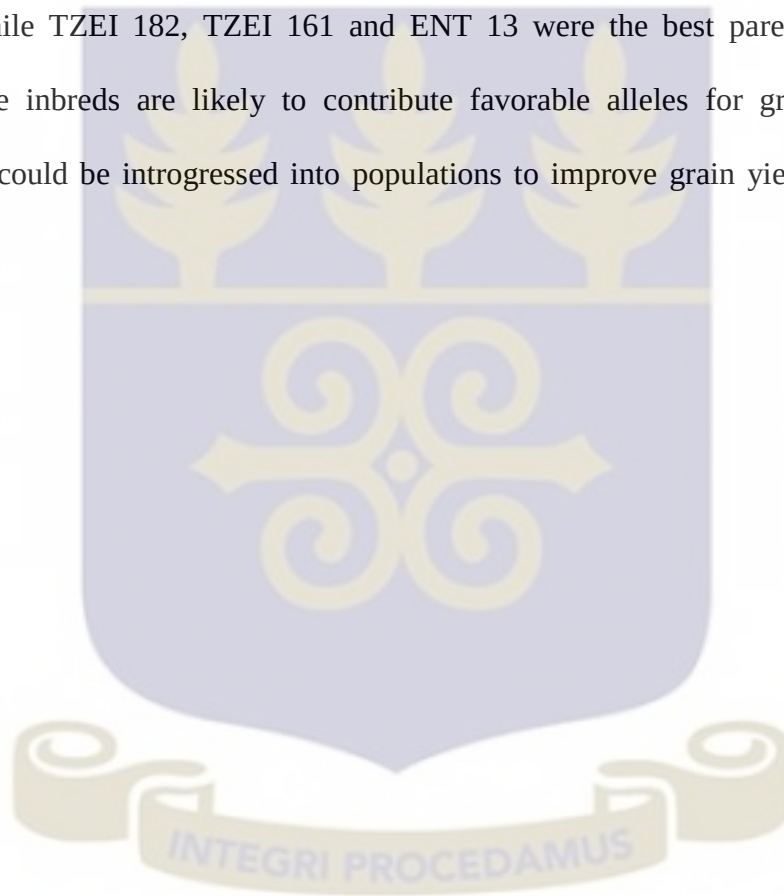
The HSGCA method defined heterotic groups that show higher heterosis for grain yield compared to the SCA_PY method. In contrast, the SCA_PY method identified inter-group crosses that show the highest average grain yield (which is more desirable in breeding) compared to the HSGCA method. In the present study, the HSGCA method offered no advantage over the SCA method since identical or better inbred classification could be obtained when SCA effects are submitted to the procedure described by Fan et al., (2009) for grouping inbreds. These results are in disagreement with the findings of Fan et al. (2009), Badu-Apraku et al. (2013c) and Akinwale et al. (2014) who found the HSGCA method to be more efficient in classifying inbreds than the SCA method. Models of the HSGCA and SCA methods (Appendix 4.2) show that while the SCA method targets specific combinations where hybrids performed relatively better or worse than would be expected based on the GCA effects of **both line and tester**, the HSGCA method focuses on combinations where hybrids performed relatively higher or lower than would be expected based on GCA effects of **the tester alone** (see Appendix 4.2). The HSGCA method is likely to be less efficient than the SCA method when appropriately used. However more studies are needed to investigate this issue.

The two heterotic groups defined by the SCA_PY method will be retained in this study since their inter-group crosses displayed the highest average grain yield. The first group is composed of inbreds TZEI 160, ENT 13 and TZEI 161 while the second group includes TZEI 157, TZEI 129 TZEI 124 and ENT 4. These inbreds could be recombined according to heterotic classification to develop new inbred lines and new versions of the high yielding hybrids ENT 13 x TZEI 124 and TZEI 160 x TZEI 157.

4.5. Conclusions

This study was set out to explore the genetic diversity among IITA and CIMMYT early maturing tropical yellow maize inbreds for breeding for drought tolerance. Drought remains a serious constraint that frequently challenges maize production particularly in sub Saharan African countries. Genotypes possessing drought tolerant genes are therefore needed to prevent drastic yield losses in case of drought occurrence during maize cropping season. IITA and CIMMYT maize breeding programs have developed outstanding early maturing maize inbreds that carry drought tolerant genes; however, their potential in hybrid combinations still needs to be explored in combining ability studies. Early maturing single crosses developed from a 15 x 15 diallel were evaluated in Niger under managed drought and well-watered conditions to examine the combining ability and the mode of gene action for drought tolerance among the 15 inbred lines, to classify inbreds into heterotic groups using two classification methods i.e. the SCA effects of grain yield and the HSGCA method, and to assess the yield performance and stability of the hybrids under contrasting environments. The study revealed that appropriate yield reduction due to water stress in drought experiments in Niger could be achieved if irrigation is stopped three to two weeks before anthesis, thereafter, an application of a “rescue irrigation” two weeks later and finally the resumption of the normal irrigation 10 to 12 days later. Significant GCA and SCA effects for grain yield and most measured traits were found across test environments with a predominance of additive gene effects over non- additive gene effects suggesting that inbred lines with high GCA effects for grain yield and other traits are likely to contribute favorable alleles for a better yield performance of their progeny across environments. Seven early maturing yellow maize inbreds were classified into two heterotic groups under well-watered environments based on the SCA_PY method which could identify more superior inter-group crosses than the HSGCA method. Under well-watered environments, the best single cross hybrids were TZEI 124

x ENT 13 and TZEI 124 x TZEI 23 while the single cross hybrids TZEI 182 x ENT 13 and TZEI 160 x TZEI 157 were the best under drought. The CIMMYT drought tolerant line ENT 13 was the most attractive general combiner across environments that could be a desirable parent for the development of synthetics and hybrids as well as for inclusion in breeding populations for grain yield and drought tolerance improvement. Inbreds TZEI 124, TZEI 129 and ENT 13 were the most promising parental inbreds for the development of hybrids and synthetics in well-watered environments while TZEI 182, TZEI 161 and ENT 13 were the best parents under drought conditions. These inbreds are likely to contribute favorable alleles for grain yield to their progenies. They could be introgressed into populations to improve grain yield and to increase genetic diversity.



CHAPTER FIVE

5.0. Assessment of yield performance of modified single crosses of varying maturity under drought and well-watered conditions

5.1. Introduction

Maize (*Zea mays* L.) is an important staple and cash crop which is increasingly consumed by Nigerien households. The production of this crop in the country remains low due to multiple factors including recurrent drought, low soil fertility, lack of availability of improved cultivars and poor crop management practices. Farmers grow Open Pollinated Varieties (OPVs) whose seeds are obtained from the market or through saving seeds or farmer-to-farmer seed exchanges. The Rapid Rural Appraisal study conducted in maize production sites in Niger revealed that drought is a major constraint which dissuades farmers from producing maize under rainfed conditions and that the preferred maize cultivars in the country are the yellow-endosperm that combines extra-early (70-84 days) or early maturity (85-94 days) and high yield potential. Earliness is thus an important trait desired by farmers in Niger including those who produce maize under irrigation. However, this trait has been reported to be negatively correlated with high yield potential (Pswarayi and Vivek, 2008). It is therefore important to develop maize genotypes of varying maturity periods that also carry drought tolerance genes and allow farmers to test their yield performance. This will give them the opportunity to compare the advantages of using one type over the other (Tiwari *et al.*, 2009).

In Niger farmers' accessibility to high quality seeds of improved varieties is currently being facilitated by emerging private seed companies which are involved in commercial production of seeds of these varieties. For maize production, a promising approach to increase farmers' maize production and productivity and raise the seed companies' income is to introduce high yielding

maize hybrid varieties to replace the old low yielding OPVs currently grown by farmers. The best option to significantly increase farmers' maize production is to adopt maize single cross hybrids. However one of the main problems of single cross hybrids is the inbreeding depression usually associated with the inbred lines used as parents (Castellanos *et al.*, 2009). The problem is more crucial in the extra-early and early maturing maize for which appropriate testers are still lacking (Pswarayi and Vivek, 2008; Badu-Apraku and Oyekunle, 2012; Badu-Apraku *et al.*, 2013a; Badu-Apraku *et al.*, 2013c). Modified single-cross (MSC) hybrids represent an attractive alternative to single cross hybrids (Castellanos *et al.*, 2009). MSCs are developed from three to four inbred lines. Instead of crossing two inbreds as in conventional single cross hybrids, either one or both parents of the MSCs is a related single cross i.e. a cross derived from two genetically related lines (Hallauer *et al.*, 2010). The use of related single crosses (RSCs) as female parents in commercial hybrid production overcomes the problem of low amount of hybrid seeds often obtained when inbred parents are used.

The present study is conducted to address the issues raised on: (i) the necessity to develop superior and drought tolerant maize genotypes of varying maturity periods and give farmers the opportunity to compare their merits and demerits, and (ii) the necessity to find an alternative to the low yield potential of inbreds used in commercial hybrid seed production. The objectives of this study were to (i) identify and select three RSCs with high yield potential across contrasting environments, (ii) develop MSCs from the three selected RSCs and inbreds of varying maturity cycles, (iii) assess the yield performance of MSC hybrids under drought and well-watered conditions and (iv) examine the relationship between grain yield and maturity.

5.2. Materials and methods

5.2.1. Genetic materials

Seven extra-early yellow maize inbred lines developed from two broad-based maize streak resistant populations were used in the present study (Table 5.1). The seven inbreds had been classified into three opposing heterotic groups by Badu-Apraku and Oyekunle (2012) in a previous study (Table 5.1). Inbreds from the same heterotic groups were used to develop five RSCs. Two single-cross hybrids and the local OPV P₃Kollo were used as checks in the evaluation of the five RSCs (Table 5.2). Three out of the five RSCs were selected as female parents and crossed to 36 inbred lines of varying maturity (Table 5.3) to develop 103 MSCs. The maturity of the 36 inbreds was determined based on the results of an evaluation of the inbreds at INRAN Maradi during the rainy season of 2012.

Table 5.1 Characteristics of extra-early maturing maize inbred lines used in the study

Inbreds	Pedigree	Reaction to drought	Classification
TZEEI 95	TZEE-Y Pop Co S6 Inbred 47-3-4	DT	Heterotic group A
TZEEI 79	TZEE-Y Pop Co S6 Inbred 47-2-4A	DT	
TZEEI 78	TZEE-Y Pop Co S6 Inbred 44	DS	
TZEEI 63	TZEE-Y SR BC1×9450 STR S6 Inb 7B	DT	Heterotic group B
TZEEI 58	TZEE-Y SR BC1×9450 STR S6 Inb 1A	DT	
TZEEI 82	TZEE-Y SR BC1 ×9450 STR S6 Inb 10B	DT	Heterotic group C
TZEEI 76	TZEE-Y SR BC1 × 9450 STR S6 Inb 8B	DT	

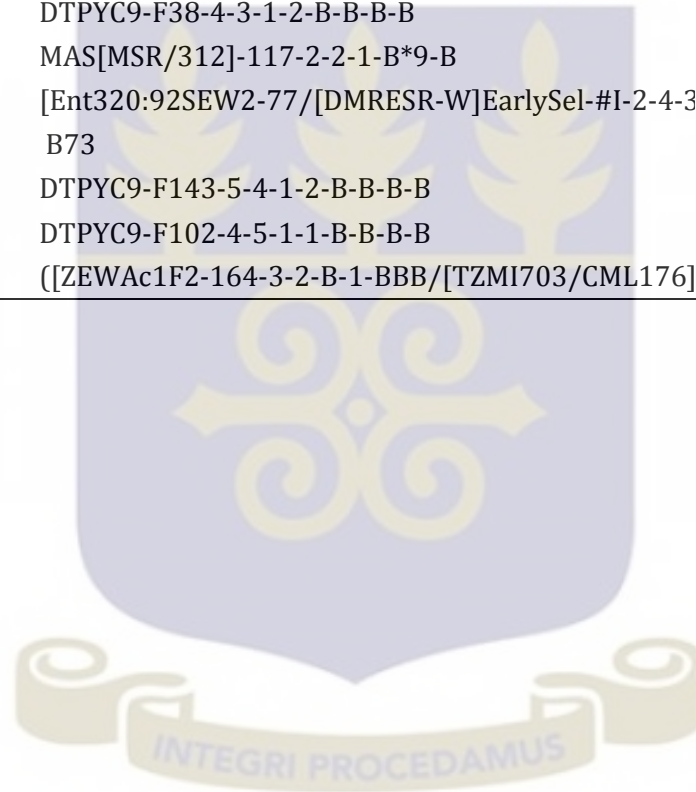
Table 5.2. the related single crosses developed from intra-group crosses, the two single cross checks and the local OPV check used in the study

Related single-crosses	Checks
TZEEI 95 x TZEEI 78	TZEEI 79 x TZEEI 63
TZEEI 95 x TZEEI 79	TZEEI 79 x TZEEI 76
TZEEI 78 x TZEEI 79	P ₃ Kollo
TZEEI 63 x TZEEI 58	
TZEEI 76 x TZEEI 82	

Table 5.3. Selected inbred lines of varying maturity periods used in the development of the modified single cross hybrids

No	Inbreds	Source	Pedigree	Number of days to anthesis	Maturity group
1	TZEEI 63	IITA	TZEE-Y SR BC1×9450 STR S6 Inb 7B	41	Extra-early
2	TZEEI 64	IITA	TZEE-Y SR BC1 x 9450 STR S6 Inb 8A	41	Extra-early
3	TZEEI 87	IITA	TZEF-Y POP STR COS6 Inb 47-24B	43	Extra-early
4	TZEEI 89	IITA	TZEF-YSR BC1 X 9450 STR S6inb 13A	43	Extra-early
5	TZEEI 67	IITA	TZEE-Y SR BC1 x 9450 STR S6 Inb 10B	43	Extra-early
6	TZEEI 58	IITA	TZEE-Y SR BC1×9450 STR S6 Inb 1A	44	Extra-early
7	TZEEI 81	IITA	TZEF-Y SR BC1 x 9450 STR S6 Inb 9A	46	Extra-early
8	TZEEI 96	IITA	TZEE-Y Pop Co S6 Inbred 78	47	Extra-early
9	TZEI 182	IITA	TZE-Y Pop STR Co S6 Inbred 152-2-2	46	Extra-early
10	TZEI 157	IITA	TZE-Y Pop STR Co S6 Inbred 102-1-2	46	Extra-early
11	TZEI 23	IITA	TZE-Y Pop STR C0 S6 Inbred 62-2-3	45	Extra-early
12	TZEI 129	IITA	TZE-Y Pop STR Co S6 Inbred 16-1-3	48	Early
13	TZEI 158	IITA	TZE-Y Pop STR Co S6 Inbred 102-2-2	48	Early
14	TZEI 124	IITA	TZE-Y Pop STR Co S6 Inbred 3-1-3	51	Early
15	TZEI 13	IITA	TZE Comp5-Y C6 S6 Inbred 12	53	Early
16	ENT 13	CIMMYT	[M37W/ZM607#bF37sr-2-3sr-6-2-X]-8-2-X-1-BB-B-	51	Early
17	CMK ENT 20	CIMMYT Kenya	[[Ent52:92SEW1-2/[DMRESR-W]EarlySel-#L-2-1-	51	Early
18	TZEI 16	IITA	TZE Comp5-Y C6 S6 Inbred 31	53	Early
19	CMZ ENT 2	CIMMYT Zimbabwe	DTPYC9-F46-1-2-1-2-B-B-B	53	Early
20	TZd 164	IITA	TZE-W POP STR 104 S5 88/160-1/3	52	Early
21	TZd 181	IITA	TZE-W POP STR 108 S5 164/198-1/1-1/5-1/2-5/5	53	Early
22	Cam Inbgp ₁	IRAD Cameroon	TzmSR/BW-SR	54	Early
23	CMZ ENT 5	CIMMYT Zimbabwe	DTPYC9-F46-3-4-1-1-B-B-B-B	54	Early
24	9848	IITA	Hi29 x RppSR	55	Intermediate

25	CMK ENT 22	CIMMYT Kenya	ZEWBc2F2-79-1-BBB-B-B	55	Intermediate
26	TZd 176	IITA	TZE-Y POP STR 106 S5 17/194-2/2-2/2-1/4-1/5	56	Intermediate
27	TZd 177	IITA	TZE-Y POP STR 106 S5 17/194-2/2-2/2-1/4-3/5	56	Intermediate
28	88069	IRAD Cameroon	Gusau BulSR/TzB	56	Intermediate
29	CMZ ENT 8	CIMMYT Zimbabwe	DTPYC9-F143-1-6-1-B-B-B	56	Intermediate
30	CMZ ENT 12	CIMMYT Zimbabwe	DTPYC9-F38-4-3-1-2-B-B-B-B	56	Intermediate
31	CMK ENT 8	CIMMYT Kenya	MAS[MSR/312]-117-2-2-1-B*9-B	56	Intermediate
32	CMK ENT 23	CIMMYT Kenya	[Ent320:92SEW2-77/[DMRESR-W]EarlySel-#I-2-4-3	56	Intermediate
33	9450	IITA	B73	57	Intermediate
34	CMZ ENT 3	CIMMYT Zimbabwe	DTPYC9-F143-5-4-1-2-B-B-B-B	57	Intermediate
35	CMZ ENT 6	CIMMYT Zimbabwe	DTPYC9-F102-4-5-1-1-B-B-B-B	58	Intermediate
36	CMK ENT 24	CIMMYT Kenya	([ZEWAc1F2-164-3-2-B-1-BBB/[TZMI703/CML176]	59	Intermediate



5.2.2. Experimental design and evaluation sites

The five RSCs and three checks were evaluated under managed drought and well-watered conditions using RCBD with 2 replications at 3 sites: (i) INRAN research station at Maradi (N 13°26' E 7°06'; 350 m altitude; 490 mm average annual rainfall), (ii) INRAN research station at Konni (N 13°47' E 5°14'; 260 m altitude; 530 mm average annual rainfall), and (iii) FESA Seed Company (N 13° 39' E 7° 04'; 382 m altitude; 500 mm average annual rainfall). The evaluation was conducted under managed drought and well-watered conditions during the dry season of 2012 at INRAN Maradi and INRAN Konni. It was conducted under well-watered conditions during the rainy season of 2013 at FESA Seed Co. and INRAN Maradi. The combination of location, cropping season, and water treatment was considered as an environment. Thus, the evaluation of the RSCs and checks was carried out under the following six environments:

1. MDS12WWC: Maradi (M), dry season of 2012 (DS12), under well-watered conditions
2. KDS12WWC: Konni (K), dry season of 2012 (DS12), under well-watered conditions
3. MRS13WWC: Maradi (M), rainy season of 2013 (RS13), under well-watered conditions
4. FRS13WWC: FESA (F), rainy season of 2013 (RS13), under well-watered conditions
5. MDS12WSC: Maradi (M), dry season of 2012 (DS12), under water stress conditions
6. KDS12WSC: Konni (K), dry season of 2012 (DS12), under water stress conditions.

The seven extra-early maturing inbreds used in the development of the RSCs were also evaluated in separate blocks under managed drought and well-watered conditions using RCBD with two replications in the six environments to assess the high parent heterosis for grain yield.

Based on the results of the evaluations of RSCs, three were selected and crossed to 36 inbreds of varying maturity to obtain 103 MSCs. The 103 MSCs plus the three extra-early RSC parents and two early maturing single-cross hybrids used as checks were evaluated during the dry season of 2013/2014 at INRAN station at Maradi and INRAN station at Konni. The 108 genotypes were divided into three maturity groups, each comprising 36 genotypes. The first group consisted of 33 extra-early MSCs plus the three RSC parents; the second group contained 34 early MSCs plus the two early maturing single-cross checks and the third group was made up of 36 intermediate maturing MSCs (appendix 5.1). At each evaluation site, the three maturity groups were evaluated separately under managed drought and well-watered conditions using a 9 x 4 alpha lattice design with 2 replications. The combination of location and water treatment was considered as an environment. Thus, the evaluation of the MSCs and checks was conducted at the following four contrasting environments:

1. MDWSC: INRAN station at Maradi (MD) under water stress conditions (WSC),
2. KNWSC: INRAN station at Konni (KN) under water stress conditions (WSC),
3. MDWWC: INRAN station at Maradi (MD) under well-watered conditions (WWC),
4. KNWWC: INRAN station at Konni (KN) under well-watered conditions (WWC).

5.2.3. Stress management

The RSCs and the MSCs were all evaluated using the same stress management conditions. In the well-watered blocks, plants were irrigated twice a week until crop maturity. In the stressed blocks, plants were irrigated twice a week from planting to about 2 weeks before anthesis; thereafter, irrigation was stopped and the stress intensity was monitored. A rescue irrigation was applied in the stressed blocks (12 to 15 days after stress application) when 50% of the plants had started showing signs of severe water stress i.e. leaf rolling early in the morning, leaf senescence,

tassel blasting and wilting. Between 10 to 12 days later, the normal irrigation was continued until crop maturity.

5.2.4. Field management practices

Except for the water treatments, all field management practices were similar for both the stressed and the well-watered blocks. Each entry was planted in a single row of 5 m length with spacing of 40 cm within rows and 75 cm between rows. Three seeds were planted per hill at planting and the seedlings thinned to two plants per hill about two weeks after emergence to give a final population density of 66 000 plants ha⁻¹. A compound fertilizer (NPK-15-15-15) was applied at the rate of 52 kg N ha⁻¹, 52 kg P ha⁻¹, and 52 kg K ha⁻¹. Urea was top-dressed at the rate of 46 kg of N ha⁻¹ 20 days later. Weeds were controlled manually.

5.2.5. Data collection

Data for grain yield and other agronomic traits were recorded as follow:

DYA: (days to anthesis) number of days from planting to when 50% of the plants had shed pollen;

DYS: (days to silking) number of days from planting to when 50% of the plants had emerged silks;

ASI: (anthesis-silking interval) number of days between DY A and DYS;

PLTH: (Plant height) measured as the distance from the base of the plant to the position of the first tassel branch. PLTH was computed as the average height of **10 plants** randomly chosen in the row;

EHT: (ear height) measured as the distance from the base of the plant to the node bearing the upper ear. This was computed as the average ear height of **10 plants** randomly chosen in the row;

PASP: (plant aspect) estimated based on the overall plant appeal on a scale of 1 to 5, where 1 = excellent plant type and 5 = poor plant type;

HUSK: (husk cover) rated on a scale of 1 to 5, where 1 = husks tightly arranged and extended beyond the ear tip and 5 = open tip cover.

NPHARV: (number of plants harvested) the total number of plants in the plot at harvest;

EHARV: (number of ears harvested) the number of ears bearing at least one developed kernel in the plot;

EPP: (number of ears per plant) estimated by dividing the total number of ears per plot by the number of plants harvested;

EASP: (ear aspect) estimated based on absence of disease and insect damage, ear size, uniformity of ears, and grain filling. It is scored on a scale of 1 to 5, where 1 = clean, uniform, large, and well-filled ears and 5 = ears with undesirable features.

YLD_HA : grain yield adjusted to 15% moisture content and converted to kg ha⁻¹; it is computed from the shelled grain weight at harvest.

SGREEN 1 and 2 (stay-green characteristic) scored for the water-stressed blocks at 90 and 100 days after planting on a scale of 1 to 9, where 1 = almost all leaves green and 9 = virtually all leaves dead.

5.2.6. Statistical analysis

Analysis of variance (ANOVA) was performed on plot means for grain yield and other agronomic characters for each environment and across environments using PROC GLM procedure of SAS software, version 9.2 TS2M0 (SAS Institute, 2002). Entries (103 MSCs, 3 RSCs and 2 checks) were considered as fixed factors while environments, replications and blocks were considered as random factors.

The statistical model used for the combined analysis is as follows:

$$Y_{lki} = \mu + \alpha_l + b_{kl} + v_i + (\alpha v)_{il} + e_{lki}$$

Y_{lki} = observed trait value from each experimental unit

(l = environment, k = replication, i = genotypes);

μ = population mean;

α_l = environment effect;

b_{kl} = replication within environment effect;

v_i = genotype effect;

$(\alpha v)_{il}$ = interaction between genotypes and environments;

e_{lki} = residual effect (adapted from Zhang and Kang (1997)).

The high-parent (HPH) heterosis values exhibited by the RSCs were computed for grain yield as:

$$\text{HPH} = \left\{ \frac{\text{RSC} - \text{HP}}{\text{HP}} \right\} \times 100$$

where,

RSC = Mean grain yield of the RSC,

HP = Mean grain yield of the best inbred parent

5.3. Results

5.3.1. Performance of related single crosses and inbred parents under drought and well-watered conditions

The analysis of variance for the RSCs evaluated under drought stress showed significant differences among genotypes (G) and environments (E) for grain yield and most measured traits except PASP, EASP and SGREEN for G and E; ASI and EHT for G. In contrast for genotype by environment interactions (GEI), no significant differences were observed in the measured traits except the grain yield, DYA and EHT (Table 5.4).

The ANOVA across the well-watered environments also revealed significant differences among G and E for most measured traits except PASP for E; ASI, PASP and EASP for G. Similarly significant differences were detected for GEI for grain yield and all other traits except DYA, ASI and EPP (Table 5.4).

Mean grain yield of the RSCs under drought was 1,522 kg ha⁻¹ representing 38.68% of the grain yield under well-watered conditions (3,934 kg ha⁻¹). Under drought stress, grain yield for the RSCs ranged from 1,111 kg ha⁻¹ for TZEEI 95 x TZEEI 78 to 1,950 kg ha⁻¹ for TZEEI 95 x TZEEI 79 (Table 5.4). The 3 top yielding RSCs under drought stress were TZEEI 95 x TZEEI 79 (1,950 kg ha⁻¹); TZEEI 76 x TZEEI 82 (1,794 kg ha⁻¹) and TZEEI 78 x TZEEI 79 (1,602 kg ha⁻¹). The mean grain yield of these three RSCs under drought stress respectively was 72.4%, 66.6% and 59.5% of the grain yield of the best extra-early single cross check (TZEEI 79 x TZEEI 76) which was 2,692 kg ha⁻¹ (Table 5.4).

Under well-watered conditions, grain yield of the RSCs ranged from 3,078 kg ha⁻¹ for TZEEI 63 x TZEEI 58 to 4,482 kg ha⁻¹ for TZEEI 78 x TZEEI 79 (Table 5.4). The 3 top yielding RSCs were TZEEI 78 x TZEEI 79 (4,482 kg ha⁻¹); TZEEI 95 x TZEEI 79 (4,235 kg ha⁻¹) and TZEEI 76 x TZEEI 82 (4,004 kg ha⁻¹) representing 93.7 %, 88.5% and 83.7% of the grain yield of the best extra-early single cross check (TZEEI 79 x TZEEI 76) which was 4,782 kg ha⁻¹ (Table 5.4).

The RSCs exhibited high parent heterosis of 9.7% to 92% for grain yield under drought stress and of -5.7% to 64% under well-watered conditions (Table 5.4). The best three RSCs i.e. TZEEI 95 x TZEEI 79, TZEEI 78 x TZEEI 79 and TZEEI 76 x TZEEI 82 displayed high parent heterosis for grain yield of 64%, 64% and 35.3% respectively under well-watered conditions and 92.1 %, 37.3% and 57.5% , respectively under drought (see table 5.4).

Table 5.4 Grain yield and other agronomic traits of the related single crosses and checks evaluated under drought stress and well-watered conditions in Niger in 2012 and 2013

Entry	YIELD kg ha ⁻¹		DYA		ASI		PLHT		EHT		PASP		EASP		EPP		SGR1	SGR2	HPH	HPH
	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WSC	WSC	WWC	WSC
TZEEI 95 x TZEEI 78	3872	1111	59	67	1.5	4.7	177	160	82	48	2.8	2.3	2.3	3.7	1.2	0.7	2.2	7.3	41.7	57.9
TZEEI 95 x TZEEI 79	4235	1950	56	64	1.8	4.2	175	151	81	43	2.7	2.7	2.7	3.5	1.0	0.8	2.7	7.8	64.0	92.1
TZEEI 78 x TZEEI 79	4482	1602	60	67	2.5	5.2	188	167	97	53	2.5	3.2	2.8	3.7	1.0	0.8	1.3	7.0	64.0	37.3
TZEEI 63 x TZEEI 58	3078	1152	58	68	1.4	3.8	180	149	88	46	3.1	3.8	2.6	4.3	1.1	0.6	1.5	6.8	-5.7	9.7
TZEEI 76 x TZEEI 82	4004	1794	57	66	1.5	3.8	168	154	83	52	4.0	3.7	3.2	3.7	1.3	0.7	1.5	7.2	35.3	57.5
TZEEI 79 x TZEEI 63 (Chk)	4663	2374	56	65	2.1	3.2	173	151	85	47	2.9	2.8	2.8	3.4	1.0	0.9	1.7	6.3	42.9	126.1
TZEEI 79 x TZEEI 76 (Chk)	4782	2692	56	63	1.3	2.8	181	164	91	53	2.5	2.2	2.3	3.2	1.2	0.8	1.3	6.0	66.1	136.4
P ₃ Kollo Chk	3863	1608	54	62	1.4	6.3	172	163	87	50	2.4	2.7	2.7	4.1	1.2	0.7	1.3	5.7		
Overall mean	4122	1786	57	65	1.7	4.25	177	157	87	49	2.9	2.9	2.7	3.7	1.1	0.7	1.7	6.7		
Lsd	741	699	1.3	1.7	1.5	2	8.5	9.5	4.8	9.3	2.1	2.3	0.4	0.6	0.1	0.2	0.8	1.2		
Entry	*	*	**	*	ns	ns	*	*	**	ns	ns	ns	ns	ns	**	**	ns	ns		
Environment	**	**	**	**	**	**	**	**	**	**	ns	ns	*	ns	**	**	ns	ns		
Entry x Environment	*	*	ns	*	ns	ns	*	ns	**	**	**	ns	*	ns	ns	ns	ns	ns		

WWC: well-watered conditions; WSC: water stress conditions; Chk: check

YIELD: Grain yield; DY A: days to anthesis; ASI: anthesis silking interval; PLTH (cm): plant height;

EHT (cm): ear height; PASP (1-5): plant aspect; EASP (1-5): ear aspect; EPP: number of ears per plant;

SGR 1 and 2: stay green characteristic at 90 and 100 days after planting on a scale of 1 to 9; HPH (%): high parent heterosis for grain yield;

*Significant at the 0.05 probability level; **Significant at the 0.01 probability level; ns: not significant

Across the six test environments, the combined analysis of variance revealed significant mean squares for G, E and GEI for grain yield and all the measured traits except EASP for G, PASP for E and ASI for G and GEI (Table 5.5).

The 3 top yielding RSCs (TZEEI 78 x TZEEI 79; TZEEI 95 x TZEEI 79; and TZEEI 76 x TZEEI 82) identified under well-watered conditions were also the best RSCs across the six test environments (Figure 5.1). They were therefore selected to be used as female parents in the development of the MSC hybrids.



Table 5.5 Mean squares from the combined analysis of variance for grain yield and other agronomic traits of the related single crosses and checks evaluated across six environments in Niger in 2012 and 2013

Source of variation	DF	Yield (kg ha ⁻¹)	DYA	DYS	ASI	PLTH (cm)	EHT (cm)	PASP (1-5)	EASP (1-5)	EPP
Environments	5	65923555**	2495**	2654**	132**	4304**	26390**	3.8 ^{ns}	7.83**	1.45**
Rep (ENV)	12	1587928*	5.6*	12**	10**	360**	186**	2.3**	1.28**	0.03 ^{ns}
Genotypes	7	4662126**	65**	77**	4 ^{ns}	578**	366**	4.4*	1.08 ^{ns}	0.09*
G x E interactions	35	1082532*	4.6*	9**	4 ^{ns}	171*	89**	1.7**	0.54**	0.04**
Residual	84	663742	2.5	4.4	3.3	94	34	0.6	0.3	0.02

*Significant at the 0.05 probability level

**Significant at the 0.01 probability level

ns: not significant



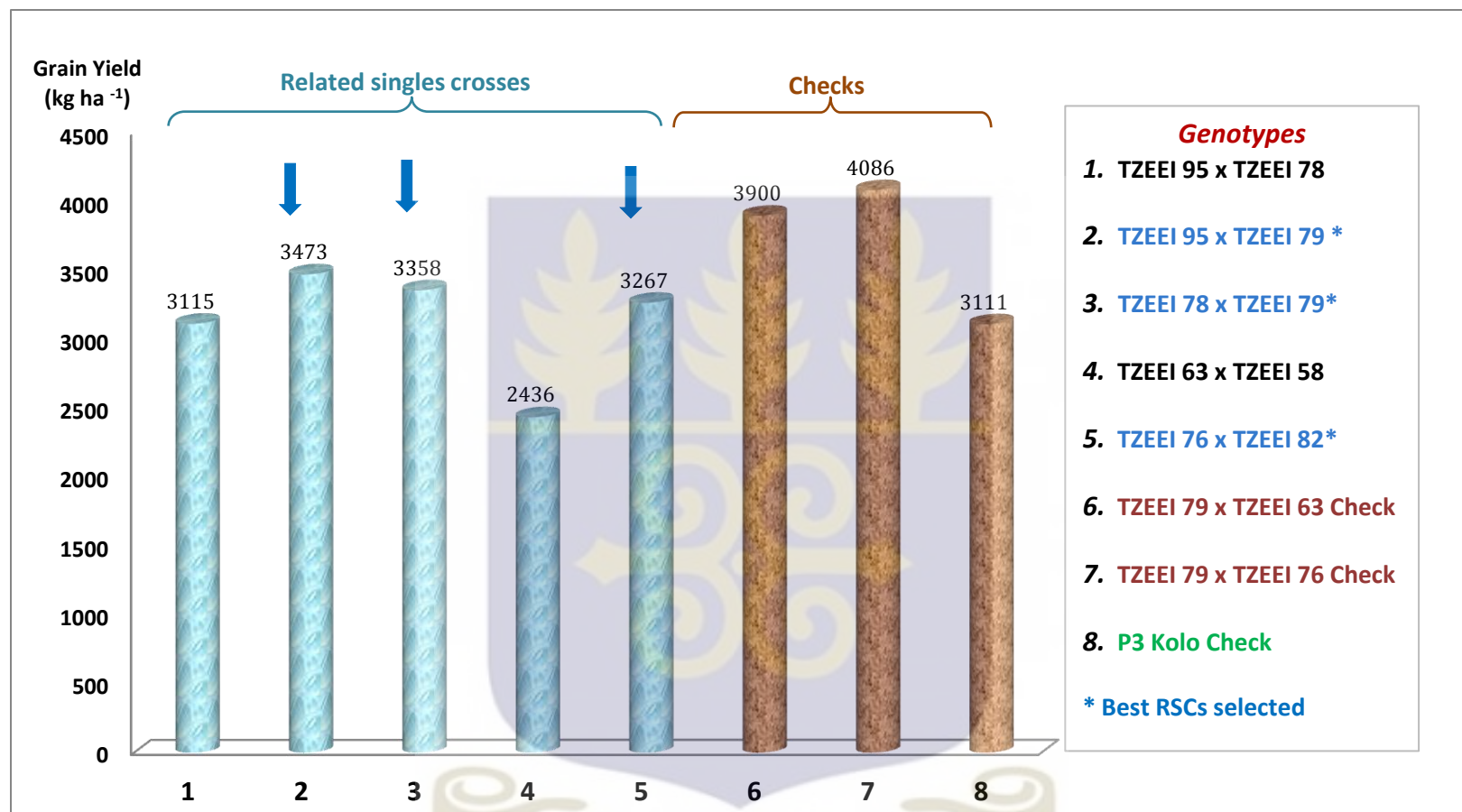


Figure 5.1 Grain yield (Kg ha⁻¹) of the related single crosses and checks evaluated across six contrasting environments in Niger in 2012 and 2013

The analysis of variance for the extra-early inbred parents (used in the development of the five RSCs) evaluated under drought and well-watered conditions revealed no significant differences among the inbreds for most traits except grain yield, flowering dates, PLTH and EHT (Table 5.6). Mean grain yield of the inbreds ranged from 591 Kg ha⁻¹ for TZEEI 78 to 1,139 Kg ha⁻¹ for TZEEI 76 and from 2,192 Kg ha⁻¹ for TZEEI 95 to 3,263 Kg ha⁻¹ for TZEEI 63 under drought stress and well-watered conditions, respectively (Table 5.6). The average grain yield of the inbreds was 923 Kg ha⁻¹ and 2,692 Kg ha⁻¹ under drought stress and well-watered conditions, respectively, representing 60.6% and 68.4% of the average grain yield of their RSCs under similar conditions (1,522 Kg ha⁻¹ and 3,934 Kg ha⁻¹).

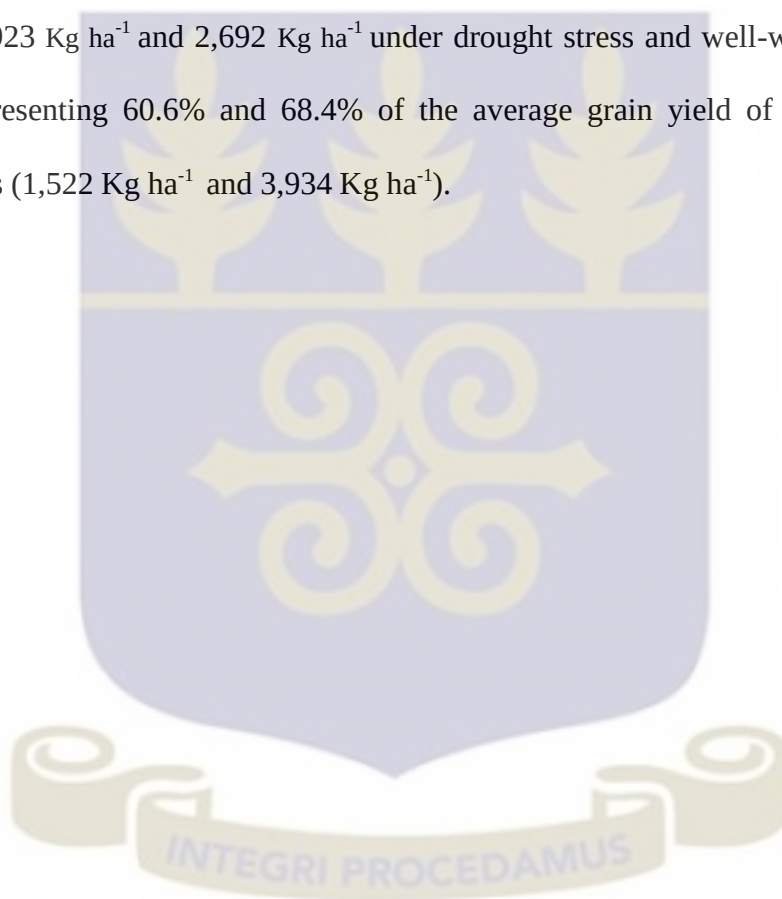


Table 5.6 Grain yield and other agronomic traits of the extra-early maturing inbreds evaluated under drought stress and well-watered conditions in six contrasting environments in Niger, 2012 and 2013

Entry	YIELD kg ha ⁻¹		DYA		DYS		ASI		PLHT		EHT		SGREEN
	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	
TZEEI 78	2733	591	73	76	77	81	3.5	4.5	162	153	93	101	7.0
TZEEI 79	2582	809	68	71	71	77	3.0	6.0	142	135	75	89	7.0
TZEEI 95	2192	1015	66	67	67	74	0.5	7.0	108	118	40	49	6.0
TZEEI 76	2880	1139	65	64	66	70	1.0	5.5	145	149	78	83	6.0
TZEEI 82	2959	970	66	68	67	76	1.0	8.0	149	164	80	109	6.5
TZEEI 63	3263	1050	65	64	66	70	1.0	5.5	152	149	78	83	6.0
TZEEI 58	2239	886	66	67	67	74	0.5	7.0	108	118	40	49	6.0
Overall mean	2692	923	67	69	69	75	1.8	6.2	141	143	73	86	6.5
Lsd	343	529	2.6	6.3	3	11	3.6	7.7	17.2	44.0	15.5	26.9	1.7
Entry	**	**	**	*	**	ns	ns	ns	**	ns	**	*	ns
Environment	ns	ns	ns	ns	ns	ns	ns	**	ns	ns	ns	ns	ns
Entry x Environment	ns	ns	ns	ns	ns	ns	ns	**	ns	ns	ns	ns	ns

WWC: well-watered conditions; **WSC:** water stress conditions;

YIELD: Grain yield; **DYA:** days to anthesis; **DYS:** days to silk; **ASI:** anthesis silking interval; **PLTH (cm):** plant height;

EHT (cm): ear height; **SGREEN:** stay green characteristic at 90 days after planting on a scale of 1 to 9 ;

*Significant at the 0.05 probability level; **Significant at the 0.01 probability level ; **ns:** not significant

5.3.2. Performance of modified single crosses under drought and well-watered conditions

Due to failure of the irrigation system at Konni, the trial involving the evaluation of the MSCs at INRAN station at Konni in 2013 was lost. Therefore, only the results of the trial from the Maradi Station are reported in this study. Significant differences due to genotypes were observed for grain yield and all other traits (Table 5.7 and Appendix 5.1) under both drought and well-watered conditions. Under drought stress the average grain yield of the MSCs was 1,429 Kg ha⁻¹ representing 37.7% of the grain yield obtained under well-watered conditions (3,788 Kg ha⁻¹). The grain yield of the MSCs ranged from 377 Kg ha⁻¹ to 3383 Kg ha⁻¹ under drought and from 1765 Kg ha⁻¹ to 5399 Kg ha⁻¹ under well-watered conditions (Table 5.7).

Under drought stress, 27 MSCs out-yielded the best single cross check ENT 13 x CamInbgp.1-17 (1770 Kg ha⁻¹); 72 MSCs yielded higher than their respective RSC parents while 56 MSCs displayed high parent heterosis for grain yield superior to 50% (Appendix 5.1). The 5 top yielding MSCs under stress were (TZEEI 76 x TZEEI 82) x CMK ENT 23 (3,383 Kg ha⁻¹); (TZEEI 76 x TZEEI 82) x CMZ ENT 8 (2,959 Kg ha⁻¹); (TZEEI 95 x TZEEI 79) x CMK ENT 8 (2,937 Kg ha⁻¹); (TZEEI 78 x TZEEI 79) x CMK ENT 23 (2,778 Kg ha⁻¹) and (TZEEI 78 x TZEEI 79) x CMK ENT 8 (2,754 Kg ha⁻¹) (Table 5.7). They out-yielded the best single cross check ENT 13 x CamInbgp.1-17 by 91%, 67%, 66%, 57% and 56%, respectively.

Under well-watered conditions 18 MSCs out-yielded the best single cross check TZEI 124 x ENT 13 (4,524 Kg ha⁻¹); 85 MSCs yielded higher than their respective RSC parents and 33 MSCs displayed high parent heterosis for grain yield superior to 50% (Appendix 5.1). The 5 top yielding MSCs under well-watered conditions were (TZEEI 76 x TZEEI 82) x TZEI 124 (5,399 Kg ha⁻¹); (TZEEI 78 x TZEEI 79) x ENT 13 (5,328 Kg ha⁻¹); (TZEEI 95 x TZEEI 79) x CMZ

ENT 5 (5,293 Kg ha⁻¹); (**TZEEI 76** x **TZEEI 82**) x **TZd 164** (5,272 Kg ha⁻¹) and (**TZEEI 76** x **TZEEI 82**) x **TZEI 129** (5,202 Kg ha⁻¹) (Table 5.7). They out-yielded the best single cross check **TZEI 124** x **ENT 13** by 19.3%, 17.8%, 17%, 16.5% and 15%, respectively.



Table 5.7 Grain yield and other agronomic traits of the 5 highest yielding MSCs, the 5 lowest yielding MSCs and 5 checks evaluated under drought stress and well-watered conditions in Maradi in 2014.

Entry	Extra-early Early Intermediate	YIELD		DYA		ASI		PLTH		EHT		PASP		EPP		SGREEN	
		WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC
(TZEEI 76 x TZEEI 82) x TZEI 124		5399	1834	66	68	2.0	6.0	173	164	90	98	2.0	2.5	1.0		6.5	
(TZEEI 78 x TZEEI 79) x ENT 13		5328	2376	70	71	0.5	3.0	201	182	130	123	1.5	3.0	1.0		6.0	
(TZEEI 95 x TZEEI 79) x CMZ ENT 5		5293	1016	66	69	1.0	7.0	177	145	90	96	2.0	3.5	1.0		7.5	
(TZEEI 76 x TZEEI 82) x TZd 164		5272	1440	68	72	-0.5	2.0	171	139	93	92	2.0	3.0	1.2		7.0	
(TZEEI 76 x TZEEI 82) x TZEI 129		5202	2044	67	70	1.5	6.0	182	153	110	96	2.0	2.5	1.0		6.0	
(TZEEI 76 x TZEEI 82) x CMK ENT 23		4092	3383	71	71	-0.5	2.0	163	169	83	109	3.0	2.5	1.1		6.5	
(TZEEI 76 x TZEEI 82) x CMZ ENT 8		4350	2959	68	70	0.5	3.0	158	161	78	100	3.0	2.0	0.9		6.5	
(TZEEI 95 x TZEEI 79) x CMK ENT 8		3108	2937	68	72	0.5	1.0	135	141	78	86	3.5	2.5	1.0		8.0	
(TZEEI 78 x TZEEI 79) x CMK ENT 23		3109	2778	70	72	1.5	8.5	154	168	83	103	3.5	2.5	1.0		7.0	
(TZEEI 78 x TZEEI 79) x CMK ENT 8		4662	2754	67	70	0.0	2.0	159	176	88	104	3.0	2.5	1.0		7.0	
(TZEEI 76 x TZEEI 82) x TZEEI 63		1984	1002	66	69	1.0	5.5	139	136	80	88	4.5	3.5	1.5		5.5	
(TZEEI 95 x TZEEI 79) x TZEEI 96		1835	744	68	72	2.0	2.5	144	126	80	87	4.5	3.5	0.7		7.0	
(TZEEI 95 x TZEEI 79) x CMK ENT 20		4616	499	68	75	2.0	11.0	160	133	80	79	2.5	4.0	1.0		7.5	
(TZEEI 76 x TZEEI 82) x TZEEI 89		3058	419	65	69	2.0	6.5	133	122	65	80	4.5	4.5	1.0		6.0	
(TZEEI 78 x TZEEI 79) x TZEEI 87		2094	396	68	71	3.0	7.0	163	125	88	78	4.5	4.0	1.2		7.5	
(TZEEI 78 x TZEEI 79) x TZEEI 96		1765	377	71	73	2.5	9.5	138	138	85	92	5.0	4.5	0.9		8.0	
TZEI 124 x ENT 13 check		4524	1498	75	81	2.5	4.5	177	154	100	103	2.5	3.0	1.0		5.5	
ENT 13 x CamInbgp.1-17 Check		4081	1770	70	70	1.5	11.0	178	153	108	92	3.0	2.5	1.0		6.0	
TZEEI 78 x TZEEI 79 Check		3571	1053	66	69	1.5	2.5	167	159	85	95	3.0	2.0	1.3		7.0	
TZEEI 76 x TZEEI 82 Check		3166	534	65	69	1.0	4.0	132	134	75	88	3.5	4.0	1.1		5.5	
TZEEI 95 x TZEEI 79 Check		2353	821	69	71	4.5	6.5	153	136	80	91	3.5	4.0	0.8		8.0	
Overall mean		3788	1429	67	71	1.9	5.7	158	142	83	90	2.9	3.2	1		6.8	
Lsd		1538	918	2.2	4.2	2.3	5.5	20	23	20	17	1.3	1.2	0.2		1.7	
Rep		ns	ns	ns	**	**	ns	*	ns	ns	ns	ns	ns	*		**	
Block(Rep)		**	**	*	**	ns	ns	**	**	**	**	*	**	ns		**	
Entry		**	**	**	**	**	**	**	**	**	**	**	*	*		**	

WWC: well-watered conditions; WSC: water stress conditions; YIELD (Kg ha⁻¹): Grain yield; DY A: days to anthesis; ASI: anthesis silking interval; PLTH (cm): plant height; EHT (cm): ear height; PASP (1-5): plant aspect; EPP: number of ears per plant; SGREEN: stay green characteristics (1- 9) ; *Significant at the 0.05 probability level; **Significant at the 0.01 probability level ; ns: not significant

5.3.3. Relationship between yield performance and maturity group of modified single crosses

The evaluation of the MSCs was carried out during the cold and dry season in Maradi (November, 2013 to February, 2014). It is important to note that during that period, the low night and morning temperatures influenced the maturity cycles of plants by increasing the days to maturity by about 20 days compared to that observed during the main rainy season (June to September).

The classification of the MSCs into different maturity groups i.e. extra-early, early and intermediate was based on the days to maturity of the inbreds used as male parents of the MSCs. From the evaluation of the MSCs under drought and well-watered conditions during the cold and dry season (2013/2014) in Maradi, the maturity groups of the MSCs as indicated by the number of days to anthesis for 50% of the plants in the plots was not consistent with the classification based on prediction from the maturity groups of the male inbred parents. Some MSCs classified in the intermediate group were among the 10 MSCs that were the first to flower while others from the extra-early group were among the 15 MSCs that flowered late. The number of days to anthesis varied from 67 to 85 under drought and from 62 to 75 under well-watered conditions. All the MSCs flowered earlier than the early maturing single cross check, TZEI 124 x ENT 13 (Appendix 5.1). Out of the top 30 MSCs that flowered early, 22 were from the extra-early group, 3 from the early group and 5 from the intermediate group. Of the 30 MSCs that flowered late, 3 were from the extra-early group, 11 from the early group and 16 from the intermediate group.

The top five MSCs under well-watered conditions, (TZEEI 76 x TZEEI 82) x **TZEI 124**; (TZEEI 78 x TZEEI 79) x **ENT 13**; (TZEEI 95 x TZEEI 79)x **CMZ ENT5**; (TZEEI 76 x TZEEI 82) x **TZd 164** and (TZEEI 76 x TZEEI 82)x **TZEI 129** were all from the early group.

Of the 20 top yielding MSCs under well-watered conditions none was from the extra-early group while 12 were from the early group and 8 from the intermediate group (Appendix 5.1).

Under drought stress, the 5 top yielding MSCs (TZEEI 76 x TZEEI 82) x **CMK ENT 23**; (TZEEI 76 x TZEEI 82) x **CMZ ENT8**; (TZEEI 95 x TZEEI 79) x **CMK ENT8**; (TZEEI 78 x TZEEI 79) x **CMK ENT 23** and (TZEEI 78 x TZEEI 79)x **CMK ENT 8** were all from the intermediate maturing group.

Of the 20 top yielding MSCs under drought stress five were from the extra-early group, three from the early group and 12 from the intermediate group (Appendix 5.1). Across water regimes, four out of the 30 top yielding MSCs were from the extra-early group, 11 from the early group and 15 from the intermediate group. In contrast, 16 out of the 30 lowest yielding MSCs were from the extra-early group, 9 from the early group and 5 from the intermediate group.

The analysis of variance for grain yield and other traits revealed significant differences among the maturity groups for grain yield and most other traits under drought and well-watered conditions except for EHT and PASP under drought, as well as ASI and EPP under well-watered conditions (Table 5.8). Under drought and well-watered conditions the intermediate and early groups yielded significantly higher than the extra-early group while the extra-early group flowered earlier than the other groups under both water regimes.

Table 5.8 Grain yield and other agronomic traits of the three maturity groups of the modified single crosses evaluated under drought stress and well-watered conditions in Maradi in 2014

Maturity group	YIELD		DYA		DYS		ASI		PLTH		EHT		PASP		EPP	
	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC
Extra-early	3279	1285	66	69	68	74	2.0	4.9	152	138	80	89	3.4	3.3	1.0	0.7
Early	4141	1281	68	72	70	79	2.0	6.7	165	141	88	90	2.7	3.3	1.0	0.7
Intermediate	3944	1722	68	72	70	78	1.8	5.5	157	149	81	91	2.8	3.1	1.0	0.7
Overall mean	3788	1429	67	71	69	77	1.9	5.6	158	142	83	90	3	3.2	1	0.7
Lsd	305	244	0.8	1.16	0.81	1.5	0.47	1.12	4.8	5.9	5	4.2	0.26	1.9	0.04	0.06
Rep	ns	ns	ns	*	ns	ns	**	ns	ns	ns	ns	ns	ns	ns	ns	ns
Maturity group	**	**	**	**	**	**	ns	**	**	**	**	ns	**	ns	ns	**

WWC: well-watered conditions; **WSC:** water stress conditions; **YIELD (Kg ha⁻¹):** Grain yield; **DYA:** days to anthesis; **DYS:** days to silking;
ASI: anthesis silking interval; **PLTH (cm):** plant height; **EHT (cm):** ear height; **PASP (1-5):** plant aspect; **EPP:** number of ears per plant;
 *Significant at the 0.05 probability level; **Significant at the 0.01 probability level; ns: not significant

5.4. Discussion

In hybrid maize seed production, yield of the female parent is a major factor determining the seed production cost. One strategy to reduce the cost of hybrid seed production is to use RSCs which are the F_1 between two highly related inbred lines (Lee *et al.*, 2006). An important objective of this study was to identify RSCs with acceptable grain yield that could be used as female parents in hybrid seed production. The study revealed a significant increase in grain yield of the RSCs (grain yield ranging from 3078 kg ha⁻¹ to 4482 kg ha⁻¹) compared to their parental inbred lines (grain yield ranged from 2239 kg ha⁻¹ to 2733 kg ha⁻¹). These results suggest that the RSCs would be better female parents in hybrid seed production because of their higher grain yield potential compared to inbred lines. The higher performance of the RSCs is also confirmed by the high parent heterosis for grain yield (35% to 64%) exhibited over their inbred parents. Similar results were reported by Castellanos *et al.* (2009) who found an average grain yield of 5000 kg ha⁻¹ to 8700 kg ha⁻¹ for the RSCs compared to an average grain yield of 2700 kg ha⁻¹ to 5700 kg ha⁻¹ for the sister lines and an average heterosis for grain yield of 37% displayed by the RSCs over their inbred parents. The performance of the RSCs is in general more stable or predictable than that of the unrelated parental inbred lines (Lee *et al.*, 2006). Average grain yields of 3800 kg ha⁻¹ to 5400 kg ha⁻¹ have been reported for intermediate and late maturing inbred lines (Duvick, 1999; Lee *et al.*, 2006; Castellanos *et al.*, 2009). In the present study, the relatively low grain yield of the extra-early inbreds (2239 to 2733 kg ha⁻¹) and their corresponding RSCs (3078 to 4482 kg ha⁻¹) is explained by the fact that extra-early maize genotypes are inherently lower yielding than early, intermediate and late maturing genotypes. For instance, Badu-Apraku (unpublished) reported an average grain yield of 2955 kg ha⁻¹ for extra-early varieties across seven locations compared to an average grain yield of 4463 kg ha⁻¹ for early varieties across six locations in a regional trial in

2009 (Badu-Apraku and Oyekunle, 2012). Similarly a study on the productivity and optimum planting periods for five varieties representing five maturity groups in the Guinea savanna of Ghana conducted by Sallah *et al.* (1995) revealed an average grain yield of 3890, 5250, 5800, 5830 and 5880 kg ha⁻¹ for the extra-early, early, normal endosperm intermediate, Quality Protein intermediate and the late maturing varieties, respectively.

Another important objective of the present study was to determine the yield performance of the MSCs under drought and well water conditions. The significant differences observed among the MSCs for grain yield and most measured traits under water stress and well-watered conditions indicated that adequate genetic variation existed among the genotypes which could allow good progress from selection under the contrasting environments. The yields of MSCs under drought (37.7% of the well-watered yield) were slightly above the limits recommended by Bolaños and Edmeades (1996) who reported that the average yields under drought and low soil nitrogen conditions have to be between 20% and 30% of what the average yield would have been in the same location under optimum management.

Modified single crosses have been reported to perform as well as their corresponding single cross hybrids (Fuhe *et al.*, 1995; Lee *et al.*, 2006; Castellanos *et al.*, 2009). This is because a similar set of genes are associated with yield in both types of hybrids (Castellanos *et al.*, 2009). In most cases MSCs display no “yield penalty” compared to their corresponding single crosses particularly when attention is paid to the degree of relatedness of the sister lines used (Fuhe *et al.*, 1995). In the present study 27 and 18 MSCs out-yielded the best single cross checks of this study under well-watered and drought stress. Furthermore 56 MSCs under drought and 33 MSCs under well-watered conditions out-yielded their respective RSC parents by at least 50% confirming the hypothesis that MSCs may represent an attractive alternative to single cross hybrids in a situation

where low grain yield of inbreds constitutes a major constraint to commercial maize single cross hybrid production. These results are in agreement with the findings of Lee et al., (2006) and Castellanos et al., (2009).

The highest yielding MSCs hybrids under well-watered conditions were obtained from crosses with the early maturing inbreds TZEI 124 and ENT 13 confirming the results of the previous diallel study conducted in the same environment which revealed the outstanding combining ability of these two inbred lines under optimal growing conditions. The five highest yielding MSC hybrids under water stress conditions were obtained from crosses with the intermediate maturing CIMMYT lines CMK ENT 23 and CMZ ENT 8 suggesting that these lines carry genes conferring tolerance to drought.

The present study also sought to assess the relationships between the yield performance of the MSCs and their maturity. The higher and significant grain yield displayed by MSCs from the intermediate and early maturity groups over MSCs from the extra-early group under both water regimes suggests that hybrids from parents of varying maturity groups may show high level of grain yield heterosis compared to within-maturity group crosses. These results are in disagreement with the findings of IITA and CIMMYT maize breeders who reported a failure of their outstanding intermediate to late maturing testers to discriminate effectively between early and extra-early maturing inbreds (Pswarayi and Vivek, 2008; Badu-Apraku *et al.*, 2013a). The differences in the findings of this study and those of CIMMYT and IITA workers may be attributed to the differences in the germplasm used.

5.5. Conclusions

The present study was conducted to develop and select related single crosses with higher grain yield potential; to develop modified single cross hybrids from crosses between the selected RSCs and inbred lines from varying maturity groups, and to assess the yield performance of the MSCs under drought and well-water conditions as well as the relationships between the yield performance of the MSCs and their maturity. Results of the study revealed an average grain yield of 3,934 kg ha⁻¹ for the RSCs versus 2,692 kg ha⁻¹ for their parental inbred lines. Furthermore the selected RSCs displayed high parent heterosis for grain yield of 57% to 92% and 35% to 64% respectively under drought and well-watered conditions suggesting that they would be good female parents for hybrid seed production.

The study revealed that a moderate level of moisture stress (37.7% yield reduction) was achieved in the evaluation of the MSCs. Under drought stress, the 3 top yielding MSCs i.e. (TZEEI 76 x TZEEI 82) x CMK ENT 23; (TZEEI 76 x TZEEI 82) x CMZ ENT 8; and (TZEEI 95 x TZEEI 79) x CMK ENT 8 out-yielded the best single cross check (ENT 13 x CamInbgp.1-17) by 91%, 67%, and 66% respectively. Under well-watered conditions, the 3 highest yielding MSCs i.e. (TZEEI 76 x TZEEI 82) x TZEI 124; (TZEEI 78 x TZEEI 79) x ENT 13 and (TZEEI 95 x TZEEI 79) x CMZ ENT 5 out-yielded the best single cross check TZEI 124 x ENT13 by 19.3%, 17.8% and 17% respectively. Overall, 27 and 18 MSCs out-yielded the best single cross checks and displayed high parent heterosis for grain yield of 72% and 32% under drought and well-watered conditions, respectively, indicating that MSCs could be a good alternative to single cross hybrids where farmers could not afford maize hybrid seeds because of the high prices resulting from the lower grain yield of the inbred parents. MSCs developed from crosses with early and intermediate maturing inbreds yielded significantly higher than those developed from extra-early inbreds

suggesting that MSC hybrids from the early and intermediate inbreds may be recommended for maize production in environments where complementary irrigation can be provided in case of drought. It is important to note, however, that in this study, results from the evaluation of the MSCs were from only one site in 2014. Therefore, no strong conclusions could be made about the performance of the MSCs under drought and well-water environments. It would be necessary to evaluate the MSCs at more sites to validate the results of the present study.



CHAPTER SIX

6.0. Research Overview

6.1. Introduction

Maize (*Zea mays L.*) is an important staple food crop in Niger. However, the current level of the production of maize grain is far below the national demand. Common crop production constraints i.e. drought, low soil fertility, poor crop management practices and lack of availability of improved varieties limit maize production in the country. Limited studies have been conducted on the production of this crop in Niger and very few cultivars (mostly open pollinated varieties) are available to farmers. Recently, maize has been included among the strategic crops whose production in multiple cropping systems is being promoted by Nigerien authorities through a national policy towards achieving food security in the country. More money is now being invested in purchasing maize seeds and developing small scale irrigation facilities and large public irrigation schemes to promote maize production in the country. In order to boost the national production from its current level, greater understanding of maize growing environments is needed and new maize improved varieties should be developed and/or introduced and tested in the different maize production areas of the country.

Three major activities were conducted. The first activity was a Rapid Rural Appraisal to assess the performance of maize crop management practices used by farmers in Niger, identify maize cultivars' traits preferred by farmers, and identify major factors that limit maize production in Niger. The second activity included: (i) a drought experiment to test the efficiency of the CIMMYT/IITA screening methodology for maize drought trials in Niger, and (ii) a diallel study involving fifteen early maturing yellow maize inbreds. The objectives of the diallel study was to estimate the combining ability and the mode of gene action for drought tolerance among the fifteen

early maturing inbred lines, classify the inbreds into contrasting heterotic groups using two different classification methods, and assess the yield performance and stability of the diallel single cross hybrids under drought and well-watered conditions. The third activity was a study of the agronomic performance of modified single cross hybrids developed from crosses between three extra-early maturing related single crosses (used as female parents) and thirty-six inbreds of varying maturity periods. The study sought to assess the yield performance of the modified single crosses under drought and well-watered conditions and examine the relationship between the grain yield and the maturity of the modified single crosses.

6.2. Major findings and their implications

The main findings of the thesis are activity specific and were discussed within the corresponding chapters. The following paragraphs aim at synthesizing these findings according to the different objectives targeted under each of the three activities conducted as well as providing their implications in the field of plant breeding and agriculture.

- **Maize production in Niger is performed under poor crop management practices.** The study revealed common practices among farmers consisting of land preparation with animal drawn ploughs before sowing but rare application of manure, sowing at low planting densities, thinning to three or four plants per hill, low application of mineral fertilizers and practice of fertilizer application on the ground near the stalks. The poor crop management practices added to the low fertility of soils in Niger and the lack of availability of maize improved varieties worsen the conditions of maize production in the country. This could explain the low maize grain yields recorded in the country. The implications of these findings are that the current national policy for boosting crop production in the country

which consists of facilitating farmers' access to fertilizers, improved varieties and other agricultural inputs is likely not to be sufficient to significantly increase maize production in the country. Therefore, in addition to this strategy, training and increasing farmers' awareness about appropriate crop management practices will undoubtedly contribute to boost the national maize production from its current level.

- **Yellow maize varieties combining earliness and high yield potential are predominantly preferred by maize growers in Niger.** Farmers' preference for extra-early and early maturing maize germplasm is justified because such germplasm could complete their growth cycle in environments where the beginning and the end of the rainy season are frequently challenged by drought. Several authors reported earliness and high yield potential to be of major importance to farmers (Defoer *et al.*, 1997; Abebe *et al.*, 2005; Obaa *et al.*, 2005; Ouma *et al.*, 2010; Sibiya *et al.*, 2013). Farmers believe that yellow endosperm provides more flour and higher amounts of a locally consumed meal "*Tuwo massara*" than the white type. This should be investigated by researchers from food technology and consumer sciences. Earliness, yield and endosperm color are therefore traits to be taken into consideration by the maize breeding program in Niger to increase the chance of adoption of new maize cultivars by farmers. However extra-early and early maturing germplasm has been reported to yield lower than intermediate and late maturing germplasm (Sallah *et al.*, 1995, Pswarayi and Vivek, 2008, Badu-Apraku and Oyekunle, 2012). Therefore intermediate germplasm should also be introduced and tested in Niger particularly in areas where irrigation facilities are available. A study from Tiwari *et al.*, (2009) revealed that farmers could be convinced by the yield advantage of late germplasm and could therefore trade off earliness for yield under certain circumstances.

- **Low soil fertility, recurrent drought and the lack of availability of improved varieties are major factors limiting maize production in Niger.** Drought and low soil fertility are the most important threat to sustainable crop production and thus the most important obstacles to achieving food security in African countries. Drought challenges maize grain production in both temperate and tropical environments (Edmeades, 2008; Ribaut *et al.*, 2009) and its effects are expected to be exacerbated due to global climate change (Witcombe *et al.*, 2008; IAEA, 2013). Low soil fertility (Low phosphorus and nitrogen availabilities) is believed to become in the long run a more serious concern than the lack of moisture in West Africa (Bationo and Mokwunye, 1991; Gruhn *et al.*, 2000) because of soil deficiency coupled with continuous cropping of the land over decades with no restitution. In Niger the majority of farmers are aware of the problem but seem helpless to change the situation. Therefore drought and low soil fertility have to be important priorities in the maize breeding program in Niger. The new cultivars should display improved productivity in low input systems and decreased input requirements in high input systems (IAEA, 2013). It is also important to develop and promote integrated crop, soil and nutrient management practices that could help farmers achieve sustainable crop production (IAEA, 2013).
- **An appropriate stress management procedure for maize drought trials in Niger consists of (i) stopping the irrigation 3 to 2 weeks before anthesis, (ii) applying a “rescue irrigation” 13 to 15 days after the stress imposition, and (iii) resuming the normal irrigation 10 to 12 days later until crop maturity.** An important challenge to breeding maize for drought tolerance is the development of an efficient field screening methodology that will correctly discriminate and elicit true differences among genotypes (Badu-Apraku *et al.*, 2004). A good drought screening method should bring the grain yield

from the stressed blocks to about 15-20% or 20-30% of well-watered yields (Bolaños and Edmeades, 1996; Bänziger *et al.*, 2000). In drought experiments conducted in Sahelian countries like Niger, frequent windy weather conditions and low relative humidity coupled with low water holding capacity of the soils lead to a rapid development of the stress and a rapid collapse of plants. A moderate stress that brings the grain yield from the stressed blocks to about 30-40% of well-watered yields should therefore be targeted in such environments to prevent the loss of the trial. This includes application of rescue irrigations when necessary as suggested by Badu-Apraku *et al.* (2004). Careful monitoring of the stress intensity is therefore necessary and the rescue irrigations should be applied when about 50% of plants in the stressed blocks present signs of severe stress i.e. leaf rolling, leaf senescence, tassel blast and stem wilting early in the morning.

- An important requirement for a commercially successful maize hybrid program is the availability of information on the combining ability and heterotic patterns of the inbreds in the program (Badu-Apraku *et al.*, 2013a). **In the present study, significant GCA and SCA effects for grain yield and most measured traits were found under drought, well-watered conditions and across test environments with a large predominance (> 80%) of GCA effects over SCA effects.** This suggests that grain yield and the other traits are predominantly controlled more by additive gene action than non additive gene action. The breeding implication of the significant GCA and SCA effects for grain yield and other traits is that appreciable breeding progress could be made using hybridization, backcrossing, and recurrent selection for the development of hybrids and synthetic varieties as well as in population improvement (Ifie, 2013). Inbreds with favorable GCA effects for grain yield and other traits are likely to transmit their characteristics to the progeny and could be useful

in a breeding program. Such inbreds could be used as parents to form a synthetic population that could be improved for stress environments (Makumbi et al., 2011; Badu-Apraku et al., 2012). Significant GCA by environments effects were also found in the study suggesting that the combining abilities of the inbreds were not consistent across environments. A stability analysis of the GCA effects of the inbreds was therefore carried out to identify those with high and stable GCA effect across environments. The CIMMYT line ENT 13 had the highest and most stable GCA effect under drought and well-watered conditions. It was the most attractive general combiner across environments, which is likely to contribute desirable alleles to progeny. Based on the display of high GCA effects, inbreds TZEI 124, TZEI 129 and ENT 13 were the most promising parents under well-watered environments while TZEI 182, TZEI 161 and ENT 13 were the best parents under drought conditions. These inbreds could be used to form synthetics or varietal hybrids or crossed accordingly to heterotic classification to develop source populations from which superior inbred lines could be extracted. Furthermore, favorable alleles from inbreds ENT 13, TZEI 182 and TZEI 161 could be introgressed into breeding populations of national maize programs for drought tolerance improvement (Ifie, 2013).

- **The heterotic grouping of inbreds based on the SCA_PY method was more useful than based on the HSGCA method in the sense that the groups defined by the SCA_PY method displayed the highest average grain yield for inter-groups crosses compared to those defined by the HSGCA method.** Sprague cited by Reif et al., (2005) stated: *"The single most important element of a breeding program is the recognition and utilization of heterotic pattern. This recognition both simplifies and increases the efficiency of all subsequent operations"*. The efficiency of the classification of inbreds into heterotic

groups greatly depends on the classification methods used (Fan *et al.*, 2009). These authors proposed the use of the percentage of high yielding hybrids obtained across the total number of inter-heterotic group crosses as a means of assessing the grouping efficiency of a classification method. In this study the grouping efficiency was 95% for the HSGCA method versus 77% for the SCA_PY method. The HSGCA method was also more efficient in identifying heterotic groups that display the highest heterosis for grain yield compared to the SCA_PY method. In contrast the SCA_PY method was more efficient in identifying inter-group crosses that showed the highest average grain yield (5449 kg ha⁻¹) compared to the HSGCA method (5055 kg ha⁻¹). The heterotic grouping based on the SCA_PY would therefore be more useful for the future activities of the breeding program. The inbreds (TZEI 160, ENT 13 and TZEI 161 for the first group and TZEI 157, TZEI 129 TZEI 124 and ENT 4 for the second group) constituting the two heterotic groups defined by the SCA_PY method could be recombined according to heterotic classification to develop new inbred lines and new versions of the high yielding hybrids ENT 13 x TZEI 124 and TZEI 160 x TZEI 157.

- The purpose of multilocal trials (MLT) is to determine genotypes whose performance is consistent across environments and those that perform better only in specific environments (Yan and Tinker, 2006). The interaction between genotypes and environments is also useful as it provides guidelines for the choice of crucial test sites in a wide adaptation prospect (Annicchiarico, 1997). A requirement for successful MLTs is an adequate variability among test environments. **In this study significant mean squares for grain yield and related traits were found among environments** suggesting that each environment is different and unique. This implies that valid inferences about the broad or

specific adaptation of the tested hybrids could be drawn from their evaluation in those environments. **The significant mean squares for grain yield and other traits among the single cross hybrids under drought, well-watered conditions and across environments suggests that the hybrids displayed these traits differently.** Therefore valid inferences on the agronomic performance of the hybrids could be made from this study. The least significant difference test used for mean separation combined with the stability test based on the GGE biplot analysis and the selection index under drought revealed that the single cross hybrids TZEI 160 x TZEI 157 and TZEI 182 x ENT 13 were the best hybrids under drought and also the most stable high yielding hybrids across environments. They could therefore be recommended to farmers who grow maize under rain-fed conditions in Niger. The single cross TZEI 124 x ENT 13 was the outstanding hybrid under well-watered environments. It could therefore be considered as a good candidate for commercial production under irrigation.

- Modified single crosses (MSCs) could be an attractive alternative to single cross hybrids when the low grain yield of inbreds remains a challenge to minimizing the costs of hybrid seed production (Castellanos *et al.*, 2009). An important advantage of MSCs in commercial maize hybrid seed production is the higher yield potential of related single crosses (RSCs) used as female parents compared to inbred lines. **In this study the RSCs used to develop the MSCs, TZEEI 95 x TZEEI 79, TZEEI 78 x TZEEI 79 and TZEEI 76 x TZEEI 82 displayed high inbred parent heterosis for grain yield of 37.3% to 92.1% under drought and 35.3% to 64% under well-watered conditions suggesting that RSCs were better female parents for increasing hybrid seed production.** Another advantage of MSCs is that they show no yield penalty compared to their corresponding single cross

hybrids (Fuhe *et al.*, 1995; Lee *et al.*, 2006; Castellanos *et al.*, 2009). **In this study three MSCs i.e. (TZEEI 76 x TZEEI 82)x TZEI124; (TZEEI 78 x TZEEI 79)x ENT13 and (TZEEI 95 x TZEEI 79)x CMZENT5 out-yielded the best single cross check under well-watered conditions (TZEI 124 x ENT13) by 19.3%, 17.8% and 17% respectively. Three other MSCs i.e.(TZEEI 76 x TZEEI 82)x CMKENT23; (TZEEI 76 x TZEEI 82)x CMZENT8 and (TZEEI 95 x TZEEI 79) x CMKENT8 out-yielded the best single cross check under drought (ENT13 x CamInbgp.1-17) by 91%, 67% and 66% respectively.** These results suggest that the MSCs above could be recommended to seed companies in Niger for a better commercial hybrid seed production.

- Earliness is of major importance to maize growers in Niger even those for whom water availability is not a great concern. However earliness is often associated with low grain yield potential (Sallah *et al.*, 1995; Pswarayi and Vivek, 2008; Badu-Apraku and Oyekunle, 2012). A strategy to increase the chances of adoption of new maize improved cultivars by farmers is to expose them to wide genotypes diversity and give them the opportunity to compare the advantages of one type over the other (Tiwari *et al.*, 2009). One hundred and three MSCs of varying maturity were developed and evaluated under drought and well-watered conditions in this study. **Significant differences among MSCs were found for grain yield and all traits. The grain yield of MSCs ranged from 377 Kg ha⁻¹ to 3383 Kg ha⁻¹ under drought and from 1765 Kg ha⁻¹ to 5399 Kg ha⁻¹ under well-watered conditions. Under the two water treatments the intermediate and early groups yielded significantly higher than the extra-early group.** These results indicate adequate genetic variability that can be tested in participatory variety selection trials on farmers' fields. This

will increase the chance of replacing the old and low yielding farmers OPVs by higher yielding improved cultivars.

6.3. Limits of the study and recommendations for future research

- In this study a rapid rural appraisal method was adopted to understand the maize production system in Niger. This method is a less participatory approach (Freudenberger, 1999) because the information gathering process is time-challenged (Chambers, 1981) and farmers' participation is limited to providing only information that meets the researcher's objectives. Future studies on maize production systems in Niger should adopt more participatory approaches that will emphasize farmers' active participation in the diagnosis of maize production constraints, determination of maize breeding priorities and planning projects that will meet farmers' expectations from the maize breeding program. Furthermore the RRA sites covered by this study might not be representative of all the maize production zones in Niger. Future studies should target the different maize production zones in the country particularly the sites along the Komadougou River and Chad Lake in Diffa region which has a high potential for maize production.
- The screening methodology to identify drought tolerant maize genotypes that involves stopping the irrigation two weeks before flowering is likely to work only in environments characterized by shallow soils, low relative humidity and frequent windy weather conditions. An alternative approach for applying the water stress should be adopted if the drought trials are to be conducted in environments where the soil water retention capacity is much higher i.e. INRAN stations of Diffa, Tara and Bengou. The application of rescue irrigations to reduce the stress intensity is likely to disturb the effect of water deficit on

plants particularly when soil variability is high. Traits like days to anthesis and silking, anthesis silking interval and grain yield might not be reliable. Therefore the performance of maize genotypes inferred from such drought trials where rescue irrigations have been applied should be validated in different environments where maize drought trials require no application of rescue irrigation.

- The heterotic grouping based on the HSGCA method was proposed by Fan et al., (2009) as a good alternative to SCA_PY method in assigning new inbreds to known heterotic groups. In diallel studies where no known appropriate tester is included, this method tended to define a large number of heterotic groups which are of no practical use in a breeding program. This indicates that the diallel is probably not the best design to adopt in assessing the grouping efficiency of the HSGCA method. Similarly the heterotic grouping based on the SCA_PY method was not done appropriately because of the minor importance of SCA effects compared to GCA effects in this particular set of inbreds. Most SCA effects of crosses used to assign inbreds into heterotic groups were not significant. The use of SCA_PY method for an efficient classification of inbreds is more appropriate in lines x tester designs where elite inbred testers are available. Given the current situation where such elite testers are limited in the extra-early and early maize germplasm, the use of diallel and North Carolina designs to identify testers and attempt the heterotic grouping of inbreds is a valid approach even though these designs are not the best to identify elite single cross hybrids with high and significant SCA effects for grain yield (Duvick, 2005a; Mikel, 2008; Gracen, 2012).

- The evaluation of the modified single crosses under water stress and well watered conditions at Konni during the dry season 2013/2014 was lost due to a failure of the irrigation system. Only results from the evaluation of the MSCs under drought and well-watered conditions at the INRAN station at Maradi were considered for the analysis. Therefore no strong conclusions could be made about the performance of the MSCs under drought and well-water environments. It would therefore be necessary to evaluate the MSCs at more sites to validate the results of the present study.



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APPENDICES

Appendix 3.1. Checklist for Focus group discussion

1. Maize production system

- 1.1 What is the importance of maize among the cereals grown in your village?
- 1.2 Do you grow maize under irrigation or rainfed conditions?
- 1.3 Is maize grown in mono or poly-cropping system? At what period of the year do you grow maize?
- 1.4 Do you grow maize as food or cash crop?
- 1.5 What type of usage is maize used for?
- 1.6 Estimate the proportion of area devoted to maize production compared to other crops in your village?
- 1.7 How does maize production impact your income?

2. Maize varieties and crop management

- 2.1 What varieties are you currently growing on your fields? What are their characteristics (endosperm colour, plant height, maturity, yield etc.)?
- 2.2 What is your most preferred variety? Why?
- 2.3 Where do you get seeds for planting?
- 2.4 Can you describe how you manage your maize field from land preparation to harvest (land ploughing, planting, plant density, weeding, organic and mineral fertilizer application etc.)?

3. Farmers preferred traits

- 3.1 Give maize cultivars characteristics you pay attention to when selecting the variety you decide to grow on your fields
- 3.2 Give in descending order the most important traits that you take into consideration in adopting new maize cultivars

4. Maize production constraints

- 4.1 What problems do you face in maize production?
- 4.2 Give in descending order the most important ones
- 4.3 What are the solutions you are currently using to deal with those problems?

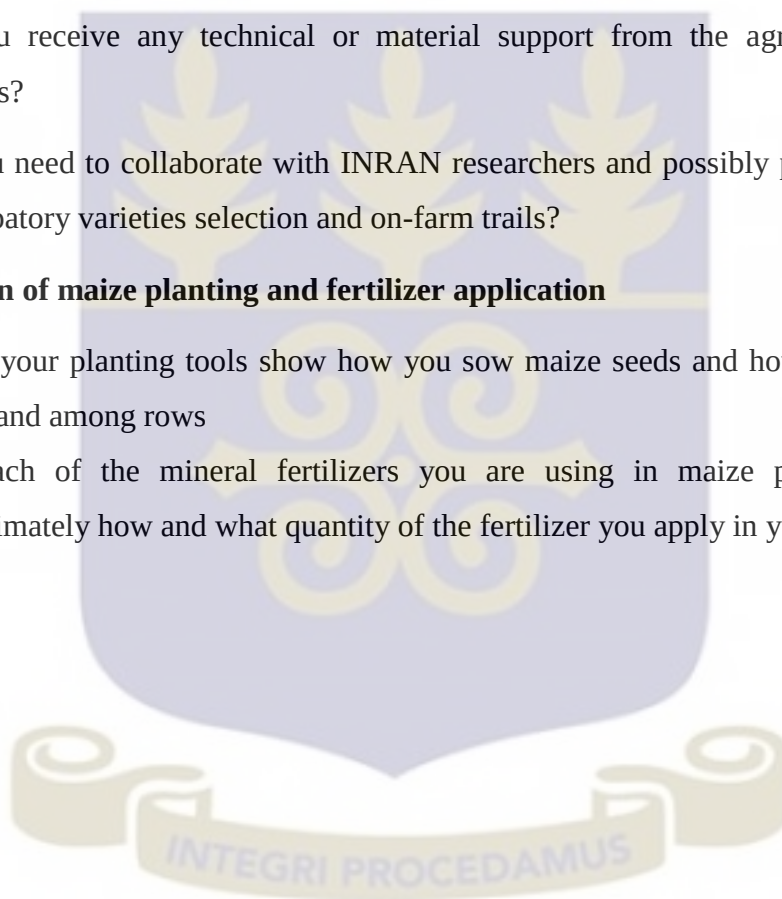
4.4. What are your expectations from the maize breeding program of INRAN?

5. New technologies

- 5.1 Are you aware of maize new cultivars released by INRAN or other research institutions or seed companies outside the country?
- 5.2 Do you have access to those improved cultivars?
- 5.3 Have you ever received training on maize production? If yes what the training was about? Who gave the training? Where and When?
- 5.4 Do you receive any technical or material support from the agricultural extension services?
- 5.5 Do you need to collaborate with INRAN researchers and possibly participate training, participatory varieties selection and on-farm trials?

6. Simulation of maize planting and fertilizer application

- 6.1. Using your planting tools show how you sow maize seeds and how you space plants within and among rows
- 6.2. For each of the mineral fertilizers you are using in maize production indicate approximately how and what quantity of the fertilizer you apply in your fields.



Appendix 4.1. Grain yield and other agronomic traits of 105 single cross hybrids derived from 15 × 15 diallel cross among 15 early maturing yellow- grained maize inbred lines and 5 checks evaluated under drought stress and well-watered environments

Hybrids	Yield Kg ha ⁻¹			DYA		DYS		ASI		PLTH (cm)		PASP		EPP		EASP		SGC2	Index
	WWC	WSC	Across	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WSC	WSC
TZEI 160 x TZEI 129	5599	1661	3911	57	70	57	75	1	6	180	145	2.8	3.3	1.2	0.9	2.3	3.9	7.0	-0.55
TZEI 160 x ENT 15	4734	2020	3571	58	68	58	72	1	4	164	145	3.1	2.8	1.1	1.0	2.7	3.5	6.8	2.96
TZEI 160 x ENT 17	4732	2393	3730	59	70	60	74	1	4	165	144	3.3	3.0	1.2	1.1	2.5	3.6	6.7	4.18
TZEI 160 x TZEI 182	3808	1942	3008	57	66	57	72	1	7	155	141	3.4	3.5	1.2	1.0	3.1	3.6	6.3	1.46
TZEI 160 x TZEI 167	3801	1128	2655	60	72	60	78	0	6	155	125	3.3	4.2	1.1	1.0	2.9	4.2	7.3	-3.91
TZEI 160 x TZEI 14	3865	1212	2728	59	71	60	79	1	9	156	130	3.3	3.5	1.1	0.8	2.9	3.9	6.5	-3.12
TZEI 160 x TZEI 124	5483	1819	3913	55	66	56	74	1	8	178	166	2.4	3.2	1.1	0.9	1.9	3.5	8.0	-0.92
TZEI 160 x TZEI 16	4884	1546	3454	58	71	59	76	1	6	173	140	3.0	3.3	1.4	1.1	2.5	3.8	6.3	0.76
TZEI 160 x ENT 4	5070	1923	3717	57	69	57	75	0	6	172	143	3.1	3.5	1.1	1.0	2.2	3.2	5.7	2.69
TZEI 160 x TZEI 161	2533	1043	1894	59	70	58	77	-1	6	131	111	4.0	4.2	1.1	0.9	4.1	4.4	7.3	-4.68
TZEI 160 x TZEI 23	2596	1213	2003	58	67	58	73	-1	5	132	121	3.8	4.3	1.1	0.8	3.9	4.3	7.0	-4.15
TZEI 160 x ENT 13	5190	2222	3918	57	69	57	73	-1	5	172	149	2.9	2.8	1.2	1.2	2.3	3.3	7.7	3.69
TZEI 160 x TZEI 135	5350	2210	4004	56	68	57	71	0	4	175	151	2.6	3.5	1.2	1.0	2.5	3.3	7.0	3.07
TZEI 160 x TZEI 157	5708	2570	4363	56	68	57	72	1	5	182	157	2.8	3.0	1.2	1.1	2.5	3.0	6.7	5.48
TZEI 129 x ENT 15	4770	1591	3408	59	72	61	78	2	6	193	152	3.3	3.5	1.1	1.1	2.2	3.7	6.7	0.24
TZEI 129 x ENT 17	5141	2399	3966	59	71	60	75	1	4	191	156	3.0	3.0	1.2	1.0	2.2	3.1	6.2	5.26
TZEI 129 x TZEI 182	4915	2216	3758	57	71	58	77	1	6	176	144	3.3	3.2	1.1	1.2	2.4	3.1	6.0	5.01
TZEI 129 x TZEI 167	5528	1873	3962	59	72	60	78	2	6	186	160	2.4	3.3	1.1	1.1	1.9	3.6	6.2	2.21
TZEI 129 x TZEI 14	4943	1558	3492	60	71	61	78	2	7	192	150	2.8	3.7	1.1	0.9	2.0	3.6	6.0	-0.16
TZEI 129 x TZEI 124	4958	1048	3282	58	69	59	79	2	10	188	156	2.5	3.3	1.1	1.1	1.9	3.7	7.7	-3.36
TZEI 129 x TZEI 16	4826	1042	3204	59	73	62	79	3	6	192	147	2.9	4.0	1.2	1.1	2.4	4.4	7.0	-3.39
TZEI 129 x ENT 4	5607	1635	3905	58	70	59	78	1	7	189	153	2.5	3.7	1.1	1.0	1.9	3.6	7.2	-0.93
TZEI 129 x TZEI 161	5056	1550	3554	57	67	58	74	2	7	180	157	2.8	4.0	1.1	0.8	2.3	3.5	7.2	-2.1
TZEI 129 x TZEI 23	4803	2158	3669	57	68	57	75	1	7	172	141	3.3	3.5	1.2	1.1	2.8	3.5	6.5	2.32
Overall mean	4571	1684	3334	58	70	60	76	1	7	174	145	3.0	3.5	1.1	0.9	2.6	3.7	6.5	0.00
Lsd	865	775	605	1.5	2.4	1.7	3.9	1.3	3.2	12	15	0.5	0.9	0.1	0.3	0.4	0.7	1.1	5.4
Genotypes	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	*	**	**	**
Environments	**	**	**	**	**	**	**	**	**	**	**	**	*	**	**	**	ns	**	**
G x E	**	*	**	**	**	**	ns	**	**	*	ns	**	ns	**	ns	**	*	*	ns

WWC: well-watered conditions; **WSC:** water stress conditions; **Across:** across environments

YIELD: Grain yield; **DYA:** days to anthesis; **DYS:** days to silk; **ASI:** anthesis silking interval; **PLTH:** plant height; **PASP:** plant aspect;

EPP: number of ears per plant; **EASP:** ear aspect; **SGC2:** stay-green 2;

Index: selection index under water stress conditions

*Significant at the 0.05 probability level; **Significant at the 0.01 probability level ; **ns:** not significant

Appendix 4.1. Continued

Hybrids	Yield Kg ha ⁻¹			DYA		DYS		ASI		PLTH (cm)		PASP		EPP		EASP		SGC2	Index
	WWC	WSC	Across	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WSC	WSC
TZEI 129 x ENT 13	5255	2212	3951	57	70	59	75	2	5	201	160	2.6	3.3	1.1	0.9	1.8	2.9	6.8	3.36
TZEI 129 x TZEI 135	4417	1197	3037	58	69	60	78	2	9	196	155	3.1	4.2	1.1	0.9	2.8	3.9	6.0	-3.33
TZEI 129 x TZEI 157	4890	1661	3506	56	68	58	73	3	5	183	149	3.0	3.5	1.0	1.1	2.6	3.6	6.2	1.78
ENT 15 x ENT 17	4043	984	2732	61	74	61	82	1	8	183	139	3.1	4.3	1.1	0.7	2.6	4.1	7.5	-6.53
ENT 15 x TZEI 182	4272	1680	3161	57	68	59	75	2	7	164	151	2.9	3.3	1.1	1.0	2.6	3.8	6.2	0.49
ENT 15 x TZEI 167	4354	1069	2946	61	73	64	82	3	9	175	137	3.0	4.3	1.1	0.9	2.7	4.2	7.3	-5.68
ENT 15 x TZEI 14	4020	849	2661	60	74	63	83	3	9	177	137	3.4	4.3	1.1	0.7	2.6	4.3	7.2	-7.24
ENT 15 x TZEI 124	5290	736	3339	58	71	61	83	3	12	189	156	2.5	4.2	1.2	0.5	2.1	4.2	7.7	-9.55
ENT 15 x TZEI 16	4164	1776	3140	60	72	63	79	3	7	177	159	3.4	3.3	1.1	1.0	2.8	3.7	6.3	0.5
ENT 15 x ENT 4	2021	594	1410	64	77	66	84	2	7	167	131	4.4	4.3	1.0	0.8	3.4	4.2	7.2	-6.8
ENT 15 x TZEI 161	4825	1544	3419	59	70	60	78	1	8	184	150	3.1	3.5	1.1	0.8	2.2	3.7	6.5	-1.59
ENT 15 x TZEI 23	4916	2048	3687	58	67	58	73	1	7	168	137	2.8	3.2	1.2	1.1	2.9	3.5	6.7	2.54
ENT 15 x ENT 13	4846	1536	3427	61	74	62	82	1	7	195	142	2.9	3.8	1.0	0.9	2.1	3.7	6.3	-1.06
ENT 15 x TZEI 135	4777	1591	3412	57	70	60	77	3	7	184	144	3.0	3.7	1.1	0.9	2.5	3.6	7.3	-1.3
ENT 15 x TZEI 157	5534	1678	3882	57	68	59	75	2	7	181	147	2.3	3.5	1.1	0.9	2.2	3.5	7.2	-0.94
ENT 17 x TZEI 182	4427	1899	3344	58	69	59	74	0	6	162	140	3.1	3.2	1.2	1.0	2.6	3.4	5.2	3.51
ENT 17 x TZEI 167	5141	1579	3614	60	75	60	78	0	3	176	134	2.5	3.2	1.3	1.0	2.4	3.9	6.5	1.27
ENT 17 x TZEI 14	3947	1290	2809	61	74	62	81	2	7	174	140	3.1	4.0	1.2	0.8	2.9	3.8	6.2	-2.4
ENT 17 x TZEI 124	4859	721	3085	60	74	60	84	1	10	190	142	2.8	4.5	1.2	0.7	2.2	4.6	7.8	-9.15
ENT 17 x TZEI 16	3948	1237	2787	61	76	63	80	1	4	178	140	3.1	3.3	1.2	1.0	3.1	4.1	6.0	-0.11
ENT 17 x ENT 4	4582	1529	3274	61	74	62	78	1	5	181	140	3.3	3.3	1.1	0.8	2.4	3.9	6.7	-0.64
ENT 17 x TZEI 161	4964	2043	3712	58	69	58	74	0	6	172	152	3.1	3.3	1.2	0.9	2.6	3.5	7.0	1.52
ENT 17 x TZEI 23	4911	1797	3576	57	68	57	77	1	9	163	136	3.0	3.5	1.2	1.0	2.7	3.6	6.3	-0.12
ENT 17 x ENT 13	4647	1886	3463	60	71	61	77	1	6	182	142	3.0	2.7	1.2	1.0	2.4	3.5	5.8	3.22
Overall mean	4571	1684	3334	58	70	60	76	1	7	174	145	3.0	3.5	1.1	0.9	2.6	3.7	6.5	0.00
Lsd	865	775	605	1.5	2.4	1.7	3.9	1.3	3.2	12	15	0.5	0.9	0.1	0.3	0.4	0.7	1.1	5.4
Genotypes	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	*	**	**	**
Environments	**	**	**	**	**	**	**	**	**	**	**	**	*	**	**	**	ns	**	**
G x E	**	*	**	**	**	**	ns	**	**	*	ns	**	ns	**	ns	**	*	*	ns

WWC: well-watered conditions; WSC: water stress conditions; Across: across environments

YIELD: Grain yield; DIA: days to anthesis; DYS: days to silk; ASI: anthesis silking interval; PLTH: plant height; PASP: plant aspect;

EPP: number of ears per plant; EASP: ear aspect; SGC2: stay-green 2; Index: selection index under water stress conditions

*Significant at the 0.05 probability level; **Significant at the 0.01 probability level; ns: not significant

Appendix 4.1. Continued

Hybrids	Yield Kg ha ⁻¹			DYA		DYS		ASI		PLTH (cm)		PASP		EPP		EASP		SGC2	Index
	WWC	WSC	Across	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WSC	WSC
ENT 17 x TZEI 135	4336	1268	3021	58	71	60	79	2	8	188	141	3.4	3.8	1.1	0.9	2.6	3.9	6.2	-2.4
ENT 17 x TZEI 157	4787	1539	3395	59	71	60	77	0	6	184	147	2.8	3.7	1.2	1.0	2.4	3.8	6.5	-0.47
TZEI 182 x TZEI 167	4179	2063	3272	58	71	59	76	1	5	164	148	3.0	3.0	1.1	1.0	2.7	3.5	5.2	4.25
TZEI 182 x TZEI 14	4181	1604	3077	59	71	60	77	1	6	165	130	3.1	3.3	1.1	1.0	2.8	3.7	4.7	2.06
TZEI 182 x TZEI 124	4597	1759	3381	58	66	60	74	2	8	185	152	2.9	3.3	1.1	0.9	2.5	3.5	5.8	0.65
TZEI 182 x TZEI 16	4176	1937	3216	59	69	60	74	1	6	174	147	3.1	3.2	1.3	1.0	3.0	3.6	5.3	3.05
TZEI 182 x ENT 4	4322	1879	3275	57	69	59	76	1	7	175	146	3.0	3.3	1.1	1.2	2.6	3.4	6.2	2.51
TZEI 182 x TZEI 161	4045	2401	3340	57	67	58	71	2	4	166	145	3.4	3.2	1.1	1.1	2.8	3.4	4.7	6.4
TZEI 182 x TZEI 23	3850	1927	3026	54	65	55	73	1	7	148	131	3.1	3.5	1.1	0.9	3.1	3.9	5.8	0.66
TZEI 182 x ENT 13	5416	2753	4275	57	67	58	72	1	5	189	158	2.6	2.7	1.1	1.0	2.2	2.9	6.0	7.07
TZEI 182 x TZEI 135	3604	2388	3083	56	67	57	73	1	6	168	155	3.4	3.3	1.1	1.0	2.9	3.4	6.2	3.63
TZEI 182 x TZEI 157	2397	1298	1926	58	68	59	74	1	7	150	141	4.5	4.5	1.0	0.9	3.6	4.0	5.5	-2.29
TZEI 167 x TZEI 14	2248	1183	1792	64	76	66	80	2	4	151	131	3.8	4.2	1.0	1.1	3.5	4.3	5.7	-1.11
TZEI 167 x TZEI 124	5149	1200	3456	60	71	61	79	1	9	193	153	2.1	3.8	1.1	0.8	2.1	4.0	7.7	-4.73
TZEI 167 x TZEI 16	3465	1110	2455	61	76	63	81	2	5	166	133	3.4	4.0	1.1	0.9	3.2	4.4	6.3	-2.92
TZEI 167 x ENT 4	3996	952	2691	60	74	62	82	3	8	174	138	3.0	4.3	1.0	0.8	2.5	4.4	7.7	-6.85
TZEI 167 x TZEI 161	4100	1493	2982	58	70	58	76	0	7	158	137	3.3	3.5	1.1	0.8	2.9	4.0	6.2	-1.2
TZEI 167 x TZEI 23	3879	2031	3087	56	68	57	71	2	3	148	140	3.4	2.8	1.1	0.9	2.9	3.5	6.2	3.79
TZEI 167 x ENT 13	5711	2297	4248	60	72	61	77	2	5	181	141	2.4	2.8	1.1	1.0	2.0	3.2	6.2	4.59
TZEI 167 x TZEI 135	4216	2076	3299	59	73	61	76	1	3	169	141	3.0	3.0	1.1	1.0	2.7	3.8	6.3	3.19
TZEI 167 x TZEI 157	4715	1773	3454	59	70	60	76	1	6	178	149	2.6	3.3	1.0	0.9	2.4	3.7	6.5	0.64
TZEI 14 x TZEI 124	4614	1628	3334	59	68	61	78	2	10	177	146	2.6	3.3	1.1	0.7	2.4	3.7	6.2	-2.03
TZEI 14 x TZEI 16	1995	819	1491	65	81	67	85	2	4	150	119	4.1	4.2	1.1	0.8	3.8	4.5	6.2	-4.23
TZEI 14 x ENT 4	3457	1108	2450	61	74	63	79	3	6	164	144	3.4	4.2	1.2	0.9	3.0	4.3	6.7	-3.87
Overall mean	4571	1684	3334	58	70	60	76	1	7	174	145	3.0	3.5	1.1	0.9	2.6	3.7	6.5	0.00
Lsd	865	775	605	1.5	2.4	1.7	3.9	1.3	3.2	12	15	0.5	0.9	0.1	0.3	0.4	0.7	1.1	5.4
Genotypes	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	*	**	**	**
Environments	**	**	**	**	**	**	**	**	**	**	**	**	*	**	**	**	ns	**	**
G x E	**	*	**	**	**	**	ns	**	**	*	ns	**	ns	**	ns	**	*	*	ns

WWC: well-watered conditions; WSC: water stress conditions; Across: across environments

YIELD: Grain yield; DY A: days to anthesis; DYS: days to silk; ASI: anthesis silking interval; PLTH: plant height; PASP: plant aspect;

EPP: number of ears per plant; EASP: ear aspect; GC2: stay-green 2; Index: selection index under water stress conditions

*Significant at the 0.05 probability level; **Significant at the 0.01 probability level; ns: not significant

Appendix 4.1. Continued

Hybrids	Yield Kg ha ⁻¹			DYA		DYS		ASI		PLTH (cm)		PASP		EPP		EASP		SGC2		Index	
	WWC	WSC	Across	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WSC	WSC	WSC	WSC
TZEI 14 x TZEI 161	4286	2130	3362	57	68	59	76	2	8	156	143	3.0	3.2	1.0	0.9	2.6	3.4	6.0	2.32		
TZEI 14 x TZEI 23	3712	2251	3086	59	69	60	76	1	7	155	140	3.0	2.7	1.2	1.0	2.8	3.2	6.0	4.06		
TZEI 14 x ENT 13	4858	2304	3763	60	71	62	78	2	7	180	144	2.6	3.3	1.1	1.0	2.4	3.5	6.3	2.51		
TZEI 14 x TZEI 135	3949	1526	2911	59	71	62	81	3	10	171	142	3.4	3.5	1.1	1.0	3.0	3.8	5.8	-0.79		
TZEI 14 x TZEI 157	3126	1218	2308	60	72	62	79	2	6	159	122	3.1	3.8	1.1	0.9	2.9	4.2	6.0	-2.31		
TZEI 124 x TZEI 16	5121	1164	3425	59	70	61	80	2	10	185	146	2.4	3.7	1.1	0.8	2.1	4.0	6.8	-4.13		
TZEI 124 x ENT 4	5097	649	3190	59	68	60	82	2	14	182	154	2.5	4.2	1.1	0.7	2.1	4.3	7.3	-9.46		
TZEI 124 x TZEI 161	5205	1811	3750	57	68	57	74	0	6	180	158	2.6	3.2	1.1	0.9	1.9	3.4	8.0	-0.22		
TZEI 124 x TZEI 23	5806	1897	4131	55	64	56	70	1	6	170	151	2.5	3.2	1.1	1.0	2.2	3.6	7.5	0.73		
TZEI 124 x ENT 13	6584	1993	4617	57	68	58	77	1	9	194	164	1.1	2.7	1.1	1.0	1.4	3.3	6.2	2.48		
TZEI 124 x TZEI 135	4634	949	3055	58	71	60	81	2	10	187	154	2.8	4.2	1.1	0.7	2.3	4.2	7.2	-7.1		
TZEI 124 x TZEI 157	4550	1877	3405	59	71	60	77	2	6	190	153	2.1	3.0	1.0	0.9	2.3	3.7	5.5	2.2		
TZEI 16 x ENT 4	4426	1254	3066	60	71	62	80	2	9	185	149	2.9	3.7	1.3	0.8	2.5	4.0	6.8	-4.02		
TZEI 16 x TZEI 161	5652	2125	4140	57	69	59	76	1	7	175	142	2.9	2.7	1.2	1.0	2.5	3.3	6.7	2.83		
TZEI 16 x TZEI 23	5032	1567	3547	58	69	59	77	1	8	160	135	3.0	3.5	1.3	1.0	2.6	3.9	6.5	-0.81		
TZEI 16 x ENT 13	5097	2155	3836	60	71	62	77	2	6	197	161	2.5	2.8	1.1	1.1	2.3	3.2	6.0	4.71		
TZEI 16 x TZEI 135	4501	1146	3063	60	72	62	80	2	8	180	143	3.0	4.0	1.3	1.0	2.6	4.1	6.0	-2.83		
TZEI 16 x TZEI 157	5123	1914	3748	58	69	60	74	2	5	183	155	2.6	3.0	1.2	0.9	2.8	3.6	6.2	2.29		
ENT 4 x TZEI 161	5288	2256	3989	58	69	59	75	1	6	178	145	3.1	3.7	1.2	1.0	2.1	3.1	6.0	3.36		
ENT 4 x TZEI 23	5344	1840	3842	57	68	57	75	0	7	167	140	3.3	3.5	1.1	1.0	2.3	3.7	6.5	0.54		
ENT 4 x ENT 13	5067	1444	3514	60	71	61	78	1	7	192	146	2.8	4.0	1.0	0.9	2.1	4.0	6.5	-2.18		
ENT 4 x TZEI 135	4102	1376	2934	59	71	60	80	1	9	175	146	3.3	3.8	1.2	1.0	2.7	3.8	6.5	-2.11		
ENT 4 x TZEI 157	4372	1690	3222	59	70	61	78	2	8	173	145	2.9	3.7	1.1	1.0	2.5	3.8	6.8	-0.98		
TZEI 161 x TZEI 23	3343	1228	2436	57	68	57	74	0	6	142	124	3.8	4.5	1.2	0.7	3.7	4.2	7.0	-4.75		
Overall mean	4571	1684	3334	58	70	60	76	1	7	174	145	3.0	3.5	1.1	0.9	2.6	3.7	6.5	0.00		
Lsd	865	775	605	1.5	2.4	1.7	3.9	1.3	3.2	12	15	0.5	0.9	0.1	0.3	0.4	0.7	1.1	5.4		
Genotypes	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	*	**	**	**		
Environments	**	**	**	**	**	**	**	**	**	**	**	**	*	**	**	**	ns	**	**		
G x E	**	*	**	**	**	**	ns	**	**	*	ns	**	ns	**	ns	**	*	*	ns		

WWC: well-watered conditions; WSC: water stress conditions; Across: across environments

YIELD: Grain yield; DY A: days to anthesis; DYS: days to silk; ASI: anthesis silking interval; PLTH: plant height; PASP: plant aspect;

EPP: number of ears per plant; EASP: ear aspect; GC2: stay-green 2;

Index: selection index under water stress conditions

*Significant at the 0.05 probability level; **Significant at the 0.01 probability level; ns: not significant

Appendix 4.1. Continued

Hybrids	Yield Kg ha ⁻¹			DYA		DYS		ASI		PLTH (cm)		PASP		EPP		EASP		SGC2	Index
	WWC	WSC	Across	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WSC	WSC
TZEI 161 x ENT 13	4854	2383	3795	57	69	57	73	0	4	182	150	2.8	2.8	1.2	1.0	2.5	3.1	6.5	5.01
TZEI 161 x TZEI 135	4982	2088	3742	57	69	57	74	1	5	175	153	3.0	3.7	1.1	0.9	2.6	3.7	6.3	1.57
TZEI 161 x TZEI 157	5625	2207	4160	55	68	56	71	1	4	176	156	2.6	3.7	1.2	1.2	2.3	3.6	7.2	2.97
TZEI 23 x ENT 13	4589	2211	3570	56	68	57	73	1	5	163	141	3.0	3.0	1.1	1.1	2.7	3.3	6.7	3.98
TZEI 23 x TZEI 135	4389	1741	3254	55	66	57	72	1	6	164	136	2.9	3.7	1.1	1.0	2.9	3.7	6.8	0
TZEI 23 x TZEI 157	4633	1467	3276	55	65	56	71	1	6	160	144	3.1	3.5	1.1	0.9	2.8	3.7	6.7	-0.64
ENT 13 x TZEI 135	5426	1590	3782	58	71	60	77	2	6	187	147	2.6	3.5	1.1	1.0	2.3	4.0	6.7	-0.6
ENT 13 x TZEI 157	5454	2560	4213	58	69	60	75	1	6	195	161	2.1	2.7	1.2	1.0	2.0	2.9	5.5	6.61
TZEI 135 x TZEI 157	5303	2004	3889	56	68	57	76	1	7	187	147	3.1	3.0	1.1	0.9	2.4	3.6	5.2	2.93
P3 Kollo Check	4690	1439	3297	54	64	55	70	1	6	172	156	3.0	3.8	1.3	0.9	2.9	4.1	6.8	-2.42
TZEI 9 x TZEI 16 Ck	4981	1835	3633	58	69	59	76	1	7	164	144	2.5	3.5	1.1	1.0	2.4	3.6	7.0	-0.19
TZEI 82 x TZEI 93 Ck	3792	2309	3156	63	74	65	78	2	4	175	147	2.9	2.3	1.0	1.0	3.3	3.5	5.2	6.28
TZEI 16 x TZEI 8 Ck	4423	2008	3388	58	69	59	76	1	7	156	135	2.8	3.2	1.2	1.0	2.8	3.4	7.3	1
TZEI 23 x TZEI 13 Ck	5063	1992	3747	58	72	59	76	1	4	168	134	2.9	3.3	1.3	1.1	2.7	3.5	6.5	2.96
Overall mean	4571	1684	3334	58	70	60	76	1	7	174	145	3.0	3.5	1.1	0.9	2.6	3.7	6.5	0.00
Lsd	865	775	605	1.5	2.4	1.7	3.9	1.3	3.2	12	15	0.5	0.9	0.1	0.3	0.4	0.7	1.1	5.4
Genotypes	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	*	**	**	**
Environments	**	**	**	**	**	**	**	**	**	**	**	**	*	**	**	**	ns	**	**
G x E	**	*	**	**	**	**	ns	**	**	*	ns	**	ns	**	ns	**	*	*	ns

WWC: well-watered conditions; **WSC:** water stress conditions; **Across:** across environments

YIELD: Grain yield; **DYA:** days to anthesis; **DYS:** days to silk; **ASI:** anthesis silking interval; **PLTH:** plant height; **PASP:** plant aspect;

EPP: number of ears per plant; **EASP:** ear aspect; **GC2:** stay-green 2; **Index:** selection index under water stress conditions

*Significant at the 0.05 probability level; **Significant at the 0.01 probability level; ns: not significant

Appendix 4.2 Comparison of the efficiency of the SCA_PY and the HSGCA methods in classifying inbreds into heterotic groups based on their models

Fan et al., (2009) reported the above equations:

$$SCA = \text{Cross mean } (X_{ij}) - \text{Line mean } (X_{.}) - \text{Tester mean } (X_{i.}) + \text{Overall mean } (X_{..})$$

$$GCA_L = \text{Line mean } (X_{.j}) - \text{Overall mean } (X_{..})$$

$$HSGCA = \text{Cross mean } X - \text{Tester mean } (X_{i.}) = \mathbf{GCA_L} + \mathbf{SCA}.$$

What could we obtain when we develop these equations ?

Eq1: $\mathbf{SCA} = \text{Cross mean } (X_{ij}) - \text{Line mean } (X_{.}) - \text{Tester mean } (X_{i.}) + \text{Overall mean } (X_{..})$

Eq2: $\mathbf{GCA_L} = \text{Line mean } (X_{.j}) - \text{Overall mean } (X_{..}) \Leftrightarrow \text{Line mean } (X_{.j}) = \mathbf{GCA_L} + \text{Overall mean } (X_{..})$

Eq3: $\mathbf{GCA_T} = \text{Tester mean } (X_{i.}) - \text{Overall mean } (X_{..}) \Leftrightarrow \text{Tester mean } (X_{i.}) = \mathbf{GCA_T} + \text{Overall mean } (X_{..})$

Eq4: $HSGCA = \text{Cross mean } X - \text{Tester mean } (X_{i.})$

Eq1, Eq2 and Eq3 $\Leftrightarrow SCA = \text{Cross mean } (X_{ij}) - \text{Line mean } (X_{.}) - \text{Tester mean } (X_{i.}) + \text{Overall mean } (X_{..})$

$$SCA = \text{Cross mean } (X_{ij}) - (\mathbf{GCA_L} + \text{Overall mean}) - (\mathbf{GCA_T} + \text{Overall mean}) + \text{Overall mean}$$

$$SCA = \text{Cross mean } (X_{ij}) - \mathbf{GCA_L} - \text{Overall mean} - \mathbf{GCA_T} - \text{Overall mean} + \text{Overall mean}$$

Eq5: $SCA = \text{Cross mean } (X_{ij}) - \mathbf{GCA_L} - \mathbf{GCA_T} - \text{Overall mean}$

Eq3 and Eq4 $\Leftrightarrow HSGCA = \text{Cross mean } (X_{ij}) - \text{Tester mean } (X_{i.})$

$$HSGCA = \text{Cross mean } (X_{ij}) - (\mathbf{GCA_T} + \text{Overall mean})$$

Eq6: $HSGCA = \text{Cross mean } (X_{ij}) - \mathbf{GCA_T} - \text{Overall mean}$

Let us see the relation between the SCA and the HSGCA methods:

Eq5 and Eq6:
$$\begin{cases} \mathbf{SCA} = \text{Cross mean } (X_{ij}) - \mathbf{GCA_L} - \mathbf{GCA_T} - \text{Overall mean} \\ \mathbf{HSGCA} = \text{Cross mean } (X_{ij}) - \mathbf{GCA_T} - \text{Overall mean} \end{cases}$$

SCA identifies specific combinations where the hybrids performed better or worse than would be predicted based on **GCA effects of both line and tester**. HSGCA method identifies combinations where the hybrids performed higher or lower than would be expected based on the **GCA effect of the tester** involved in the testcross. The SCA method is likely to be more efficient than the HSGCA method.

Appendix 5.1. Grain yield and other agronomic traits of 103 MSCs of varying maturity groups and 5 checks evaluated under drought stress and well- watered environments

Entry	Extra-early		YIELD		DYA		ASI		PLTH		EHT		PASP		EPP		SGREEN		HPH	
	Early	Intermediate	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC
(TZEEI 76 x TZEEI 82) x TZEI 182			4293	2654	66	67	1.5	5.0	169	151	85	101	3.0	2.0	1.0	6.0	36	397		
(TZEEI 76 x TZEEI 82) x TZEEI 96			4249	859	66	70	2.0	7.5	178	136	100	89	2.5	4.0	1.1	7.0	34	61		
(TZEEI 95 x TZEEI 79) x TZEEI 63			4068	1760	63	67	3.0	4.5	162	144	73	86	2.5	3.0	1.0	7.0	73	114		
(TZEEI 76 x TZEEI 82) x TZEI 157			4034	1785	65	70	2.5	5.5	158	148	80	96	3.0	3.0	1.0	4.5	27	234		
(TZEEI 78 x TZEEI 79) x TZEEI 67			4016	2345	66	69	1.5	4.0	161	153	90	99	3.0	2.5	1.0	7.5	12	14		
(TZEEI 78 x TZEEI 79) x TZEI 23			3999	1297	69	73	0.5	3.0	163	121	98	80	3.0	3.0	1.0	6.0	12	-37		
(TZEEI 95 x TZEEI 79) x TZEI 23			3983	1640	63	67	2.5	5.0	134	136	68	84	3.0	3.0	1.0	6.5	69	100		
(TZEEI 95 x TZEEI 79) x TZEEI 67			3971	2096	64	68	1.5	5.0	158	133	85	84	2.5	2.5	1.0	5.0	69	155		
(TZEEI 76 x TZEEI 82) x TZEI 23			3844	1912	64	67	1.5	4.5	138	129	70	80	3.0	3.0	1.0	6.5	21	258		
(TZEEI 78 x TZEEI 79) x TZEI 157			3739	2307	68	69	1.5	4.0	145	166	83	109	3.0	2.5	1.0	6.0	5	12		
(TZEEI 76 x TZEEI 82) x TZEEI 67			3718	1624	65	70	1.5	2.5	168	127	98	86	3.0	3.0	1.0	6.5	17	204		
(TZEEI 76 x TZEEI 82) x TZEEI 81			3679	851	67	71	1.0	3.0	152	154	73	112	3.0	3.5	1.0	6.0	16	59		
(TZEEI 95 x TZEEI 79) x TZEEI 64			3671	1122	65	70	0.5	5.0	156	130	83	81	3.0	3.0	1.1	7.0	56	37		
(TZEEI 95 x TZEEI 79) x TZEI 157			3658	1543	67	71	0.5	4.0	161	134	100	89	3.0	3.0	0.9	5.5	55	88		
(TZEEI 78 x TZEEI 79) x TZEEI 64			3621	1595	65	68	0.5	5.0	160	142	95	98	3.0	3.0	1.0	6.5	1	-22		
Overall mean			3788	1429	67	71	1.9	5.7	158	142	83	90	2.9	3.2	1	6.8	32	78		
Lsd			1538	918	2.2	4.2	2.3	5.5	20	23	20	17	1.3	1.2	0.2	1.7				
Rep			ns	ns	ns	**	**	ns	*	ns	ns	ns	ns	ns	*	**				
Block(Rep)			**	**	*	**	ns	ns	**	**	**	**	*	**	ns	**				
Entry			**	**	**	**	**	**	**	**	**	**	**	*	*	**				

WWC: well-watered conditions; WSC: water stress conditions; HPH (%): heterosis for grain yield over the best RSC parent

YIELD: Grain yield; DY A: days to anthesis; ASI: anthesis silking interval; PLTH (cm): plant height; EHT (cm): ear height;

PASP (1-5): plant aspect; EPP: number of ears per plant; SGREEN: stay green characteristics at 90 and 100 days after planting on a scale of 1 to 9 ;

*Significant at the 0.05 probability level; **Significant at the 0.01 probability level ; ns: not significant

Appendix 5.1. Continued

Entry	Extra-early		YIELD		DYA		ASI		PLTH		EHT		PASP		EPP		SGREEN		HPH	
	Early	Intermediate	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC
(TZEEI 78 x TZEEI 79) x TZEEI 89			3560	740	63	68	4.0	4.5	150	121	70	75	3.0	3.5	1.0	7.0	0	-64		
(TZEEI 78 x TZEEI 79) x TZEEI 81			3509	1390	69	75	1.5	4.0	161	156	78	105	3.0	3.5	1.0	6.0	-2	-32		
(TZEEI 76 x TZEEI 82) x TZEEI 64			3495	664	66	70	-0.5	8.0	139	139	85	94	3.5	3.5	1.1	6.0	10	24		
(TZEEI 78 x TZEEI 79) x TZEEI 182			3458	1296	69	71	2.0	5.0	167	139	88	95	3.5	3.0	0.9	6.5	-3	-37		
(TZEEI 95 x TZEEI 79) x TZEEI 89			3371	1145	62	68	2.5	4.0	128	124	63	73	3.0	3.5	1.0	6.0	43	39		
(TZEEI 95 x TZEEI 79) x TZEEI 182			3286	1628	67	70	1.5	5.0	145	134	70	86	3.5	3.0	1.0	5.5	40	98		
(TZEEI 95 x TZEEI 79) x TZEEI 81			3147	1131	65	70	3.0	3.0	145	134	65	86	4.0	3.0	1.0	6.0	34	38		
(TZEEI 76 x TZEEI 82) x TZEEI 89			3058	419	65	69	2.0	6.5	133	122	65	80	4.5	4.5	1.0	6.0	-3	-21		
(TZEEI 78 x TZEEI 79) x TZEEI 63			3041	749	65	70	2.5	6.0	153	138	75	90	4.0	3.5	1.0	7.0	-15	-64		
(TZEEI 76 x TZEEI 82) x TZEEI 58			2918	903	66	69	2.0	4.5	154	144	75	89	3.5	3.0	1.1	6.5	-8	69		
(TZEEI 95 x TZEEI 79) x TZEEI 58			2677	1453	62	70	4.0	3.0	150	138	65	87	4.0	3.0	0.9	6.5	14	77		
(TZEEI 95 x TZEEI 79) x TZEEI 87			2623	1034	65	69	2.0	5.0	153	138	73	90	4.0	3.5	1.0	6.5	11	26		
(TZEEI 78 x TZEEI 79) x TZEEI 58			2444	616	64	71	3.5	6.0	141	131	75	82	4.0	4.5	0.9	7.0	-32	-70		
(TZEEI 76 x TZEEI 82) x TZEEI 87			2150	1785	66	68	3.0	5.0	149	147	83	98	4.5	3.0	1.0	6.5	-32	234		
(TZEEI 78 x TZEEI 79) x TZEEI 87			2094	396	68	71	3.0	7.0	163	125	88	78	4.5	4.0	1.2	7.5	-41	-81		
(TZEEI 76 x TZEEI 82) x TZEEI 63			1984	1002	66	69	1.0	5.5	139	136	80	88	4.5	3.5	1.5	5.5	-37	88		
Overall mean			3788	1429	67	71	1.9	5.7	158	142	83	90	2.9	3.2	1	6.8	32	78		
Lsd			1538	918	2.2	4.2	2.3	5.5	20	23	20	17	1.3	1.2	0.2	1.7				
Rep			ns	ns	ns	**	**	ns	*	ns	ns	ns	ns	ns	*	**				
Block(Rep)			**	**	*	**	ns	ns	**	**	**	**	*	**	ns	**				
Entry			**	**	**	**	**	**	**	**	**	**	**	*	*	**				

WWC: well-watered conditions; WSC: water stress conditions; HPH (%): heterosis for grain yield over the best RSC parent

YIELD: Grain yield; DY A: days to anthesis; ASI: anthesis silking interval; PLTH (cm): plant height; EHT (cm): ear height;

PASP (1-5): plant aspect; EPP: number of ears per plant; SGREEN: stay green characteristics at 90 and 100 days after planting on a scale of 1 to 9 ;

*Significant at the 0.05 probability level; **Significant at the 0.01 probability level ; ns: not significant

Appendix 5.1. Continued

Entry	Extra-early		YIELD		DYA		ASI		PLTH		EHT		PASP		EPP		SGREEN		HPH	
	Early	Intermediate	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC
(TZEEI 95 x TZEEI 79) x TZEEI 96			1835	744	68	72	2.0	2.5	144	126	80	87	4.5	3.5	0.7		7.0		-22	-9
(TZEEI 78 x TZEEI 79) x TZEEI 96			1765	377	71	73	2.5	9.5	138	138	85	92	5.0	4.5	0.9		8.0		-51	-82
TZEEI 78 x TZEEI 79 Check			3571	1053	66	69	1.5	2.5	167	159	85	95	3.0	2.0	1.3		7.0		95	95
TZEEI 76 x TZEEI 82 Check			3166	534	65	69	1.0	4.0	132	134	75	88	3.5	4.0	1.1		5.5		95	95
TZEEI 95 x TZEEI 79 Check			2353	821	69	71	4.5	6.5	153	136	80	91	3.5	4.0	0.8		8.0			
(TZEEI 76 x TZEEI 82) x TZEI 124			5399	1834	66	68	2.0	6.0	173	164	90	98	2.0	2.5	1.0		6.5		71	243
(TZEEI 78 x TZEEI 79) x ENT 13			5328	2376	70	71	0.5	3.0	201	182	130	123	1.5	3.0	1.0		6.0		49	16
(TZEEI 95 x TZEEI 79) x CMZ ENT 5			5293	1016	66	69	1.0	7.0	177	145	90	96	2.0	3.5	1.0		7.5		125	24
(TZEEI 76 x TZEEI 82) x TZd 164			5272	1440	68	72	-0.5	2.0	171	139	93	92	2.0	3.0	1.2		7.0		67	170
(TZEEI 76 x TZEEI 82) x TZEI 129			5202	2044	67	70	1.5	6.0	182	153	110	96	2.0	2.5	1.0		6.0		64	283
(TZEEI 76 x TZEEI 82) x ENT 13			5084	2486	68	69	2.0	4.5	163	151	83	104	1.5	2.5	1.1		9.0		61	365
(TZEEI 76 x TZEEI 82) x CMK ENT 20			4928	533	68	72	0.5	11.0	186	114	98	72	2.0	4.5	1.0		7.0		56	0
(TZEEI 78 x TZEEI 79) x TZEI 124			4855	984	69	69	2.5	9.5	173	149	80	93	2.0	3.5	1.0		8.5		36	-52
(TZEEI 95 x TZEEI 79) x CMK ENT 20			4616	499	68	75	2.0	11.0	160	133	80	79	2.5	4.0	1.0		7.5		96	-39
(TZEEI 76 x TZEEI 82) x CMZ ENT 5			4499	681	68	73	1.5	11.0	165	120	93	77	2.0	3.5	1.0		5.5		42	27
(TZEEI 95 x TZEEI 79) x TZEI 158			4474	1616	66	72	1.5	3.0	164	134	88	83	3.0	3.0	1.0		6.5		90	97
Overall mean			3788	1429	67	71	1.9	5.7	158	142	83	90	2.9	3.2	1		6.8		32	78
Lsd			1538	918	2.2	4.2	2.3	5.5	20	23	20	17	1.3	1.2	0.2		1.7			
Rep			ns	ns	ns	**	**	ns	*	ns	ns	ns	ns	ns	*		**			
Block(Rep)			**	**	*	**	ns	ns	**	**	**	**	*	**	ns		**			
Entry			**	**	**	**	**	**	**	**	**	**	**	*	*		**			

WWC: well-watered conditions; WSC: water stress conditions; HPH (%): heterosis for grain yield over the best RSC parent

YIELD: Grain yield; DY A: days to anthesis; ASI: anthesis silking interval; PLTH (cm): plant height; EHT (cm): ear height;

PASP (1-5): plant aspect; EPP: number of ears per plant; SGREEN: stay green characteristics at 90 and 100 days after planting on a scale of 1 to 9 ;

*Significant at the 0.05 probability level; **Significant at the 0.01 probability level ; ns: not significant

Appendix 5.1. Continued

Entry	Extra-early		YIELD		DYA		ASI		PLTH		EHT		PASP		EPP		SGREEN		HPH	
	Early	Intermediate	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC
(TZEEI 76 x TZEEI 82) x TZEI 158			4467	1268	64	69	3.0	6.0	158	145	65	90	2.5	3.0	1.0	6.5	41	137		
(TZEEI 76 x TZEEI 82) x CMZ ENT 2			4421	1336	68	72	-1.0	2.5	177	139	98	91	2.5	3.5	1.0	7.0	40	150		
(TZEEI 95 x TZEEI 79) x CMZ ENT 2			4232	987	68	69	0.5	8.0	155	139	73	91	2.5	3.5	0.9	7.0	80	20		
(TZEEI 76 x TZEEI 82) x TZd 181			4214	1092	69	70	1.5	6.0	152	139	65	91	3.0	3.5	1.1	7.0	33	104		
(TZEEI 76 x TZEEI 82) x TZEI 13			4159	1968	67	71	1.5	7.5	147	139	78	98	3.0	3.0	1.0	6.5	31	269		
(TZEEI 76 x TZEEI 82) x TZEI 16			4004	1058	68	72	4.0	4.0	168	134	105	88	2.5	3.5	1.2	7.5	26	98		
(TZEEI 78 x TZEEI 79) x CMZ ENT 5			3966	823	68	70	2.0	13.5	163	155	88	103	3.0	3.5	1.0	6.0	11	-60		
(TZEEI 76 x TZEEI 82) x CamInb			3900	767	69	78	2.5	8.0	160	145	93	95	2.5	4.0	1.0	6.5	23	44		
(TZEEI 95 x TZEEI 79) x ENT 13			3863	1336	67	70	2.0	10.5	153	129	75	86	3.0	3.0	1.0	7.0	64	63		
(TZEEI 78 x TZEEI 79) x CMZ ENT 2			3823	1538	68	72	1.0	4.0	171	158	90	106	2.5	3.0	1.0	6.5	7	-25		
(TZEEI 78 x TZEEI 79) x TZd 181			3761	1431	67	72	4.0	4.0	163	138	80	76	3.0	3.5	1.0	7.5	5	-30		
(TZEEI 78 x TZEEI 79) x TZEI 129			3735	1255	70	72	2.5	10.0	173	141	98	88	3.0	3.5	1.1	8.0	5	-39		
(TZEEI 78 x TZEEI 79) x TZd 164			3655	1416	68	72	2.5	4.0	163	151	83	101	3.0	3.0	1.0	8.0	2	-31		
(TZEEI 78 x TZEEI 79) x TZEI 16			3574	989	71	74	2.0	9.5	158	151	78	103	3.0	3.5	1.0	7.0	0	-52		
(TZEEI 78 x TZEEI 79) x CMK ENT 20			3455	836	70	77	1.5	8.0	157	124	70	81	3.0	3.5	1.0	7.5	-3	-59		
(TZEEI 95 x TZEEI 79) x TZEI 124			3438	1441	62	69	5.0	10.0	143	145	60	81	3.5	3.0	1.0	8.0	46	76		
Overall mean			3788	1429	67	71	1.9	5.7	158	142	83	90	2.9	3.2	1	6.8	32	78		
Lsd			1538	918	2.2	4.2	2.3	5.5	20	23	20	17	1.3	1.2	0.2	1.7				
Rep			ns	ns	ns	**	**	ns	*	ns	ns	ns	ns	ns	*	**				
Block(Rep)			**	**	*	**	ns	ns	**	**	**	**	*	**	ns	**				
Entry			**	**	**	**	**	**	**	**	**	**	**	*	*	**				

WWC: well-watered conditions; WSC: water stress conditions; HPH (%): heterosis for grain yield over the best RSC parent;

YIELD: Grain yield; DY A: days to anthesis; ASI: anthesis silking interval; PLTH (cm): plant height; EHT (cm): ear height;

PASP (1-5): plant aspect; EPP: number of ears per plant; SGREEN: stay green characteristics at 90 and 100 days after planting on a scale of 1 to 9 ;

*Significant at the 0.05 probability level; **Significant at the 0.01 probability level ; ns: not significant

Appendix 5.1. Continued

Entry	■ Extra-early ■ Early ■ Intermediate	YIELD		DYA		ASI		PLTH		EHT		PASP		EPP	SGREEN	HPH	
		WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC
(TZEEI 95 x TZEEI 79) x TZEI 16		3422	726	68	73	3.0	6.0	161	123	98	80	3.0	4.0	1.0	7.5	45	-12
(TZEEI 78 x TZEEI 79) x TZEI 158		3418	993	68	71	2.5	7.0	168	137	93	86	3.0	3.5	1.1	7.0	-4	-52
(TZEEI 95 x TZEEI 79) x TZd 181		3404	756	66	70	2.5	5.5	152	116	65	67	3.5	3.5	0.9	8.5	45	-8
(TZEEI 95 x TZEEI 79) x CamInb		3290	1275	71	85	1.5	1.5	164	131	88	76	4.0	3.0	1.0	6.5	40	55
(TZEEI 95 x TZEEI 79) x TZEI 129		3179	1647	67	71	2.5	6.0	165	139	100	88	3.5	3.0	0.9	7.0	35	101
(TZEEI 78 x TZEEI 79) x CamInb		3146	578	72	80	3.5	6.0	169	138	113	87	3.5	4.0	0.9	7.0	-12	-72
(TZEEI 95 x TZEEI 79) x TZd 164		2989	1814	65	71	2.5	3.0	138	126	68	74	3.0	3.0	0.9	8.0	27	121
ENT 13 x CamInbgp.1-17 Check		4081	1770	70	70	1.5	11.0	178	153	108	92	3.0	2.5	1.0	6.0	98	98
TZEI 124 x ENT 13 check		4524	1498	75	81	2.5	4.5	177	154	100	103	2.5	3.0	1.0	5.5	106	106
(TZEEI 76 x TZEEI 82) x CMZ ENT 12		5182	1694	64	70	2.0	3.0	143	129	70	77	2.5	3.0	1.0	8.0	64	217
(TZEEI 76 x TZEEI 82) x CMK ENT 8		4841	2124	65	69	0.5	4.5	150	135	83	84	2.5	2.5	1.0	7.5	53	298
(TZEEI 76 x TZEEI 82) x CMZ ENT 6		4779	2121	68	70	2.0	6.5	167	150	95	93	2.0	3.0	1.0	7.0	51	297
(TZEEI 78 x TZEEI 79) x CMK ENT 8		4662	2754	67	70	0.0	2.0	159	176	88	104	3.0	2.5	1.0	7.0	31	34
(TZEEI 76 x TZEEI 82) x CMZ ENT 3		4654	1055	66	69	2.0	7.5	147	137	78	84	2.0	3.5	1.0	7.0	47	98
(TZEEI 78 x TZEEI 79) x CMZ ENT 3		4580	1586	71	70	0.0	4.0	159	173	80	93	2.5	3.5	1.0	8.0	28	-23
(TZEEI 76 x TZEEI 82) x 88069		4576	2627	71	74	1.0	4.0	163	146	88	94	2.0	2.0	1.0	7.5	45	392
Overall mean		3788	1429	67	71	1.9	5.7	158	142	83	90	2.9	3.2	1	6.8	32	78
Lsd		1538	918	2.2	4.2	2.3	5.5	20	23	20	17	1.3	1.2	0.2	1.7		
Rep		ns	ns	ns	**	**	ns	*	ns	ns	ns	ns	ns	*	**		
Block(Rep)		**	**	*	**	ns	ns	**	**	**	**	*	**	ns	**		
Entry		**	**	**	**	**	**	**	**	**	**	**	*	*	**		

WWC: well-watered conditions; WSC: water stress conditions; HPH (%): heterosis for grain yield over the best RSC parent;

YIELD: Grain yield; DYA: days to anthesis; ASI: anthesis silking interval; PLTH (cm): plant height; EHT (cm): ear height;

PASP (1-5): plant aspect; EPP: number of ears per plant; SGREEN: stay green characteristics at 90 and 100 days after planting on a scale of 1 to 9 ;

*Significant at the 0.05 probability level; **Significant at the 0.01 probability level ; ns: not significant

Appendix 5.1. Continued

Entry	■ Extra-early ■ Early ■ Intermediate	YIELD		DYA		ASI		PLTH		EHT		PASP		EPP	SGREEN	HPH	
		WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC
(TZEEI 95 x TZEEI 79) x CMZ ENT 3		4568	601	65	70	2.0	6.5	153	122	70	73	2.5	4.5	1.0	6.5	94	-27
(TZEEI 95 x TZEEI 79) x CMK ENT 23		4464	1370	69	75	0.5	2.5	166	142	80	86	2.5	3.5	1.0	7.0	90	67
(TZEEI 76 x TZEEI 82) x CMK ENT 24		4360	930	69	77	1.0	3.0	167	134	90	80	2.0	3.5	1.0	4.5	38	74
(TZEEI 76 x TZEEI 82) x CMZ ENT 8		4350	2959	68	70	0.5	3.0	158	161	78	100	3.0	2.0	0.9	6.5	37	454
(TZEEI 78 x TZEEI 79) x CMZ ENT 8		4326	2451	67	73	3.0	7.0	148	173	65	103	2.5	2.5	1.0	6.5	21	19
(TZEEI 78 x TZEEI 79) x CMZ ENT 12		4325	1316	66	70	2.0	10.0	173	144	95	87	2.5	3.0	1.1	7.0	21	-36
(TZEEI 76 x TZEEI 82) x CMK ENT 22		4151	1967	68	71	1.0	3.5	158	156	88	94	2.5	3.0	1.1	6.0	31	268
(TZEEI 95 x TZEEI 79) x 9450		4098	1288	71	79	2.0	5.0	153	131	88	87	2.5	3.5	1.0	7.0	74	57
(TZEEI 76 x TZEEI 82) x CMK ENT 23		4092	3383	71	71	-0.5	2.0	163	169	83	109	3.0	2.5	1.1	6.5	29	533
(TZEEI 76 x TZEEI 82) x 9450		4090	1579	70	75	1.0	8.0	153	149	83	104	3.0	3.0	1.0	6.5	29	196
(TZEEI 95 x TZEEI 79) x 9848		4090	2084	65	70	2.0	4.0	152	134	83	86	3.0	3.0	1.0	7.5	74	154
(TZEEI 95 x TZEEI 79) x TZd 177		4064	1493	67	71	4.5	6.5	158	150	73	86	3.0	3.0	0.9	7.0	73	82
(TZEEI 95 x TZEEI 79) x 88069		3971	1448	68	71	1.5	5.0	164	156	93	101	3.0	3.0	1.0	6.5	69	76
(TZEEI 95 x TZEEI 79) x TZd 176		3947	1398	67	72	2.5	3.0	155	135	78	80	3.0	3.5	1.1	8.5	68	70
(TZEEI 78 x TZEEI 79) x CMK ENT 24		3938	726	72	76	1.5	9.0	162	149	88	96	2.5	4.5	1.0	5.0	10	-65
(TZEEI 95 x TZEEI 79) x CMZ ENT 6		3913	2204	66	70	3.5	5.5	168	173	93	99	2.5	2.0	1.0	6.5	66	169
Overall mean		3788	1429	67	71	1.9	5.7	158	142	83	90	2.9	3.2	1	6.8	32	78
Lsd		1538	918	2.2	4.2	2.3	5.5	20	23	20	17	1.3	1.2	0.2	1.7		
Rep		ns	ns	ns	**	**	ns	*	ns	ns	ns	ns	ns	*	**		
Block(Rep)		**	**	*	**	ns	ns	**	**	**	**	*	**	ns	**		
Entry		**	**	**	**	**	**	**	**	**	**	**	*	*	**		

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*Significant at the 0.05 probability level; **Significant at the 0.01 probability level; ns: not significant

Appendix 5.1. Continued

Entry	■ Extra-early ■ Early ■ Intermediate	YIELD		DYA		ASI		PLTH		EHT		PASP		EPP	SGREEN	HPH	
		WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC	WWC	WSC
(TZEEI 95 x TZEEI 79) x CMK ENT 22		3714	2152	68	73	1.0	3.5	157	149	63	83	3.0	3.0	1.0	7.5	58	162
(TZEEI 76 x TZEEI 82) x TZd 177		3698	1664	67	71	3.0	5.5	152	148	70	88	3.0	3.5	0.9	8.0	17	212
(TZEEI 95 x TZEEI 79) x CMZ ENT 12		3639	993	64	67	2.5	8.0	147	146	58	83	3.5	4.0	1.0	7.5	55	21
(TZEEI 95 x TZEEI 79) x CMZ ENT 8		3624	1357	71	68	1.0	10.0	153	140	75	78	2.5	3.5	1.1	7.5	54	65
(TZEEI 78 x TZEEI 79) x CMZ ENT 6		3522	1297	69	72	4.0	15.0	171	158	90	99	2.5	3.0	0.8	6.5	-1	-37
(TZEEI 78 x TZEEI 79) x 9450		3477	1297	74	84	1.5	4.0	178	148	108	103	3.0	3.0	1.0	6.0	-3	-37
(TZEEI 76 x TZEEI 82) x TZd 176		3434	1604	67	71	3.5	3.5	157	141	80	84	3.0	3.5	1.1	8.5	8	200
(TZEEI 78 x TZEEI 79) x 88069		3313	1606	71	75	0.5	1.5	158	177	80	118	3.0	3.0	1.0	6.0	-7	-22
(TZEEI 78 x TZEEI 79) x CMK ENT 23		3109	2778	70	72	1.5	8.5	154	168	83	103	3.5	2.5	1.0	7.0	-13	35
(TZEEI 95 x TZEEI 79) x CMK ENT 8		3108	2937	68	72	0.5	1.0	135	141	78	86	3.5	2.5	1.0	8.0	32	258
(TZEEI 78 x TZEEI 79) x TZd 177		2918	779	69	76	2.0	6.5	149	128	75	79	3.5	3.5	1.1	7.5	-18	-62
(TZEEI 78 x TZEEI 79) x TZd 176		2255	1527	69	75	3.5	3.0	153	138	75	86	4.5	3.0	1.1	8.0	-37	-26
(TZEEI 78 x TZEEI 79) x CMK ENT 22		2161	827	72	74	3.5	14.5	160	153	75	88	4.0	3.5	1.1	6.0	-39	-60
Overall mean		3788	1429	67	71	1.9	5.7	158	142	83	90	2.9	3.2	1	6.8	32	78
Lsd		1538	918	2.2	4.2	2.3	5.5	20	23	20	17	1.3	1.2	0.2	1.7		
Rep		ns	ns	ns	**	**	ns	*	ns	ns	ns	ns	ns	*	**		
Block(Rep)		**	**	*	**	ns	ns	**	**	**	**	*	**	ns	**		
Entry		**	**	**	**	**	**	**	**	**	**	**	*	*	**		

WWC: well-watered conditions; WSC: water stress conditions; HPH (%): heterosis for grain yield over the best RSC parent;

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Appendix 6.1. Pictures of the single cross hybrid TZEI 124 x ENT 13



Single cross hybrid (TZEI 124 x ENT 13) coined **NAGODE** (Thank You) by farmers in Niger. Results of the evaluation of the hybrid at (A) Konni in 2012 ; (B) Maradi in 2012 ; (C&D) FESA Seed Co at Chadakwari in 2013