Breeding Cowpea (*Vigna unguiculata* (L.) Walp.) for Improved Drought Tolerance in Mozambique

By

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____

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As the candidate's supervisor I agree to the submission of this thesis

Supervisor	Supervisor
__________________________	__________________________
(Dr Githiri Mwangi)	(Prof. Pangirayi Tongoona)

Thesis Abstract

Cowpea yields in Mozambique can be increased through breeding farmers' accepted cultivars with drought tolerance and stability across environments. A study was conducted in the southern region of Mozambique to: (1) determine farmers perceptions on major constraints limiting cowpea production and identify preferences regarding cultivars and traits, (2) determine the variability of selected cowpea germplasm for drought tolerance, (3) determine the gene action controlling drought tolerance, yield and yield components in cowpea, and (4) assess the genotype × environment interaction and yield stability of cowpea genotypes under drought-stressed and non-stressed conditions.

The study on farmers' perceptions about the major constraints limiting cowpea production and preferences regarding cowpea cultivars and traits established that cowpea was an important crop, cultivated for its grain, leaves and fresh pods for household consumption and the market. The study revealed that cowpea grain and leaves were equally important across the three districts in the study. Differences in accessibility to markets between districts influenced the ranking of grain and leaves among districts. Grain was more important in Bilene and Chibuto districts which are situated far from the major urban centre, Maputo, while leaves were more important in Boane district which is near the major market of Maputo. Fresh pods were important in Bilene district which is situated along the major highway connecting Maputo and other provinces. Drought was the most important production constraint followed by aphids, bruchids and viral diseases. The criteria used by farmers to select cowpea varieties included high grain and leaf yield, large seed size, earliness, smoothness of the testa and potential marketability of the variety. The implication of this study is that different types of varieties need to be developed for different areas. Dual-purpose or grain-type varieties need to be developed for areas situated far away from the major markets while varieties for leaf production need to be bred for areas near major markets. During the breeding process, a selection index needs to be adopted whereby drought tolerance, high grain and leaf yield, large seed size, smooth testa, earliness, aphids and bruchids resistance should be integrated as components of the index. High grain yield should receive high weight for varieties

developed for areas located far from major markets while high leaf yield would receive high weight for varieties developed for areas located near major markets.

The study on variability of cowpea germplasm collections for drought tolerance revealed wide genotypic variability among the tested germplasm. Biplot displays indicated that the genotypes could be grouped into four categories according to their drought tolerance and yielding ability as indicated below: high yielding-drought tolerant (group A), high yielding-drought susceptible (group B), low yielding-drought tolerant (group C), and low yielding-drought susceptible (group D). Examples of high yielding-drought tolerant genotypes were Sh-50, UC-524B, INIA-24, INIA-120, IT96D-610 and Tete-2. Stress tolerance index was the best criterion for assessing genotypes for variability in drought tolerance because it enabled the identification of high yielding and drought tolerant genotypes (group A).

The assessment on gene action controlling drought tolerance (stay-green), yield and components indicated that both additive and non additive effects were involved in controlling all of these traits. Additive gene action was more important than non-additive gene affects in controlling stay-green, days to flowering, number of pods per plant, number of seeds per pod and hundred seed weight. Under no-stress conditions, additive gene action was more important than non-additive gene action while under drought-stressed conditions, non-additive gene effects were more important than additive gene effects. Stay-green can easily be assessed visually in early segregating populations while yield and yield related traits cannot. Hence, selection for drought tolerance using the stay-green trait would be effective in early segregating generations while selection for yield and number of pods per plant would be effective in late segregating generations. Selection for yield could be conducted directly under no-stress conditions and indirectly using the number of pods per plant under drought stress conditions. Genotype INIA-41 would be the most desirable to use as a parent for drought tolerance and IT93K-503-1 would be the most desirable to use as a parent for drought tolerance and yield.

The assessment on genotype × environment interaction and cowpea grain yield stability for forty-eight (48) cowpea genotypes grown under drought-stressed and non-stressed conditions indicated that cross-over genotype × environment interactions were present for yield indicating that genotypes responded differently to

varying environmental conditions. Genotypes adapted to specific environmental conditions could be identified. Genotypes IT-18, INIA-51, INIA-51A and Nhavanca were adapted to non-stressed environments that were either drought stressed or non-stressed while VAR-11D was adapted to low yielding, stressful environments. Genotypes INIA-23A, INIA-81D, INIA-24, INIA-25, INIA-16 and INIA-76 were high yielding and stable while genotypes IT-18, INIA-51, INIA-51A, Nhavanca and VAR-11D were high yielding and unstable. Genotypes Bambey-21, INIA-36, INIA-12 and Monteiro were consistently low yielding and stable except INIA-12 that was consistently unstable. Chókwè was a high yielding environment and suitable for identifying high yielding genotypes but not ideal for selection because it was not representative of an average environment while Umbeluzi was low yielding and not ideal for selection.

Overall, the study revealed that genetic improvement of drought tolerance and yield would be feasible. Potential parents for genetic improvement for yield and drought tolerance were identified. However, further studies for assessing yield stability of cowpea genotypes are necessary and could be achieved by including more seasons and sites to get a better understanding of the genotype × environment interaction and yield stability of cowpea in Mozambique.

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Dedication

This work is dedicated to my late parents Marcos João Chiulele and Virgínia Jacob Jalane and to my wife Isabel Maria, my children Denzel Clayton and Kiara Minelle who always believed in me.

Table of contents

Introduction to the Thesis

1 Background

Cowpea is one the most widely grown food crops in Africa. It is estimated that more than 90% of the world cowpea grain production of 5.7 million tonnes is produced in about 10 million hectares in Africa (FAOSTAT, 2008). The crop is most important in the semi-arid and hot areas of Africa where other crops may fail due to poor adaptation to heat, drought and low soil fertility conditions (Gwathmey and Hall, 1992; Ehlers and Hall, 1997; Singh *et al.*, 1999a; Singh and Matsui, 2002; Hall, 2004). Among the top six major world cowpea producers, five are located in Africa and include Nigeria, Niger, Burkina Faso, Senegal and Mali (Fery, 2002; FAOSTAT, 2008).

Cowpea is an important crop in Mozambique where the grain and leaves are major sources of food and family income, particularly for the resource-poor households. The crop has a high protein content of about 25% in the grain (dry weight basis) (Bressani, 1985; Singh *et al.*, 2003), and serves as a cheap source of protein, vitamins and minerals. The crop enhances the quality of the cereal based diets when its high lysine content is combined with the high content of methionine and cysteine of cereals (Lambot, 2002). In addition, the crop improves the cropping systems and soil fertility by reducing soil erosion, suppressing the weeds and fixing atmospheric nitrogen which contributes to increased yields of nitrogen demanding crops grown with or after it (Tarawali *et al.*, 2002). However, despite such importance, average cowpea yields in Mozambique have for a long time remained below 300 $kgha^{-1}$ (INIA, 2000), which represents a challenge to be addressed through research. The major constraints contributing to the low cowpea yields in the country include biotic stresses (insect pests, nematodes, diseases and weeds), abiotic stresses (low soil fertility and drought), poor agronomic practices, poor seed quality, poor extension services, cultivation of low yielding and non-improved cultivars and limited breeding work (INIA, 2003).

Drought, manifested in the form of high variability in amount and distribution of rainfall during the cropping season, has been reported to be a major cowpea yield-limiting constraint in sub-Saharan Africa (Singh, 1987; Ehlers and Hall, 1997; Hall, 2004; Agbicodo *et al.*, 2009). In southern Africa, spatial and temporal (inter- and intra-annual) rainfall variability has been increasing in recent years (Fauchereau *et al*., 2003; Sithole and Murewi, 2009). As a result, drought has become more intense and widespread (Fauchereau *et al*., 2003). This has affected the production of rain-fed crops such as cowpeas and is threatening food security in the region. Intermittent droughts do occur but terminal drought is the most limiting due to reduction in the duration of the rainy season which impacts negatively on flowering and grain filling resulting in low yields. This is exacerbated by the lack of drought tolerant cultivars amongst the commonly grown varieties in the country. Hence, the development of cowpea cultivars with enhanced tolerance to drought would be an effective and sustainable measure for ensuring increased yields in the country.

The development of drought tolerant cowpea cultivars through conventional plant breeding methods and molecular techniques has been conducted at the International Institute of Tropical Agriculture (IITA) and the University of California Riverside (UCR) (Singh, 1987; Hall *et al.*, 2002; Hall, 2004). This has resulted in the release of early maturing cultivars that can escape terminal drought (Singh, 1987) and medium maturing varieties with delayed leaf senescence (Gwathmey and Hall, 1992).

The development of cowpea cultivars with enhanced levels of drought tolerance is also necessary in Mozambique. However, there is limited information regarding genetic variability for drought tolerance among the germplasm and cultivated landraces grown in the country. Studies conducted elsewhere have indicated that genetic variability for drought tolerance which could be utilized in breeding programmes exists in cowpea (Turk *et al.*, 1980; Turk and Hall, 1980a,b; Watanabe, 1998; Mai-Kodomi *et al.,* 1999, Singh *et al.*, 1999b; Muchero *et al*., 2008). In addition, more germplasm lines need to be evaluated in order to identify new and better adapted sources for drought tolerance under Mozambican conditions. Information on gene action controlling drought tolerance, yield and its associated traits is scarce in cowpea. Romanus *et al.* (2008) reported that additive gene action was more important than non-additive gene action in controlling yield, number of seeds per pod, pod length and hundred seed weight. Umaharan *et al.* (1997) also reported the prevalence of additive gene action over the non additive gene action for pod length, pod width, pod wall thickness, inter-seed space, hundred seed weight and seediness on vegetable cowpea. However, combining ability and heritability estimates are specific to the germplasm being tested and the environment where the germplasm is tested (Falconer, 1989). So, there is a need to investigate the gene action controlling drought tolerance, yield and yield related traits in germplasm adapted to Mozambique. Such information would be useful for a cowpea breeding programme in the country.

Yield instability is among the major causes of food insecurity in Mozambique. Significant genotype x environment interactions that characterize many cowpea growing agro-ecologies are attributed to both large and variable genotype x location and genotype x season interaction effects emanating from highly variable rainfall amount and distribution over time and space, and from large differences in soil water-holding capacity and fertility across these ecologies (Hall *et al.*, 1997). Spatial as well as inter- and intra-annual rainfall variability is predicted to increase (Sithole and Murewi, 2009). This will cause rainfed crops such as cowpea to give variable yields over the years. There is, therefore, a need to conduct studies on yield stability and genotype by environment interaction under different agro-ecologies and seasons for devising adequate selection strategy in the country.

It has been suggested that farmers' participation in the early stages of any breeding programme can contribute to acceptance and adoption of new improved cultivars (Maurya *et al.*, 1988; Sperling *et al*., 1993; Franzel *et al*., 1995) since their needs and expectations are fulfilled. Elsewhere, participatory studies conducted in cowpea revealed that farmers' participation in varietal selection could improve the effectiveness and efficiency of the selection process given that farmers' selection intensity was similar to that of the breeders (Kitch *et al*., 1998). In Mozambique, participatory studies for identifying farmers' perception about cowpea production and preferences of cowpea cultivars have never been done. Farmers in the country still grow unimproved landraces despite the availability of some improved cultivars. This could probably be attributed to the fact that most of the improved cultivars were developed under different conditions from those of the farmers and, thus, they do not meet their needs and preferences. For an effective cowpea breeding programme, farmers' perceptions about the major constraints affecting the crop production as well as their preferences on the crop traits and cultivars should be determined through farmers-researcher interaction and collaboration. That interaction can provide useful information on farmers' desirable traits and the major constraints that they face in their production systems which are useful for developing suitable cultivars for their needs and conditions.

2 Research justification

Drought is increasingly becoming a major yield-limiting constraint in Mozambique. Drought is manifested in the form of high variability in rainfall amount and distribution over different agro-ecologies and seasons. Unfortunately, no drought tolerant cultivars are available. Hence, a breeding programme aimed at developing drought tolerant cultivars needs to be established. To that end, studies on genetic variability and gene action controlling drought tolerance need to be conducted to assist in the identification of suitable parents. Depending on the relative importance of additive and non-additive gene effects, decisions on when to undertake selection in segregating populations (early or late stages) can be made.

In addition, genotype by environment interaction and yield stability of different cowpea genotypes available in the country need to be investigated in order to identify the best genotypes for different locations in the country. Depending on the presence or absence of genotype by environment interactions, selection for specific adaptation or wide adaptation can be adopted.

Finally, in order to enhance the acceptance and adoption of improved cowpea cultivars, farmers need to be involved in the breeding programme. Their perceptions about the major constraints limiting cowpea production and their preferences on different crop traits and cultivars need to be identified and integrated in the breeding programme.

This study addresses the above-mentioned constraints and was conducted during the period November 2007 to August 2010.

3 Research objectives

The aim of this study was to contribute to increased food production in Mozambique through development of drought tolerant and farmer acceptable cowpea lines.

The specific objectives of the study were:

1. to determine farmers perceptions on major constraints limiting cowpea production and identify preferences regarding cultivars and traits,
2. to determine the variability of selected cowpea germplasm for drought tolerance,
3. to determine the gene action controlling drought tolerance, yield and yield related traits in cowpea, and
4. to assess the genotype by environment interaction and yield stability of cowpea genotypes under drought-stressed and non-stressed conditions.

4 Research hypothesis

This study was conducted to test the following hypotheses:

1. Farmers are aware of the major constraints limiting cowpea production in their production areas and have preferences for specific traits and cowpea cultivars.
2. Genetic variability for drought tolerance exists amongst the adapted germplasm that can be exploited in a breeding programme.
3. Additive gene action is more important than non-additive gene action in controlling drought tolerance, yield and yield related traits.
4. The cowpea germplasm in Mozambique is widely adapted.

5 Outline of thesis

The specific objectives indicated above were addressed in different chapters that comprise this thesis. The chapters were written as discrete and independent papers and therefore, overlaps are most likely to occur in terms of content and references among the different chapters. The chapters are organized as follows:

1. General Introduction to thesis
2. Chapter one: Literature review
3. Chapter two: Participatory plant breeding: assessing farmers perceptions and preferences on cowpea varieties in Mozambique
4. Chapter three: Assessment of cowpea genotypes for variability in drought tolerance
5. Chapter four: Inheritance of drought tolerance and gene action controlling drought tolerance, yield and yield related traits in cowpea
6. Chapter five: Genotype by environment interaction and grain yield stability of cowpea under drought stressed and non-stressed environments
7. Chapter six: General overview

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Chapter One: Literature Review

1.1 Introduction

This chapter provides context to the study by reviewing relevant information on cowpea research. It focuses on: (1) cowpea drought tolerance, discussing information on responses, genetic variability and progress made in drought tolerance research; (2) gene action controlling quantitative traits; (3) genotype × environment interaction and grain yield stability; and (4) farmers participation in breeding improved cultivars. Information concerning world cowpea production and major production constraits is provided. During the discussion of the published literature, progress made is indicated and gaps that need further investigation are identified.

1.2 World cowpea production and major constraints

Cowpea is cultivated on about 10 million hectares worldwide out of which more than 85% is located in Africa (FAOSTAT, 2008). Considerable production also takes place in Asia and Oceania, the Middle East, southern Europe, southern USA, and Central and South America (Singh *et al.*, 2002). Most of the world cowpea production comes from the West-Central Africa where countries such as Nigeria, Niger, Burkina Faso, Senegal, Ghana, Cameroon and Mali are the most important producers (Fery, 2002; FAOSTAT, 2008). Nigeria contributes more than 50% of the total world cowpea grain production (FAOSTAT, 2008). The crop also has significant importance in the East and Southern Africa where Ethiopia, Kenya, Tanzania, Malawi, Botswana, Zimbabwe and Mozambique are important producers (Ehlers and Hall, 1997; NGICA, 2006). Despite its widespread cultivation, average cowpea yields on the farmers' fields are low (< 300 $kgha^{-1}$) (Takim and Uddin, 2010). The low yields have been attributed to a number of the biotic stresses such as insect pests, nematodes, diseases and parasitic weeds and abiotic stresses such as drought, high temperature, low soil fertility, low pH and aluminium toxicity (Singh, 1985; Singh and Jackai, 1985; Ehlers and Hall, 1997; Hall, 2004).

Drought is currently the most important abiotic stress limiting cowpea production worldwide (Singh *et al.*, 1999a; Hall, 2004). Breeding for improved drought tolerance offers a scope for increasing production and productivity particularly in sub-Saharan

Africa. However, progress in cowpea breeding for improved drought tolerance will depend mainly on the availability of genetic variability for the traits conferring drought tolerance, adequate screening methods and knowledge of genetic control of the trait conferring drought tolerance.

1.2.1 Drought: definition, types of drought and progress made in drought research

From a meteorological point of view, drought is defined as the absence of rainfall for a long period of time to cause moisture depletion in the soil and a decrease of water potential in plant tissue (Kramer, 1980). Agriculturally, drought is defined as the inadequacy of water that is available to the plants, including precipitation and soil moisture storage capacity, in quantity and distribution during the life cycle of the crop plant, which restricts the expression of full genetic potential of the plant from reaching the genetically determined theoretical maximum yield (Begg and Turner, 1976).

Drought from an agricultural point of view is the subject of review in this study. When the rainfall is inadequate, moisture levels in the soil may be low and plants undergo drought stress or moisture stress. Drought stress develops as a result of excessive water loss, which is not replaced by root uptake (Begg and Turner, 1976; Ramanjulu and Sudhakar, 2000). This causes a decrease in plant water potential (Begg and Turner, 1976; Szegletes *et al.*, 2000) and relative water content (Hale and Orcutt, 1987; Naidu *et al.*, 2001) with consequent decrease in cell turgor. Low cell turgor reduces cell expansion and therefore, plant growth. Drought can affect the physiology of the plant which impacts directly on crop growth and development, biomass accumulation and production of seed yield.

Drought can be classified in various ways: according to the time of occurrence into intermittent and terminal, its intensity into mild, moderate and severe and its duration into short and long duration. Intermittent drought is the one that occurs at any time during the crop's vegetative growth stage and is generally difficult to predict on a year-to-year basis, although a broad pattern could be determined for a particular environment (Chauhan *et al.*, 2002). Terminal drought is the one that occurs at the end of the crop growth stage, affecting mostly the reproductive stage such as flowering and seed development (Nigam *et al.*, 2002). Intermittent drought results from variable amount and distribution of rainfall during the crop growth stage while terminal drought results from early cessation of the rains. Hall and Patel (1985) indicated that crop varieties developed to cope with drought will be effective against specific types of drought. Hence, it is important to have a clear understanding of the type of drought that takes place in the target environment for developing suitable varieties. Hall and Patel (1985) gave example of short-cycle and synchronous varieties as being appropriate for environments characterized by terminal droughts while indeterminate and long-cycle varieties with sequential flowering are suitable for environments with long but unpredictable water supply.

Both intermittent and terminal drought affect crop production but the impacts are different. Intermittent drought affects biomass accumulation directly through reduction in leaf area (Boyer and McPherson, 1975; Turk and Hall, 1980b; Hale and Orcutt, 1987; Maiti *et al.*, 1996) and stem elongation (Wien *et al.*, 1979). Leaf area is reduced through reduced leaf area initiation (Clarke and Durdley, 1981), reduced leaf expansion due to extreme sensitivity of cell expansion to reduced turgor (Hsiao, 1973; Akeampong, 1986) and/or enhanced leaf senescence (Gardner *et al.*, 1985; Ludlow and Muchow, 1990). Reduced leaf area intercepts less radiation (Mollier and Pellerin, 1999) leading to reduced biomass production (Akeampong, 1986). Leaf area maintenance would improve yield stability in intermittent drought due to better radiation interception when water is available while in terminal drought it will lead to yield instability because maintaining leaf area would result in increased rate of water use. This would increase the probability of the crop running out of water before maturity (Ludlow and Muchow, 1990). Hence, leaf maintenance would be suitable for cultivars developed to cope with intermittent drought but not for terminal drought.

Genetic variability for leaf area maintenance (commonly known as stay-green in sorghum and delayed-leaf-senescence (DLS) in cowpea) has been reported in various crops (Gwathmey and Hall, 1992; Hall, 2004). In cowpea, delayed-leaf-senescence conferred some tolerance to reproductive stage drought in erect cowpea cultivars (Gwathmey and Hall, 1992). Delayed-leaf-senescence enables cowpea plants to produce a second flush of flowers and pods that compensates for the first flush of flowers lost due to drought. This trait was reported to be controlled by a single gene (Hall, 2004). In Senegal, DLS cowpea cultivars began flowering about 35 days, produced about 2000 kgha^{-1} of grain by 60 days followed by second flush of pods with potential to produce additional 1000 kgha^{-1} by 100 days from sowing (Hall *et al.*, 2003). Despite the apparent usefulness of DLS in improving yield and yield stability of cowpea in environments characterized by intermittent drought, little has been done in incorporating this trait into improved cultivars.

Terminal drought has direct negative impact on seed yield in that it affects the production and development of reproductive organs and the translocation of photo-assimilates to the grain. Drought occurring at the beginning of the flowering stage can affect flower initiation and pre-meiotic differentiation of floral parts (Aspinall and Husain, 1970; Winkel *et al.*, 1997), but the most dramatic effects have been recorded when drought stress coincides with the beginning of meiosis and early grain initiation (O'Toole and Namuco, 1983; Westgate and Thomson Grant, 1989). Aspinall (1984) indicated that once the grain has been initiated, the sensitivity to drought declines gradually with grain development. In cowpea, there are no studies indicating precisely the most sensitive stage but drought stress during flowering and grain filling reduced the number of pods and seed weight (Turk *et al.*, 1980) due to sensitivity of pod initiation and pod filling to drought.

Breeding for tolerance to terminal drought can be achieved through development of early maturing cultivars to escape terminal drought. Progress has been made in developing early maturing cultivars in cowpea (Hall and Patel, 1985; Singh and Ntare, 1985). Early maturing cowpea cultivars were developed that can produce up to 2000 Kgha^{-1} in 60 to 70 days in many cowpea growing regions of Africa (Singh, 1987; Ehlers and Hall, 1997). Hall (2004) indicated that it was achieved by selecting plants that began flowering early and had erect plant habit and synchronous flower production (1st type) or more sequential rather than synchronous flowering, medium cycle from sowing to maturity and more spreading plant habit (2nd type). The early erect and more synchronous flowering enables the plants to escape the end-of-season drought while the spreading growth habit and sequential flowering enables them to escape mid-season drought (Hall, 2004). Unfortunately, early erect and more synchronous flowering cultivars are damaged by mid-season drought (Thiaw *et al.*, 1993) due to detrimental effects of drought on pod set and pod filling of erect synchronous flowering cultivars (Turk *et al.*, 1980). Hence, Hall (2004) proposed the use of varietal intercrop to ensure yield stability under environments characterized by both mid- and terminal droughts.

Several studies have been conducted to assess the variability of cowpea genotypes for drought tolerance. Significant differences in drought tolerance have been reported and could be utilized in breeding programmes (Turk *et al.*, 1980; Itani *et al.*, 1992a,b; Mai-Kodomi *et al.*, 1999a,b; Watanabe, 1998; Watanabe and Terao, 1998; Singh *et al.*, 1999b; Matsui and Singh, 2003; Chiulele and Agenbag, 2004; Muchero *et al.*, 2008). In these studies genotypes were evaluated at different crop growth stages (seedling stage, vegetative and reproductive) using different physiological, morphological and phenological traits.

Comparatively, terminal drought or reproductive stage drought has received more attention given its direct negative impact on seed yield (Turk *et al.*, 1980; Hall, 2004) compared to vegetative (Watanabe, 1998; Watanabe and Terao, 1998) and seedling stage drought (Matsui and Singh, 2003; Muchero *et al.*, 2008). Physiological aspects of drought tolerance such as stomatal conductance, osmotic adjustment, carbon isotope discrimination, assimilation rates, transpiration and water relations have been investigated in detail (Turk and Hall, 1980a,c; Hall and Patel, 1985; Itani *et al.*, 1992b; Hall *et al.*, 1997; Chiulele and Agenbag, 2004). Morphological aspects of drought tolerance have been conducted on root traits (Matsui and Singh, 2003) as well as shoots (Mai-Kodomi *et al.*, 1999a; Singh *et al.*, 1999b). Phenological aspects of drought tolerance in the flowering and pod filling stages have been investigated to identify genotypes that can escape drought (Gwathmey and Hall, 1992). Early flowering combined with delayed leaf senescence trait would contribute to increased yield and stability in environments characterized by mid- and terminal drought given that the resulting genotypes would be able to survive mid-season drought and terminal drought and produce the second flush of pods that would compensate for the first flush lost due to drought.

1.2.2 Drought Tolerance: definition and mechanisms

Turner (1986) defined drought tolerance as the ability of a crop plant to grow and yield satisfactorily in environments subjected to periodic water deficit while Mitra

(2001) defined drought as the ability of a crop plant to produce its economic product with minimum loss in water-deficit environment relative to the water-constraint-free environment.

The mechanisms of drought tolerance have been reviewed by several authors (Begg and Turner, 1976; Levitt, 1980; Jones and Turner, 1981; Blum, 1985; Turner, 1986; Ludlow and Muchow, 1990; Mitra, 2001) and can be grouped into three categories: escape, avoidance and tolerance (Turner, 1979; Turner, 1986; Mitra, 2001, Agbicodo *et al.*, 2009). Drought escape is the ability of a plant to complete its life cycle before serious soil and plant water deficits occur. This mechanism involves rapid phenological development (early flowering and early maturity), developmental plasticity (variation in duration of growth depending on the extent of water deficit) and remobilization of pre-anthesis photo-assimilates. Drought avoidance is the ability of plants to maintain relatively high tissue water potential despite a shortage of soil-moisture. Plants develop strategies for maintaining turgor by increasing root depth or developing an efficient root system to maximize water uptake, and by reducing water loss through reduced epidermal conductance (stomatal and lenticular), reduced absorption of radiation, by leaf rolling or folding and reduced leaf area (Turner, 1986; Mitra, 2001). Drought tolerance is the ability of plants to withstand water-deficit with low tissue water potential (Mitra, 2001). Plants that use tolerance mechanism maintain turgor through osmotic adjustment (accumulation of compatible solutes in the cell), increase cell elasticity, decreased cell volume and resistance to desiccation through protoplasmic resistance (Turner, 1986). Plants generally use more than one mechanism at a time to cope with drought.

Cowpea has been reported to be a drought tolerant crop (Ehlers and Hall, 1997; Singh *et al*., 1999a). The crop employs a combination of mechanisms that include escape, avoidance and tolerance. Cowpea drought escape results from its ability to hasten or delay its reproductive cycle (Gwathmey and Hall, 1992); avoidance results from its deep roots, strong stomatal sensitivity, reduced growth rate, leaf area reduction and selective moisture remobilization with major dedication to the upper leaves and growing tips (Turk *et al.*, 1980; Turk and Hall, 1980a; Mai-Kodomi *et al.*, 1999a; Singh *et al.*, 1999a); while tolerance results from its osmotic adjustment (Turk and Hall, 1980a; Mai-Kodomi *et al.*, 1999a; Chiulele and Agenbag, 2004).

Despite the considerable efforts made in identifying drought tolerance mechanisms in cowpea, exploitation of this information in breeding has been negligible. The only important progress registered so far has been the development of early maturing varieties such as IT84S-2246 and Bambey-21 that were released and widely adopted by farmers, particularly in West Africa (Agbicodo *et al.*, 2009). Such varieties are able to grow and yield a crop before the onset of the end-of-season drought that occurs in several locations.

The mechanisms of drought tolerance have been reported to confer some disadvantages to the varieties carrying them. For instance, a short duration variety usually yields less compared to that of normal duration; the mechanisms that reduce water loss (such as stomatal closure and reduced leaf area) usually result in reduced assimilation of carbon dioxide; osmotic adjustment increases drought resistance by maintaining plant turgor, but the increased solute concentration responsible for osmotic adjustment may have detrimental effect in addition to energy requirement for osmotic adjustment (Turner, 1979). The foregoing discussion suggests that incorporating certain mechanisms in an improved cultivar should be done focusing on the type of drought prevailing in the target environment. In addition, and as indicated by Mitra (2001), breeding for adaptation to drought must reflect a balance among escape, avoidance and tolerance while maintaining adequate productivity.

1.3 Gene action controlling quantitative traits

Gene action is the way genes express themselves. In quantitative genetics, gene action is divided into additive and non-additive effects. Non-additive gene action is further divided into dominance and epistasis (Robinson *et al.*, 1949; Falconer 1989). In the presence of additive gene action, characters of the heterozygotes in the F2 generations are the intermediate of the two parents (Falconer, 1989). The additive portion reflects the degree to which progenies are likely to resemble their parents. Non-additive gene action is observed when the additive model cannot adequately explain the variation (Falconer, 1989). According to Robinson *et al.* (1949) the size of dominance relative to the additive variance indicates the degree of dominance. The levels of dominance in the progeny can display a range from partial to over-dominance in relation to the mean of their parents.

1.3.1 Estimating gene action

To estimate gene action, a mating design is used to generate relatives which are grown in a set of environmental conditions and genetic variances calculated. There are several mating designs that have been reported in the literature and include, bi-parental crossing, North Carolina designs I, II and III and the diallel.

The diallel is the most widely used mating design and has been used by various authors to: determine general and specific combining ability to select corn maize populations for intra and inter-population breeding programmes and for hybrid development programme (Viana and Pratta, 2003), assess production traits among domestic, exotic and mutant germplasm of tomatoes (Prata *et al.*, 2003), assess yield and yield components in mungbean varieties for identifying parents to use in a breeding programme (Zubair *et al.*, 2007), determine combining ability and heterosis for stem brix and its associated traits and yield in sorghum (Makanda *et al.*, 2009; Makanda *et al.*, 2010), determine the combining ability for phaeosphaeria leaf spot and grain yield in maize (Sibiya *et al.*, 2011).

Information on combining ability analyses of cowpea drought tolerance, yield and yield related traits is scarce. Romanus *et al.* (2008) reported that additive gene action was more important than non-additive gene action in controlling yield, number of seeds per pod, pod length and hundred seed weight. Umaharan *et al.* (1997) also reported the prevalence of additive gene action over the non additive gene action for pod length, pod width, pod wall thickness, inter-seed space, hundred seed weight and seediness on vegetable cowpea. However, combining ability and heritability estimates are specific to the germplasm being tested and the environment where the germplasm is tested (Falconer, 1989). So, there is a need for investigating the gene action controlling drought tolerance, yield and yield related traits in germplasm adapted to Mozambique.

1.4 Genotype by environment interaction and yield stability

Genotype by environment interaction (G×E) is the differential genotypic expression to the change in environment (Yan and Hunt, 1998; Annicchiarico, 2002). This definition suggests that for detecting and quantifying G×E interaction for any trait, two elements are necessary, different genotypes and different environments. There are two types of genotype × environment interaction: cross-over or qualitative and non-cross-over or quantitative (Kang, 1998). Cross-over or qualitative interaction is the interaction observed when there is change in ranking of cultivars when grown in different environments while non-cross-over interaction is the interaction that is observed when genotypes show changes in magnitude of performance but the rank order of genotypes across environments remains unchanged (Kang, 1998). Studies have indicated that for cultivar development, the cross-over type of interaction is more important than the non-cross-over type. This is because the cross-over interaction complicates the selection of high yielding genotypes due to inconsistent performance of these genotypes across locations (Kang, 1998; Annicchiarico, 2002).

Genotype × environment interaction has been reported to be disadvantageous to crop improvement that targets broad adaptation, but it can also represent opportunities to genetic improvement for specific sites. It represents a barrier to crop improvement (Kang, 1998) because it can contribute to temporal and spatial instability of crop yields (Annicchiarico, 2002). Temporal instability, in particular, can impact negatively on farmers' income and, in case of staple crops, it can contribute to food insecurity at national and household level (Annicchiarico, 2002). On the other hand, G×E interactions may offer opportunities for selection and adoption of genotypes showing positive interaction with the location and its prevailing environmental conditions (exploitation of specific adaptation) or of genotypes with low frequency of poor yield or crop failure (exploitation of yield stability) (Simmonds, 1991; Ceccarelli, 1996). In addition, Yan and Hunt (1998) indicated that genotype × environment interaction motivates crop ecologists, agronomists and plant breeders to define ecological regions, mega-environments and ecotypes and to specify adaptation and yield stability of individual cultivars. Yan and Hunt (1998) concluded that exploring the positive aspects of G×E while avoiding the negative could provide a substantial opportunity for further improvement in food production worldwide.

The causes of genotype × environment interaction have been reviewed by various authors. Kang (1998) and Annicchiarico (2002) indicated that the major interaction can be expected when there is a wide variation between genotypes for morpho-physiological characters conferring resistance or avoidance to one or more stresses, and or wide variation between environments for incidence of the same stresses. Ceccarelli (1989) indicated that large G×E interactions have frequently been reported between pairs of environments with contrasting levels of one major stress defined as favourable when characterized by low stress and high mean yield and unfavourable when characterized by high stress and low yield. However, Annicchiarico (2002) inferred that large G×E interactions may also occur between pairs of unfavourable environments and even between pairs of moderately favourable environments possessing similar mean yield but with differing combinations of stresses or patterns of one major stress. Annicchiarico (2002) further reported that the type of varieties used may have an effect on G×E interaction. He indicated that pure lines, clones, single-cross hybrids tend to interact with the environment more than open-pollinated population, mixture of pure lines because of their lower richness in adaptive genes and therefore, more susceptible to variation in environmental conditions.

The accurate quantification and better understanding of the biological bases of genotype × environment interaction is crucial for improved food production. Quantification of genotype × environment interaction needs crop varieties to be evaluated in multi-environmental trials (METs). These trials can provide information for cultivar recommendation or for the final stages of selection of elite breeding material (Annicchiarico, 2002). Multi-environmental trials can be balanced or unbalanced (Yan and Hunt, 1998). The METs are said to be balanced when a set o genotypes are all evaluated in a set of environments so that a complete genotype by environment two-way table is available, or unbalanced when a different set of genotypes are evaluated in different sets of environments so that only an incomplete two-way table is available (Yan and Hunt, 1998).

Several methods have been proposed to analyse and interpret the genotype × environment interaction. These include: contrasts (Yan and Hunt, 1998), linear regression (Finlay and Wilkinson, 1963; Eberhart and Russell, 1966), multivariate analysis such as principal component analysis (Zobel *et al*., 1988) and additive main effect and multiplicative interaction (AMMI) (Zobel *et al.*, 1988; Gauch and Zobel, 1997). Recently, the genotype plus the genotype by environment interaction, commonly known as GGE biplot has been proposed (Yan *et al.*, 2000; Yan *et al.*, 2001; Yan, 2002; Yan and Tinker, 2005; Gauch, 2006; Yan *et al.*, 2007; Burgueno *et al*., 2008). The GGE biplot has been used in mega-environment analysis (Yan and Rajcan, 2002; Casanoves *et al*., 2005; Sarmonte *et al.*, 2005; Yan and Tinker, 2005; Dardanelli *et al.*, 2006), genotype and test environment evaluation (Yan and Rajcan, 2002; Blanche and Myers, 2006), trait association (Yan and Rajcan, 2002) and heterotic pattern analysis (Yan and Hunt, 2002).

The GGE biplot is constructed by plotting the two principal components (PC1 and PC2) derived from the singular value decomposition (SVD) of environmental centred data (GGE matrix) such that three component matrices are generated; the singular value matrix (array), the genotype eigenvector matrix, and the environment eigenvector matrix. From the GGE biplot the information concerning the "which-won-where" patterns or best genotypes and their winning environments, the interrelationship among test environments and the ranking of genotypes based on both mean performance and stability can be visually addressed (Yan *et al.*, 2000; Yan *et al.*, 2001; Yan, 2002).

Analyses of stability and genotype × environment interactions have been conducted in cowpea to assess: yield stability of cowpea genotypes under sole cropping and intercrop and with and without insecticide application (Blade *et al.*, 1992), genotype × row spacing and environment interaction (Cisse, 2001); stability of time to flowering (Craufurd *et al.*, 1996); stability of mixtures and pure lines (Eskine 1977); genotype × environment interaction in carbon isotope discrimination and seed yield (Ngugi *et al.*, 1994). In all these studies genotypes adapted to specific and to a wide range of environmental conditions were identified. However, none of these studies used the GGE biplot to analyse yield stability and genotype × environment interaction.

When the GGE biplot was applied to the yield data of ten years from the Ontario winter wheat performance trails, yearly winning genotypes and their winning niches were identified (Yan *et al*., 2000). From the collective analysis of the yearly biplots, two winter wheat mega-environments were identified in Ontario; the minor mega-environment of eastern Ontario and the major mega-environment of the southern and western Ontario (Yan *et al.*, 2000). Compared to other methods of analysing genotype by environment interaction and stability, the GGE biplot has the merit of showing graphically the which-won-where pattern of data (Yan *et al.*, 2000; Yan *et al.*, 2001). The which-won-where pattern enables the identification of mega-environments provided that it is repeatable over years (Yan *et al.*, 2001). In this situation, both genotype and genotype × environment interaction can be effectively exploited by selecting superior genotypes for each mega-environment (Yan, 2002). Yan *et al.* (2001) indicated that GGE biplot can still be useful to identify superior genotypes and test environments that facilitate identification of such genotypes even when the which-won-where pattern is not repeatable over years. Under that circumstances, Ramagosa and Fox (1993) and Yan and Hunt (1998) recommended to select genotypes based on yield stability and wide adaptation.

Two concepts of stability have been reported, the static or biological and the dynamic or agronomic stability (Kang, 1998). Under the static concept, a genotype is indicated to be stable when its performance does not change with change in environmental conditions while under the dynamic concept a genotype is considered to be stable when it yields well relative to the productive potential of test environments (Ramagosa and Fox, 1993). Hill *et al.* (1998) indicated that the methods used for assessing the dynamic stability derive their stability estimates from the analysis of G×E interaction.

1.5 Farmers involvement in breeding programmes

The development of high yielding cowpea varieties with enhanced resistance to biotic stress and tolerance to major abiotic stresses requires the involvement of all relevant stakeholders so that suitable varieties can be developed. There has been an increased awareness of the role of farmers' participation in agricultural research. Information obtained from different sources has suggested that the involvement of farmers in agricultural research can provide useful information that can contribute to increase crop productivity and adoption of new improved varieties (Sperling *et al.*, 1993; Banzinger *et al.*, 2000; Bellon, 2001). Experience from a maize project in Mexico indicated that using participatory methods it was possible to improve crop productivity and at the same time maintain or enhance maize diversity (Bellon, 2001).

Participatory methods have also been used in other crops including rice (Maurya *et al.*, 1988), beans (Sperling *et al.*, 1993), tree species (Franzel *et al.*, 1995), maize (De Groote *et al*., 2002) and cowpea (Kitch *et al.*, 1998; Okike *et al.*, 2002; Nkongolo *et al.*, 2009). In cowpea, Kitch *et al.* (1998) indicated that the use of participatory methods to select new improved varieties would improve the efficiency and effectiveness of the selection process because the selection intensities employed by farmers were similar to what would be employed by breeders. However, the use of participatory methods in cowpea research is still limited. Hence, many improved cowpea varieties have low adoption rates and impact minimally in peoples' livelihood and food security because they do not meet specific farmers' needs and preferences (Singh *et al.*, 1997; Inaizumi *et al.*, 1999).

Therefore, current and future breeding programmes must be conducted towards meeting the specific farmers' needs and preferences, target specific agricultural practices and production constraints for specific region and or develop cultivar with wide adaptation. This will require that farmers be involved in the breeding programme from the beginning to the variety release stage.

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Chapter Two

Participatory Plant Breeding: Assessment of Farmers' Perceptions and Preferences in Cowpea Varieties in Mozambique

Abstract

A participatory rural appraisal (PRA), participatory varietal selection (PVS) and market price survey were conducted in Bilene, Boane and Chibuto districts and Maputo to assess farmers' perceptions and preferences in cowpea varieties and to identify the major constraints affecting production. The study established that cowpea was an important crop, cultivated for its grain, leaves and fresh pods for household consumption and the market. Cowpea grain and leaves were important across the three districts in this study. Difference in accessibility to markets between districts determined differences in ranking of grain and leaves among districts. Grain was more important in Bilene and Chibuto districts which are situated far from the major urban centre of Maputo while leaves were more important in Boane, a district near the major market of Maputo. Fresh pods were important in Bilene district because it is situated in the main highway connecting Maputo and other provinces. Drought was the most important yield limiting constraint followed by aphids, bruchids and viral diseases. Farmers used various criteria to select cowpea varieties. These included high grain and leaf yield, large seed size, earliness, smoothness of the testa and potential marketability of the variety. The implication of this study for breeding is that different types of varieties need to be bred for different districts. Dual-purpose or grain type varieties need to be developed for districts situated far from the major markets while varieties for leaf production need to be developed for districts situated near urban centres. During the breeding process a selection index needs to be adopted whereby drought tolerance, high grain and leaf yield, large seed size, smooth testa, earliness, aphids and bruchids resistance should be integrated. High grain yield should receive high weight for varieties developed for the districts located far from major markets while high leaf yield would receive high weight for varieties developed for districts located near major markets.

2.1 Introduction

Cowpea (*Vigna unguiculata* L. Walp.) is an important crop in Mozambique. The crop is produced mainly in Nampula, Inhambane, Zambézia, Gaza and Maputo provinces under marginal environments characterized by low and unreliable rain and low soil fertility (INE, 2008). It is the fourth most cultivated crop after maize, cassava and groundnut in the country (INE, 2008). The crop is cultivated almost exclusively by smallholder women farmers for its grain, young leaves and fresh pods primarily for food and as a source of income, particularly for the resource-poor households. With its high protein content of about 25% in the grain (dry weight basis) (Bressani, 1985), cowpea plays an important role as a cheap source of protein. The crop also provides carbohydrates (Davis *et al.*, 1991), vitamins and minerals. In addition, cowpea improves the cropping systems and soil fertility by reducing soil erosion, suppressing weeds and fixing atmospheric nitrogen which contributes to increased yields of nitrogen demanding crops grown with or after it (Tarawali *et al.*, 2002).

Despite the cowpea's widespread production and importance in the country, the yields realised on farmers' fields are very low. On-farm cowpea grain yields range from 50 to 500 $kgha^{-1}$ (INIA, 2000) although yields as high as 2000 $kgha^{-1}$ and above have been recorded when well adapted and high yielding varieties were cultivated under good management practices (Muitia *et al.*, 2006). Drought stress coupled with high pressure from pests and diseases, poor agronomic practices, low soil fertility, lack of suitable varieties for farmers' needs and conditions and limited breeding work are amongst the major yield limiting constraints.

The lack of suitable varieties for farmers' needs and conditions has been reported as one of the reasons for low productivity and low rate of adoption of improved varieties by farmers (Nkongolo *et al*., 2009). Kitch *et al.* (1998) indicated that in many breeding programmes, farmers are only invited to participate in the later stages of a varietal development, whereby they are requested to choose amongst the lines selected by breeders. Such lines are in most cases selected based on high performance in multiple locations and seasons of uniform and favourable environments of the research stations. As a result, most released varieties lack traits preferred by farmers and do not suit farmers' needs and conditions and therefore, are generally not adopted.

The farmers need to be involved in the early stages of the breeding programme to ensure that appropriate technology adapted to their situations can be developed. There are reports suggesting that farmers' involvement in early stages of variety development may contribute to variety acceptance and eventual adoption (Maurya *et al.*, 1988; Sperling *et al*., 1993; Franzel *et al*., 1995). Sperling *et al*. (1993) indicated that farmers should be involved at the beginning of a breeding programme because they are the ones who decide whether the variety is good or not when they decide to or not to adopt. Moreover, selection criteria and perceptions of the best variety may differ between farmers and plant breeders.

Participatory methods have been used widely in agricultural research and have shown to be successful in obtaining crucial information that can contribute to increased crop productivity and adoption of new improved varieties (Sperling *et al.*, 1993). Participatory rural appraisal and participatory varietal selection were used to assess farmers' perceptions, preferences and selection criteria in rice (Maurya *et al.*, 1988), beans (Sperling *et al.*, 1993), tree species (Franzel *et al.*, 1995), maize (De Groote *et al*., 2002) and cowpea (Kitch *et al.*, 1998; Okike *et al.*, 2002; Nkongolo *et al.*, 2009). In cowpea, Kitch *et al.* (1998) indicated that the use of participatory varietal selection to select new improved varieties would improve the efficiency and effectiveness of the selection process given that the selection intensities employed by farmers were similar to what would be employed by breeders (Kitch *et al.*, 1998).

In this study, the participatory rural appraisal and participatory varietal selection were used to: (1) assess farmers' perceptions on major cowpea production constraints, and (2) determine their preferences and selection criteria of cowpea varieties. The combination of the two methods was done to accurately and easily gather the information required that could have been missed if only one method was used. In addition, market survey was conducted to identify the factors that determined the high preference for the black-eye cowpea seed types given that were not locally known.

The hypothesis tested was that farmers are aware of the major constraints limiting cowpea production in their production areas and have preferences and selection criteria for specific traits and cowpea cultivars.

2.2 Materials and Methods

To assess farmers' perceptions on major cowpea production constraints and preferences on what they perceive as a suitable variety for their needs and production conditions, three methods were used: participatory rural appraisal (PRA), participatory varietal selection (PVS) and a market survey.

2.2.1 Participatory Rural Appraisal (PRA)

The PRA was conducted in March 2009 in three major cowpea growing districts of southern Mozambique, namely, Bilene and Chibuto in Gaza province and Boane in Maputo province. Boane, Bilene and Chibuto are located 30, 160 and 200 km away from Maputo, respectively. The PRA consisted of interviews with key informants, focus group discussions and survey using semi-structured questionnaires. The total number of people interviewed was fifteen (15) for key informant, sixty (60) for focus group discussion and hundred (100) for the survey (Table 2.1). In all situations, the number of women was higher than that of men since the crop in the southern region is regarded as a women's crop. Across districts, 88% of women farmers participated in the focus group discussions and 90% in the surveys. In each district, the number of women farmers in focus group discussions and surveys ranged between 85 and 95%. The interviews were conducted with men and women in the same group. In view of their larger number in the groups, women were able to express their perceptions, preferences and selection criteria freely. The selection of communities and farmers for interviews was conducted with the assistance of extension officers. Three communities with a history of cowpea production were selected in each district, namely, Chimonzo, Chitlhango and Manzir in Bilene; Matola-rio, Chinonanquila and Tongogara in Boane; and Mabunganine, Malehice and Mutchuquete in Bilene. Selection of farmers to participate in the focus group discussions within any given community was based on knowledge and experience about the crop. Selection of farmers during the surveys was random whereby households' visits were conducted and any farmer found with experience of cowpea cultivation was interviewed. One farmer was interviewed per household. To ensure equal representation of the three communities in the district sample, equal number of farmers was selected from each community.

Table 2.1: Number of key informants and farmers involved in group discussions and surveys in Bilene, Boane and Chibuto districts

		Group discussion			Survey		
District	Key informants	Men	Women	Total	Men	Women	Total
Bilene	5	3	26	29	5	34	39
Boane	5	1	13	14	2	26	28
Chibuto	5	3	14	17	3	30	33
Total	15	7	53	60	10	90	100

Each PRA session started with the researcher explaining the objectives of the PRA. Discussions were made regarding the importance of the crop to the community, purpose of production, major production constraints, varieties grown and criteria used for selecting varieties. Farmers were asked to indicate the relative importance of cowpea to other crops, whether the crop was grown for home consumption or the market and the relative importance of the different cowpea products (grain, leaves and green pods). Farmers were then asked to list and rank the major constraints affecting cowpea production. Finally, they were asked to list and rank the various criteria that they use for selecting cowpea varieties for cultivation.

Ranking of farmers' priorities was conducted by dividing farmers randomly into three to four groups of four to seven farmers each. Using a checklist, team roles and responsibilities were assigned, and elements generated during the interview were evaluated. The elements were placed along the horizontal axis of the matrix, and the criteria for evaluating each item placed along the vertical axis of the matrix. Farmers then ranked each element according to its performance against each criterion, using a scale of 1 (highest value or most important) to 5 (lowest value or least important). Objects for ranking were purpose of cowpea cultivation, important products, production constraints, preferred traits and selection criteria.

A more inclusive survey was conducted afterwards in each district using a semi-structured questionnaire to check the perceptions on importance of the crop for the community, the major cowpea production constraints, selection criteria and preferences on cowpea varieties. The number of farmers involved in survey in each district is presented in Table 2.1. In total, one hundred (100) farmers participated in the survey.

2.2.2 Participatory variety selection (PVS)

A participatory variety selection (PVS) using twelve cowpea lines was conducted in March 2009 in the three districts where the PRA took place. Two separate evaluations were conducted; one based on field performance and the other based on seed characteristics (seed size, smoothness of the testa and seed color).

Field evaluations were planned for all the three districts where PRA was conducted. However, in Boane and Chibuto districts all the plants died during the seedling stage due to high temperature and severe droughts in January 2009 and evaluations were conducted in Bilene district only using twenty nine (29) farmers from two communities (15 farmers from Chitlhango and 14 farmers from Manzir). Selection of farmers was based on their willingness to participate as well as their experience on cowpea production. Care was taken to include people of different ages as well as men and women, but the number of men was small given that the crop in the southern region of Mozambique region is almost exclusively grown by women. Staff members from the Agricultural extension services participated in the selection of sites and farmers. Participating farmers were informed about their roles as well as the objectives and expectations of PVS activities. Each community trial was planted with twelve (12) cowpea varieties selected previously from 216 entries used in drought tolerance screening trials conducted in 2008. The selection of the twelve genotypes was based on their high yielding ability. The plot at each community trials comprised of 4 rows of 6 meters length with 90 cm and 25 cm row to row and plant to plant distances, respectively. The net plot comprised of 2 rows of 5 meters long. The trial was conducted in a randomized complete block design (RCBD) with 3 replicates. Farmers managed the community trials as a group. No fertilizers or pesticides were applied in the trials to mimic the farmers' production conditions.

Field evaluation took place when the crop was approaching physiological maturity. Due to differences in maturity amongst the tested varieties, some varieties were at pod filling stage whereas others were approaching physiological maturity at the time of PVS. To start varietal evaluation, each group of farmers was sub-divided into three groups of four to five farmers each. Farmers were asked to observe the different varieties in the field and evaluate them according to their own criteria.

Farmers were then asked to select and rank a maximum of five (5) varieties. Each of the groups was asked to record the criteria for each of their selections. Yield data was recorded afterwards from the net plots. Important characteristics of the twelve (12) varieties evaluated in the PVS activities are presented in Table 2.2.

The evaluation of twelve (12) cowpea varieties based on seed characteristics was conducted in all the three districts using remnant seed from the community trials. This activity took place after the end of each session of focus group discussion. Farmers were divided into three to four groups of four to seven farmers each and then asked to observe, evaluate and rank the twelve cowpea varieties.

Table 2.2: Important characteristics of twelve varieties used in PVS study

Accession name	Origin	Phenotypic characteristics
Bambey-21	Senegal	Medium seed size and white seeded, erect and determinate
Xingove	Moz	Large seed size, variegated, prostrate, high yield of soft leaves
FN-1-13-04	Moz	Large seed size, cream, prostrate, high yield of soft leaves
INIA-41	Moz	Large seed size, cream, prostrate
IT-18	Moz	Small seed size, brown, semi-erect, determinate, early
IT84S-2246	IITA	Medium seed size, brown, erect, rough testa, determinate
Maputo	Moz	Large seed size, grey, prostrate, high yield of soft leaves
Massava-11	Moz	Small seed size, white, prostrate, high yield of soft leaves
Sh-50	UCR	Large seed size, black eye, erect, determinate, early
Tete-2	Moz	Large seed size, variegated, prostrate
Timbawene Creme	Moz	Large seed size, cream, prostrate, high yield of soft leaves
UCR-P-24	UCR	Large seed size, black eye, erect, determinate, early

Note: Mozambican (Moz) accessions are non-improved, medium to late maturing excepting IT-18 which is improved and early. IITA = International Institute of Tropical Agriculture; UCR = University of California Riverside; IITA and UCR accessions are improved.

2.2.3 Market survey of different cowpea seed types evaluated

A survey was conducted in the three types of markets (open markets, food stores and supermarket) to assess the prices of different seed types (black-eye, “Nhantchengue” and others). Black-eye types are large white seeded with black hilum, Nhantchengue are all-white small-seeded while other types consist of a mixture of different colours and seed sizes. Prices of black-eye type were recorded in two supermarkets and one food store while those for Nhantchengue and mixture was recorded in two open markets.

2.2.4 Data analysis

Data was analyzed using GenStat 12.0 computer software (Payne *et al.,* 2009). Ranking of scores generated during interviews was conducted using Spearman's rank correlations coefficients. The percentage of farmers in different categories was also calculated. General analysis of variance was performed on yield and mean variety performance tested using least significant difference (LSD). Mean market price was averaged over three prices for black eye types and over two for Nhantchengue and seed mixtures.

2.3 Results

2.3.1 Importance of cowpea production in three districts of southern Mozambique

Farmers in the three districts indicated that they grew cowpea for household consumption (42.6%), market (18.2%) and household and market (39.3%) (Table 2.3). There were clear differences between districts in the aims of growing cowpeas. In Bilene and Chibuto cowpeas were grown mainly for household consumption while in Boane they were grown mainly for the market (Table 2.3). Grain and leaves were the most important products harvested from cowpea and were almost equally important across the districts. However, there were differences between districts; grain was more important than leaves in Bilene and Chibuto while leaves were more important in Boane. On the other hand, green pods and leaves were more important in Bilene (Table 2.4).

Table 2.3: Major purpose of growing cowpea in three districts in southern Mozambique

Purpose of growing cowpea	Respondents (%)			Average across	
	Bilene	Chibuto	Boane	Districts	Chi-Square
Household consumption	56.4	60.6	10.7	42.6	35.97**
Household consumption and market	38.5	36.4	42.9	39.3	0.56ns
Market	5.1	3	46.4	18.2	65.8**
Total respondents	39	33	28	100	

Note: *,** = Significant at 5% and 1%; ns = not significant

2.4 Most important cowpea product in three districts in southern Mozambique

Most important product	Respondents (%)			Average Across	
	Bilene	Chibuto	Boane	Districts	Chi-Square
Grain	46.1	57.6	28.6	44.1	9.7*
Leaves	30.8	39.4	71.4	47.2	19.4**
Green pods	23.1	3	0	8.7	36.2**
Total respondents	39	33	28	100	

Note: *,** = Significant at 5 and 1%; ns = not significant

2.3.2 Cowpea types grown by farmers in three districts of southern Mozambique

Three (3) main groups of cowpea were grown in the target districts: the “Nhabubo”, “Chinhawane” and “Nhantchengue”. Nhabubo are generally large seeded, high leaf producers, prostrate, late maturing with seed colour ranging from white, cream, red, light red, variegated to black. This group is grown for both grain and leaves mainly for household consumption. Nhantchengue is all-white small seeded, late maturing, prostrate and high leaf producer. This group, represented by variety Massava-11 is commonly grown for its grain for the market. Chinhawane is prostrate early maturing with seed size ranging from small to large and variable seed colour. This group is commonly grown in small plots for leaves, fresh peas and grain for household consumption. Farmers indicated that the most preferred characteristics in Chinhawane were early maturity, which allowed the cultivation of two crops per year, and indeterminate growth habit which enabled continuous harvesting of green pods and leaves. Among the three groups, Nhantchengue was the most preferred group because it fetched high market prices. However, farmers indicated that Nhantchengue was very susceptible to bruchids and drought. Cowpeas were grown as either pure crops or intercropped with other crops. Nhabubo and Nhantchengue were commonly grown in pure stands although mixtures with maize or cassava could be found.

2.3.3 Cowpea production constraints in the three districts of southern Mozambique

Drought, aphids, bruchids, Aletra, viral diseases and low soil fertility were the most important cowpea production constraints reported by farmers in the three districts of southern Mozambique. Drought was by far, the most important constraint limiting cowpea production in the region (Table 2.5). Most respondents in Bilene indicated that Nhantchengue (Massava-11) was the most drought-susceptible variety while in Chibuto and Boane the farmers did not perceive any differences among the grown varieties. Other highly ranked production constraints in all districts were aphids, bruchids and viral diseases. Farmers in Bilene perceived aphids as the second most important constraint followed by bruchids while in Chibuto bruchids were ranked second followed by aphids (Table 2.5). With regard to bruchids attack, farmers indicated that although all cowpea groups were attacked, “Nhantchengue” (Massava-11) was the most susceptible variety. Farmers in Bilene district indicated that this variety could be completely infested within one month of harvest. Farmers did not apply any strategy to alleviate the effects of drought, aphids and soil fertility. For the control of bruchids, farmers used ash, chilli or sand; for controlling viral diseases, farmers removed the infected plants and for Aletra they removed the Aletra plants. Observations from plants sampled in the field in the Faculty of Agronomy experimental farm, Nhacoongo and Umbeluzi, indicated that most drought susceptible genotypes were also susceptible to nematodes. However, nematodes were not perceived by farmers as an important cowpea production limiting constraint. Other important cowpea limiting constraints that were not perceived by farmers in the region included flower thrips and white flies. There were strong, positive and significant correlations among districts in ranking the major cowpea production constraints (Table 2.6) indicating that the rank order was consistent among the three districts.

Table 2.5: Cowpea major production constraints ranked by farmers in three districts in the southern Mozambique

Major production constraints	Districts			Mean derived scores	Rank
	Bilene	Chibuto	Boane		
Drought	1	1	1	1	1
Aphids	2	3	2	2.3	2
Bruchids	3	2	3	2.6	3
Viral diseases	5	4	4	4.3	4
Aletra	4				5
Low soil fertility	6	5		5.3	6
Others	7	6	5	6	7
Total respondents	29	17	14		

Table 2.6: Spearman's rank correlation of major cowpea production constraints among Bilene, Boane and Chibuto districts

	Bilene	Boane	Chibuto
Bilene	1.00		
Boane	0.82**	1.00	
Chibuto	0.75*	0.86 **	1.00

Note: *,** = Significant at 5 and 1% probability

2.3.4 Farmers' selection criteria of cowpea varieties

The various criteria used by farmers to select cowpea varieties are given in Table 2.7. The criteria and ranks shown are those indicated by at least two groups of farmers in each district. High grain and leaf yield were clearly the most important criteria as they were highly ranked by farmers groups in all districts. Large seed size was the third most important criterion and was highly stressed in Bilene and Chibuto. Earliness was fourth most important selection criterion across the three districts. The lowest ranked criterion was resistance to viral diseases. The correlations among the three districts of the ranking of selection criteria were strong, positive and significant (Table 2.8) indicating that the rank order was consistent among the three districts.

Table 2.7: Ranking of farmers' selection criteria in three districts in southern Mozambique

	Districts				
Criteria	Bilene	Boane	Chibuto	Mean derived scores	Rank
High grain yield	1	1	1	1	1
High leaf yield	2	2	2	2	2
Large seed size	3	4	3	3.3	3
Earliness	4	3	4	3.6	4
Long pod	5	6	7	5.6	5
Drought tolerance	7	5	6	6	6
Bruchids resistance	6	7	5	6	7
Aphids resistance	8	8	8	8	8
Resistance to viral diseases	9	9	9	9	9
Total respondents	29	17	14		

Table 2.8: Spearman's rank correlation of farmers' selection criteria among Bilene, Boane and Chibuto districts

	Bilene	Boane	Chibuto
Bilene	1.00		
Boane	0.93**	1.00	
Chibuto	0.95*	0.93 **	1.00

Note: *,** = Significant at 5 and 1% probability

2.3.5 Ranking of twelve cowpea varieties in southern Mozambique

The results of analysis of variance performed on yield of twelve varieties indicated significant differences between varities (Table 2.9). Trial and genotype x trial interactions were not significant indicating that the environmental conditions, management and genotype performance between the two trials were similar. Trial means in the two community trials were similar (1099 and 1090 kgha^{-1}). The mean yield over trials for all the entries was 1095 kgha^{-1} and the local improved variety, IT-18, produced the lowest mean yield (682 kgha^{-1}) whereas entries IT84S-2246, Maputo, Massava-11, UCR-P-24 and Tete-2 produced the highest yield with 1356, 1341, 1340, 1313, 1301 kgha^{-1}, respectively (Table 2.9).

During field evaluation, varieties IT84S-2246, Maputo, UCR-P-24, Sh-50 and Massava-11 were ranked as the top five most preferred varieties (Table 2.9). According to farmers' selection criteria, IT84S-2246 was ranked high because of its high grain yield; Maputo because of its high leaf yield and long pods; Sh-50 and UCR-P-24 because of their earliness and high grain yield and Massava-11 because of grain and leaf yield. Farmers' evaluation was consistent with varietal grain yield performance except that Tete-2, which ranked 5th in yield, was not amongst the top five ranked genotypes. The ranking of the varieties based on field performance was consistent among the two communities of Bilene since the correlation among the two communities was strong, positive and significant (Table 2.10).

Table 2.9: Cowpea yield and farmers' evaluation of 12 cowpea varieties in two community trials in Bilene district, Southern Mozambique

Variety name	Grain yield (Kgha^{-1})			Score		Mean derived scores	Rank
	Chitlhango	Manzir	Mean	Chitlhango	Manzir		
IT84S-2246	1364	1348	1356	1	2	1.5	1
Maputo	1351	1331	1341	2	1	1.5	2
UCR-P-24	1350	1276	1313	3	3	3	3
Sh-50	1222	1235	1228	4	4	4	4
Massava-11	1347	1333	1340	5	5	5	5
Xingove	1069	1097	1083	6	6	6	6
Tete-2	1273	1328	1301	9	7	8	7
FN-1-13-04	1097	1090	1094	7	11	9	8
Timbawene Crème	977	964	971	10	8	9	9
INIA-41	715	686	701	8	12	10	10
Bambey-21	734	722	728	12	9	11	11
IT-18	691	672	682	11	10	11	12
Mean	1099	1090	1095				
LSD0.05			30.8				
Total respondents				15	14		

Table 2.10: Spearman's rank correlation of farmers most preferred cowpea varieties based on field evaluation among Chitlhango and Manzir

	Chitlhango	Manzir
Chitlhango	1.00	
Manzir	0.88**	1.00

Note: *,** = Significant at 5 and 1% probability

Based on a combination of traits such as seed size, seed colour, smoothness of testa and other end-users traits, the top five ranked varieties in order of preference were UCR-P-24, Sh-50, Massava-11, Maputo and Timbawene crème (Table 2.11). Varieties UCR-P-24, Sh-50 are large seeded varieties, white colour with black eye and smooth testa; Massava-11 is small seeded white with smooth testa, Maputo is large seeded grey with smooth testa and Timbawene crème is large seeded cream with smooth testa. The ranking of the varieties based on seed characteristics was consistent among the three districts since the correlations among the three districts were strong, positive and significant (Table 2.10).

Table 2.11: Ranking of 12 cowpea varieties based on appearance and other end-users traits in three districts in southern Mozambique

	Districts			Mean derived	
Variety name	Bilene	Chibuto	Boane	scores	Rank
UCR-P-24	1	1	2	1.3	1
Sh-50	2	2	1	1.6	2
Massava-11	3	3	3	3	3
Maputo	6	5	4	5	4
Timbawene Crème	4	4	7	5	5
FN-1-13-04	5	6	5	5.3	6
Xingove	8	7	6	7	7
Tete-2	9	8	8	8.3	8
INIA-41	7	9	9	8.3	9
Bambey-21	10	10	10	10	10
IT84S-2246	11	11	11	11	11
IT-18	12	12	12	12	12
Total respondents	29	17	14		

Table 2.12: Spearman's rank correlation of farmers most preferred varieties based on seed characteristics among Bilene, Boane and Chibuto districts

	Bilene	Boane	Chibuto
Bilene	1.00		
Boane	0.92**	1.00	
Chibuto	0.97*	0.95 **	1.00

Note: *,** = Significant at 5 and 1% probability

2.3.6 Prices of three cowpea seed types in metical (Mt) at Maputo markets

The two markets surveyed had similar prices for Nhantchengue and for the mixtures (Table 2.13). The price of black eye varied among the two supermarkets and food store. The price of the black-eye types was almost four times that of Nhantchengue and mixtures. The price of Nhantchengue was also higher than that of mixtures.

Table 2.13: Price of different cowpea varieties or types in Mozambican markets

Cowpea type or variety	Price (Mt)
Black-eye peas	95
"Nhantchengue" (Massava-11)	27
Mixture	20

2.4 Discussion

The results indicated that cowpea is an important crop in the southern region of Mozambique. Farmers indicated that the cowpea was cultivated for grain, leaves and fresh pods for household consumption and market. There were clear differences among districts with regard to the aim of producing cowpea and importance of different cowpea products. Production for household consumption was a major objective in the districts situated far from Maputo while production for the market was the major objective for farmers in district near Maputo. Grain was more important in rural districts because it can be stored and transported to distant markets while leaves, which are perishable products, can only be easily sold in nearby markets. That explains why leaves were more important in Boane which is near Maputo. Fresh pods were important in the major high way to Maputo. Therefore, access to market was found to be the major force determining production of different cowpea products in different districts. These results suggested that the importance of cowpea in farmers' livelihood is strongly associated with its use as a source of income. The implications of these results for breeding are that different types of varieties are needed for specific needs and geographical areas. Varieties mainly oriented for grain production with some leaf production are needed for rural areas while varieties oriented for leaf production are needed for districts near major urban centres. In addition, varieties oriented for green pod production are needed for areas where the market for pods is developed.

Farmers in the three districts ranked drought as the most important production constraint followed by aphids, bruchids and viral diseases while low soil fertility was least ranked. These results are in agreement with Singh (1987) who indicated that drought was the most important constraint affecting cowpea production in southern Africa including Mozambique, Zimbabwe and Botswana. The consistency of ranking the constraints over the three districts suggested that these are the major constraints affecting cowpea production in the southern region of Mozambique and should be treated as priority objectives in future cowpea improvement programmes. Flower thrips, white fly and nematodes, despite being important in the southern Mozambique, were not perceived by farmers as important. Farmers did not use any control strategy for drought and aphids while in the case of bruchids they used ash, chilli and sand. However, there is no documented information on the usefulness of these methods in controlling this insect pest. Farmers also removed the plants infected with viral diseases and removed Aletra plants to control the infestation of cowpea plants with Aletra. Variety “Nhantchengue” was indicated to be the most susceptible to drought and bruchids. Farmers indicated that this variety can be infested within a month after harvest. Further studies are necessary to confirm these findings. Farmers did not perceive any varietal differences in response to infestation with viral diseases or aphids. This was most probably due to lack of genotypic variability for resistance to aphid and viral diseases among the available germplasm. These results indicated that breeding for improved drought tolerance should constitute a major breeding objective in cowpea to improve production and productivity in the country. In addition to drought tolerance, aphid and bruchids resistance should also be considered to ensure high yield and varietal acceptance by farmers.

Farmers used yield and yield related traits as the most important criteria to select cowpea varieties. High grain yield was the most highly ranked criterion followed by leaf yield, large seed size, earliness and long pods. Resistance related traits were least ranked despite the fact that farmers indicated drought and pests as the major cowpea production constraints. Apparently, farmers did not perceive the existence of genotypic variability for resistance. This suggests that in the selection process for new improved varieties, yield and yield related traits must constitute the primary selection criteria for a new improved variety to be accepted by farmers. In a conventional breeding programme, yield and yield related traits are the most important selection criteria. The agreement between farmers and breeders in some of the criteria used for selecting cowpea varieties suggests the need for collaborative work to improve the efficiency of selection. Given the importance of drought in limiting cowpea production, drought tolerance must be bred in a high yielding background. However, Subbarao *et al.* (1995) highlighted some of the problems associated with selection for yield in stress prone environments. They indicated that the most common problem is the difficulty in discriminating between genotypes on the basis of their yield in a low yielding environments compared to their performance in high-yielding ones. Under these circumstances, Muleba *et al.* (1997) proposed a strategy of combining genes for high yield and adaptation using parental lines that are highly adapted to extreme environmental conditions as the most effective. They described this strategy as the most suitable for mitigating yield losses due to environmental hazards in order to guarantee food security to resource-poor farmers. The high ranking of high grain and leaf yield indicated the role that these products play in peoples' livelihoods and food security. Cowpea grain and dried leaves are the most important food sources during the dry period (July to October) when other food sources are in limited supply.

Variety ranking using yield related traits was in close agreement with ranking using seed characteristics and other end-users traits except for variety IT84S-2246 which was ranked first using yield related traits and second last using seed characteristics. The change in ranking of IT84S-2246 is related to its rough testa which is not preferred locally. Varieties Sh-50 and UCR-P-24 were ranked third and fourth, respectively, using yield related traits and first and second, respectively, using seed characteristics. These varieties were not the highest yielding and are not known locally. The high ranking of these varieties is presumably explained by their high potential price in food stores. Kitch *et al.* (1998) indicated that high yield was an important criterion but market preferences were determinant for the selection of a variety. Market surveys conducted to determine the price of different cowpea types evaluated in this study indicated that the price of the black eye types was four times higher than that of the other seed types. Farmers' evaluation of cowpea varieties in the field was in agreement with yield performance except that Tete-2 was not amongst the top five ranked genotypes despite its high yield. The lower ranking of Tete-2 was probably associated with its leaves which are not tender and soft for vegetable preparations. The consistency of high yield as the most important criteria for selecting varieties indicated that this criterion should be considered as a major selection breeding in cowpea improvement programmes in order to ensure varietal acceptance and adoption. The fact that Tete-2 was not ranked among the top five varieties besides its high grain yield and the ranking of UCR-P-24 and Sh-50 as the most preferred varieties while they were not known locally indicated that farmers use other criteria than yield to select a variety.

The implications of these findings for genetic improvement of cowpea for smallholder farmers in the Southern region of Mozambique are that in the selection process to identify new improved varieties a selection index needs to be used that would include high grain yield, high leaf yield, drought tolerance, large seed size, earliness and characteristics determining market price. However, the weights within the selection index could vary between districts. Leaf yield would be allocated a higher weighting than grain yield in Boane while grain yield would be allocated a higher weight in Bilene and Chibuto.

2.5 Conclusions

The objectives of this study were: (1) to assess farmers' perceptions on major cowpea production constraints and, (2) determine their preferences and selection criteria of cowpea varieties. Based on the results obtained it is concluded that:

1. Farmers were aware of the constraints affecting cowpea production in their environments. Farmers ranked drought as the most important production constraint followed by aphids, bruchids, viral diseases

2. Farmers had a clear opinion of what they desire as a suitable variety for their needs and conditions.

   (a) High grain yield was the most important selection criterion followed by high leaf yield, large seed size and earliness. Potential marketability of the variety was not mentioned in the focus group discussion and participatory varietal selection but was identified as a major selection criterion.

(b) Varieties for leaf production would be desirable for districts situated near major urban centres while varieties for grain production would be desirable for districts situated in rural areas.

(c) Farmers used various criteria to select a cowpea variety and high grain yield was not always the most important criterion.

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Chapter Three

Assessment of Cowpea Genotypes for Variability in Drought Tolerance

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Abstract

A study was conducted at Chókwè Research Station, Mozambique, from June to October 2008, to assess cowpea genotypes for variability to drought tolerance. Two-hundred and sixteen (216) cowpea genotypes (136 early and 80 late maturing) were grown under drought stressed and non-stressed conditions. The early and late maturing genotypes were evaluated in separate experiments to ensure synchronization of flowering within a maturity group. Plants grown under non-stressed conditions were watered regularly from sowing to maturity while those in the stressed conditions were watered from sowing to flower bud initiation and thereafter, irrigation was withdrawn. Data on yield and yield components (number of pods per plant, number of seeds per pod and 100-seed weight) were recorded at physiological maturity and analysis of variance performed using the Mixed Models Residual Maximum likelihood (REML). Multivariate analysis was performed on stressed and non-stressed yield data and quantitative indices of drought tolerance (tolerance index, mean productivity, geometric mean productivity, stress intensity, stress susceptibility index and stress tolerance index) calculated. Drought stress reduced yields of both early and late maturing genotypes, but genotypes responded differently to the drought stress imposed indicating that genetic variability for drought tolerance existed. Biplot displays of quantitative indices of stress tolerance and genotypes yield showed that genotypes were distributed over the coordinate space indicating that genetic variability for drought tolerance existed amongst the tested germplasm with regard to yield and drought tolerance. According to their yielding ability and drought tolerance, genotypes were grouped into four categories; high yielding-drought tolerant (group A), high yielding-drought susceptible (group B), low yielding-drought tolerant (group C), and low yielding-drought susceptible (group D). Examples of genotypes in group A were Sh-50, UC-524B, INIA-24, INIA-120, IT96D-610 and Tete-2. Stress tolerance index was the best criterion for assessing genotypes for variability in drought tolerance because it enabled the identification of high yielding and stress tolerant genotypes (group A).

3.1 Introduction

Cowpea is an important crop in Mozambique where it is grown for its grain and leaves for household consumption and market. The crop is the fourth most cultivated after maize, cassava and groundnut (INE, 2008). Cowpea is grown exclusively under rainfed conditions and yields are extremely low. On-farm cowpea grain yields average less than 300 $kgha^{-1}$ although higher yields as much as 2000 $kgha^{-1}$ and above have been recorded when improved cultivars are grown as pure stands under high rainfall and adequate management practices (Muitia *et al.*, 2006). The low yields have been attributed to a number of biotic and abiotic stresses. Drought is the most important abiotic stress affecting cowpea production in the country due to high variability in amount and distribution of rainfall during the cropping season. Both intermittent and terminal droughts occur in the country but terminal drought is the most important because it impacts directly on yield formation.

Cowpea has been reported to be more drought tolerant than other crop species (Ehlers and Hall, 1997; Singh *et al.*, 1999a). The tolerance has been attributed to several drought-avoidance mechanisms that include deep rooting, strong stomatal sensitivity, reduced growth rate, leaf area reduction (Lawn, 1983; Mai-Kodomi *et al.,* 1999a; Singh *et al.,* 1999a; Turk and Hall, 1980a,b), delayed leaf senescence, hastened or delayed reproductive cycle (Gwathmey and Hall, 1992), osmotic adjustment (Chiulele and Agenbag, 2004; Mai-Kodomi *et al*., 1999a) and selective moisture remobilization with major dedication to the upper leaves and growing tips (Mai-Kodomi *et al.*, 1999a). However, the crop still suffers considerable yield reduction when exposed to severe drought stress during the vegetative growth and particularly during flowering and pod filling. Drought stress during flowering and pod filling is particularly important since it impacts negatively on flower development, pollination (Boyer and McPherson, 1975), pod setting and grain filling leading to reduced number of pods per plant and seed weight, and consequently low seed yield. Genetic variability of cowpea for drought tolerance that could be utilized in breeding programmes has been reported from various parts of the world (Hall, 2004; Itani *et al.*, 1992a,b; Singh and Matsui, 2002; Singh *et al.,* 1999b; Muchero *et al.*, 2008).

A large number of cowpea germplasm accessions has been evaluated for drought tolerance in various parts of the world and desirable lines identified. In addition, more germplasm lines still need to be evaluated in order to identify new and better adapted sources of drought tolerance under various environmental conditions. The most common method of screening cowpea genotypes for drought tolerance has been the use of: visual symptoms of wilting, plant death and recovery (Watanabe, 1998; Watanabe and Terao, 1998; Mai-Kodomi *et al.,* 1999a,b; Singh *et al.,* 1999a,b; Muchero *et al.,* 2008), physiological and morphological responses (Turk and Hall, 1980a; Turk *et al*., 1980; Itani *et al.,* 1992a,b; Chiulele and Agenbag, 2004), morphological and yield response of genotypes under stressed and non-stressed conditions (Matsui and Singh, 2003; Turk *et al*., 1980).

Several criteria have been used to quantify tolerance of genotypes to drought stress. Finlay and Wilkson (1963) and Eberhart and Russell (1966) proposed stability analysis as the most appropriate criterion of assessing genotypes for drought tolerance provided that the major component of variation in the environmental index could be attributed to moisture stress. Using this approach drought tolerance would be given by the intercept of genotype yield regressed on environmental index. Other authors proposed the use of quantitative indices of stress tolerance, which are based on the relative yield of genotypes under stressed (Ys) and non-stressed conditions (Yp). These include: drought response index (Ouk *et al.,* 2006), drought resistance index (Bidinger *et al*., 1987a,b), drought susceptibility index and stress intensity (Fisher and Maurer, 1978), mean productivity (Rosielle and Hamblin, 1981), geometric mean productivity and stress tolerance index (Fernandez, 1992; Kristin *et al*., 1997, Farshadfar and Sutka, 2003). Stress tolerance index has been indicated to be the most suitable for screening genotypes for drought tolerance because it enables the identification of high yielding and drought tolerant genotypes (Fernandez, 1992). Very few studies have used quantitative indices of stress tolerance to assess drought tolerance on cowpeas.

Therefore, this study was conducted to assess cowpea genotypes for variability in drought tolerance using the quantitative indices of stress tolerance such as stress intensity, mean productivity, tolerance index, stress susceptibility index, geometric mean productivity and stress tolerance index.

The hypothesis tested was that genotypic variability for drought tolerance exists amongst cowpea germplasm that could be exploited for breeding drought tolerant cowpea cultivars for Mozambique.

3.2 Materials and Methods

3.2.1 Site description and climatic conditions during the experimental period

The experiment was conducted at Chókwè Research Station (24^{o} 32' S; 33^{o} E; 33m above sea level) in Mozambique from June to October 2008. The temperatures at the station range between minimum of 12 and 25^{o}C and maximum of 22 and 34^{o}C. The minimum temperatures are experienced in July while the maximum are experienced in January. The station receives about 600mm of rainfall per year and the minimum rainfall takes place in July while the maximum takes place in January. Most of the rainfall occurs between November and March. The mean evaporation measured using an evaporation tank is about 1800mm per year and minimum evaporation takes place in May while maximum evaporation takes place in January. The soils at the station are clay loam with high water retention capacity and the area is semi-arid.

During the experimental period the minimum temperature ranged between 11.7^{o}C and 25.9^{o}C and maximum between 18.2^{o}C and 31.9^{o}C. The minimum temperatures were recorded in July and the maximum in October. The total rainfall received before stress impositions was 38.3mm. The lowest rainfall was recorded in July (3mm) while the highest was recorded in August (27.2mm). During the stress treatment no rainfall was received. The total evaporation measured using the evaporation tank was 673mm. The lowest evaporation took place in June (106.3mm) and the highest evaporation in September (174mm). The water deficit between the rainfall received and evaporation was made up through supplementary irrigation.

3.2.2 Trial description and data collection

Two hundred and sixteen (216) cowpea genotypes (136 early and 80 late maturing) including for checks were used in this study. The genotypes comprised a total of eight-six (86) landraces collected from farmers fields in Mozambique, seventy (70) germplasm accessions provided by the National Gene Bank at National Research Station (IIAM) and sixty (60) improved lines obtained from the University of California Riverside (UCR). The genotypes were divided into two groups based on maturity and evaluated separately to ensure synchronization of flowering time in each group. The experimental designs were 4×34 and 4×20 α-lattice designs with three replications for the early and late maturing genotypes, respectively. Each genotype was planted in a four-row plot of 5m long at inter- and intra-row spacing of 75cm and 25cm, respectively, making a plant population of 54,000 plants per hectare. Three seeds were planted per hill and seven days after germination, the weaker plants in each hill were removed leaving one plant per hill. Before planting, soil fertility analyses were conducted and fertilizer applied at the rate of 6 kg N: 12 kg P: 6 kg K ha^{-1}. The field was maintained free of weeds and insect pests throughout the experiment through weeding and insecticide application. Water stress treatment was imposed by withholding irrigation from flower bud emergence (50% of plants with flower buds) up to physiological maturity. In the non-stressed water regime, plants were watered regularly to field water capacity up to maturity. To avoid water seepage between treatments, the non-stressed water regime plots were established 30 meters away from the water stressed regime plots. Data were recorded on 36 plants from the two-centre rows of each plot leaving out two plants from the either side of the row. The parameters recorded were: number of pods per plant, number of seeds per pod, 100-seed weight in g and yield in $kgha^{-1}$.

3.2.3 Data analyses

Data on yield and yield components were analyzed using GenStat 12.0 computer software (Payne *et al.,* 2009). The mixed models residual maximum likelihood (REML) was used for computing variance components. The replications, rows, columns and their interactions were treated as random while the genotypes, water regime and their interaction were fixed. The model for REML analysis was as follows:

$$Y_{ijklm} = \mu + G_i + W_j + G{\times}W_{ij} + Linear\_c + Linear\_r + r_k + c_l + rc_{kl} + R_m + rR_{km} + cR_{lm} + rcR_{klm} + \varepsilon_{ijklm}$$

Where: μ is the general mean, G are genotype effects, W are the effects of water regime, G×W are the interaction effects of genotype by water regime, Linear_r and Linear_c are the spatial adjustments for the rows and columns, respectively, r are the row effects, c are the columns effects, rR are the row by replication interaction effects, R are replication effects, cR are the column by replication interaction effects, rcR are the interaction effects of rows, columns and replications, ε is the random term.

Quantitative indices of stress tolerance such as mean productivity (MP), tolerance index (TOL) (Rosielle and Hamblin, 1981); stress susceptibility index (SSI), stress intensity (Fischer and Maurer, 1978); geometric mean productivity (GMP) and stress tolerance index (Fernandez, 1992; Kristin *et al.,* 1997; Farshadfar and Sutka, 2003) were calculated using the following formulae:

1. Mean productivity (MP)

$$MP = \frac{Y_p + Y_s}{2}$$

2. Tolerance index (TOL)

$$TOL = Y_p - Ys$$

3. Stress susceptibility index (SSI)

$$SSI = \frac{Y_p - Y_s}{Y_p \times SI}$$

4. Stress intensity (SI)

$$SI = \frac{\bar{Y}_p - \bar{Y}_s}{\bar{Y}_p}$$

5. Geometric mean productivity (GMP)

$$GMP = \sqrt{Y_p \times Y_s}$$

6. Stress tolerance index (STI)

$$STI = \frac{Y_p \times Y_s}{\bar{Y}_p^{\,2}}$$

Where: Y_S and Y_P are the yields of each genotype under drought-stressed and non-stressed conditions and $\overline{Y_S}$ and $\overline{Y_P}$ are the mean yields of all genotypes under drought-stressed and non stressed conditions.

Stress intensity (SI) is classified into mild, moderate and severe. Stress intensity is mild when yield reduction is between 0 and 25%, moderate when yield reduction is situated between 25 and 50% and severe when yield reduction is between 50 and 100%.

Correlation analyses were conducted using yield and yield components data and calculated quantitative indices of stress tolerance. Principal component analysis was conducted using data recorded on yield and quantitative indices of stress tolerance.

3.3 Results

3.3.1 Results of 136 early maturing cowpea genotypes

3.3.1.1 Analysis of variance for yield and yield components

The analysis of variance (ANOVA) results of 136 genotypes are shown in Table 3.1. The genotypes, water regime and genotype × water regime interaction were highly significant (p<0.01) for all parameters studied (yield, number of pods per plant, number of seeds per pod and hundred seed weight). The linear adjustment for rows was not significant for all parameters studied (data not shown). The linear adjustment for columns was significant for yield, number of pods per plant and number of seeds per pod. Water regime explained a greater proportion of the variation observed in yield and number of pods per plant than genotypes and genotype × water regime interaction (Table 3.1).

Table 3.1: Analysis of variance for yield, number of pods per plant, number of seeds per pod and hundred seed weight of 136 cowpea genotypes grown under drought stressed and non-stressed conditions at Chókwè

		Wald statistics/DF			
Source	DF	Yield	Number of pods per plant	Number of seeds per pod	100-Seed weight
Replications	2				
Genotypes	135	162.20**	50.09**	23.60**	68.28**
Water regime	1	1406.77**	198.34**	16.69**	65.64**
Genotype × water regime	135	50.51**	27.82**	6.96**	4.74**
Adjusted for columns	1	6.29**	9.23**	6.96**	1.44ns
Error	540				

Note: *,** = Significant at 5% and 1%, respectively; ns = not significant

3.3.1.2 Performance of 136 cowpea genotypes under drought-stressed and non-stressed conditions

There were significant differences in yield and yield components between genotypes in both non-stressed and drought-stressed conditions (Table 3.2). The mean yields of genotypes under non-stressed and stressed conditions were 2134 and 1696 $kgha^{-1}$, respectively. The yield of genotypes ranged between 350 and 4500 $kgha^{-1}$ and 350 and 3300 $kgha^{-1}$ under non-stressed and stressed conditions, respectively. Under non-stressed conditions, genotypes INIA-19A, IT85F-3139, INIA-1, INIA-67C, VAR-50B, INIA-42F, Nhavanca, INIA-51, Namuesse-D, 85-867, Inhaca-E, INIA-11C, Sh-50 and UC-524B were high yielding and produced more than 3000 $kgha^{-1}$ while genotypes INIA-25, IT85F-2805, Yacine, IT86D-396, INIA-36H, IT97K-110-687, INIA-67B, IT86D-612, IT95K-181-9, Apagbaala, IT86D-1035, IT85F-1517, IT93K-693-2 and IT83D-338-1 were low yielding and produced less than 1100 $kgha^{-1}$ (Table 3.2). Under drought-stressed conditions, genotypes UC-524B, Sh-50, INIA-24, IT85F-2205, UCR-739, INIA-51A, FAEF-14-Inhaca-H, INIA-67C, INIA-1, INIA-19A and Nhavanca were high yielding and produced more than 2500 $kgha^{-1}$, while genotypes INIA-25, IT85F-2805, Yacine, IT86D-396, INIA-36H, IT97K-110-687, INIA-67B, IT86D-612, IT95K-181-9, Apagbaala, IT86D-1035, IT85F-1517, IT93K-693-2 and IT83D-338-1 were low yielding and produced less than 1100 $kgha^{-1}$ (Table 3.2).

Drought stress reduced yield and yield components but genotypes responded differently to the stress. The yield of genotypes IT85F-3139, INIA-19A, INIA-42F, VAR-50B, 85-867, INIA-51, INIA-1 and INIA-11C was reduced by more than 45% while that of Sh-50, UC-524B, Namuesse, Inhaca-I, INIA-25, Yacine, INIA-36H and IT83D-338-1 was not affected. The genotypes with severe yield reduction also had severe reduction in number of pods per plant. Greater yield reduction was mostly recorded in high yielding genotypes. In general, the low yielding genotypes did not register severe yield reduction. The number of seeds per pod and hundred seed weight were in general less affected by drought stress (Table 3.2).

Table 3.2: Yield, number of pods per plant, number of seeds per pod and 100-seed weight of a sub-set of 136 cowpea genotypes grown under stressed and non-stressed conditions at Chókwè

Yielding		Yield			Number of pods per plant			Number of seeds per pod			100-seed weight		
ability	Genotypes	Non-stressed	Stressed	Reduction (%)	Non-stressed	Stressed	Reduction (%)	Non-stressed	Stressed	Reduction (%)	Non-stressed	Stressed	Reduction (%)
High	INIA-19A	4403.0	1780.0	59.6	47	20	58.0	12	11	2.0	11.7	12.2	-4.1
	IT85F-3139	4129.0	1265.0	69.4	42	14	66.9	12	12	-2.1	20.2	17.9	11.5
	INIA-1	4088.0	2055.0	49.7	39	26	34.5	16	16	2.0	14.7	12.9	12.5
	INIA-67C	3907.0	2440.0	37.5	56	42	25.7	15	14	1.5	14.1	12.8	9.1
	Var-50B	3880.0	1812.0	53.3	28	15	47.5	16	14	8.5	14.1	11.9	15.5
	INIA-42F	3756.0	1604.0	57.3	37	22	39.8	14	15	-5.1	16.1	14.2	12.0
	Nhavanca	3737.0	2532.0	32.2	40	30	26.8	15	15	-5.4	16.5	15.4	6.9
	INIA-51	3660.0	1829.0	50.0	31	16	47.1	16	15	5.0	18.9	22.9	-21.2
	Namuesse-D	3555.0	2296.0	35.4	25	21	17.4	13	13	1.3	13.1	11.5	12.7
	85-867	3423.0	1536.0	55.1	54	24	55.7	11	12	-8.8	17.5	18.2	-3.9
	Inhaca E	3398.0	2177.0	35.9	38	26	30.9	13	13	-1.5	15.0	12.4	17.0
	INIA-11C	3368.0	1786.0	47.0	27	15	46.0	16	17	-7.7	13.6	13.3	2.2
	Sh-50	3340.0	3258.0	2.5	35	33	5.1	13	11	13.8	26.9	27.0	-0.7
	UC 524B	3299.0	3276.0	0.7	44	41	6.1	9	10	-11.6	26.2	24.3	7.2
Moderate	IT99K-407-8	2034.0	1827.0	10.2	26	24	8.0	9	10	-14.6	25.3	23.3	8.0
	97k-813-35	2029.0	1966.0	3.1	21	21	-0.9	14	11	22.8	16.5	14.0	15.1
	Melak	2027.0	1736.0	14.4	26	21	18.7	14	14	-1.2	18.7	17.1	8.5
	99k-205-9	2005.0	1938.0	3.3	24	23	6.5	11	12	-10.6	17.9	13.0	27.6
	IT86D-1048	1963.0	1279.0	34.8	27	22	17.3	12	12	-4.0	18.2	16.1	11.9
	Namuesse	1952.0	1933.0	1.0	27	26	2.4	15	14	7.7	11.4	10.7	6.1
	98k-2058	1945.0	1992.0	-2.4	25	27	-6.2	11	11	-0.8	16.7	14.4	13.9
	INIA-5E	1936.0	1756.0	9.3	21	23	-10.7	17	15	10.0	13.1	12.0	8.8
	INIA-71C	1934.0	1711.0	11.5	19	17	10.1	16	16	-0.4	14.7	13.8	6.1
	Namuesse-F	1920.0	1776.0	7.5	18	16	8.8	15	15	-3.6	11.7	10.2	12.6
	IT93K-2046	1905.0	1736.0	8.9	25	25	-2.8	12	9	31.6	21.4	22.7	-5.8
	IT83S-990	1864.0	1248.0	33.0	26	20	21.3	12	13	-9.2	16.0	13.4	16.7
	97k-819-118	1862.0	1908.0	-2.5	16	14	8.8	11	12	-12.2	23.7	27.5	-16.1
	Inhaca I	1859.0	1906.0	-2.5	22	24	-9.8	12	11	10.4	13.8	11.2	19.3
Low	INIA-25	1084.0	1150.0	-6.1	16	17	-6.5	16	16	1.8	11.9	10.9	8.4
	IT85F-2805	1075.0	976.0	9.2	15	13	16.5	13	12	3.3	12.1	11.2	7.9
	Yacine	1024.0	1060.0	-3.5	13	14	-7.0	10	11	-9.3	16.0	17.8	-11.5
	IT86D-396	1008.0	1055.0	-4.7	13	14	-8.3	11	12	-11.1	19.3	16.8	13.1
	INIA-36H	996.0	1005.0	-0.9	14	16	-14.4	14	13	9.6	13.2	12.9	2.7
	97k-110-687	961.0	993.0	-3.3	18	16	10.4	11	6	44.3	21.8	17.8	18.3
	INIA-67B	952.0	1009.0	-6.0	13	13	-2.2	14	13	2.3	13.1	12.5	4.7
	IT86D-612	864.0	910.0	-5.3	16	17	-2.9	11	12	-8.8	18.4	15.8	14.0
	IT95K-181-9	854.0	808.0	5.4	16	18	-8.8	11	12	-9.5	16.1	14.9	7.4
	Apagbaala	843.0	891.0	-5.7	10	11	-10.4	8	5	28.4	16.5	15.5	6.1
	IT86D-1035	832.0	861.0	-3.5	18	17	3.7	9	9	3.7	20.9	17.9	14.7
	IT85F-1517	535.0	579.0	-8.2	17	17	4.6	10	11	-13.7	15.7	14.0	10.9
	IT93K-693-2	511.0	427.0	16.4	9	7	16.9	8	8	-6.7	20.6	19.7	3.9
	IT83D-338-1	355.0	379.0	-6.8	16	18	-10.4	9	7	17.7	12.9	14.6	-12.9
Mean		2134.0	1696.0		24.5	22.7		12.4	12.8		16.5	15.6	
LSD		161.0	161.0	157.2	3.1	3.1	3.0	1.5	1.5	1.5	1.5	1.5	1.5
CV (%)		9.6	12.0		7.6	8.2		7.3	7.0		5.4	5.7	

Correlation analysis indicated that yield was only significantly correlated with number of pods per plant in both stressed and non-stressed conditions ($r=0.70$, $p<0.01$; $r=0.53$, $p<0.01$), respectively (Table 3.3 and 3.4).

Table 3.3: Correlations among yield, number of pods per plant, number of seeds per pod and 100-seed weight of 136 genotypes grown under non-stress conditions

	Yield	Pods per plant	Seeds per pod	100-seed weight
Yield	1.00			
Pods per plant	0.71**	1.00		
Seeds per pod	0.27	0.14	1.00	
100-seed weight	-0.04	-0.05	-0.48	1.00

Table 3.4: Correlations among yield, number of pods per plant, number of seeds per pod and 100-seed weight of 136 genotypes grown under drought-stressed conditions

	Yield	Pods per plant	Seeds per pod	100-seed weight
Yield	1.00			
Pods per plant	0.54**	1.00		
Seeds per pod	0.30	0.09	1.00	
100-seed weight	-0.01	0.23	-0.29	1.00

The stress tolerance indices of a subset of 136 early genotypes are indicated in Table 3.5. Genotypes that combined lower tolerance index and stress susceptibility index and higher mean productivity and stress tolerance index were drought tolerant. Examples of these genotypes are Sh-50, UC-524B, 98K-2058; 97K-819-118, Inhaca-I. In addition to drought tolerance, genotypes Sh-50 and UC-524B were high yielding. In contrast, genotypes that combined higher tolerance index and stress susceptibility index and lower mean productivity or stress tolerance index were susceptible. Examples of these genotypes are IT85F-3139, Var-50B, INIA-51, 85-867 and INIA-11C. Despite their drought susceptibility, IT85F-3139, Var-50B, INIA-51, 85-867 and INIA-11C were high yielding.

Table 3.5: Stress tolerance indices (TOL, MP, GMP, SSI and STI) of the sub-set of 136 late genotypes

Yielding ability	Genotype	Tolerance index (TOL)	Mean productivity (MP)	Geometric mean productivity (GMP)	Stress susceptibility index (SS)	Stress tolerance index (STI)
High	INIA-19A	1910	3477	3343	2.05	1.57
	IT85F-3139	2925	2690	2254	3.36	1.06
	INIA-1	1541	3347	3256	1.78	1.53
	INIA-67C	1333	3260	3191	1.62	1.50
	Var-50B	2123	2859	2654	2.58	1.24
	INIA-42F	1759	2914	2775	2.21	1.30
	Nhavanca	1260	3132	3068	1.59	1.44
	INIA-51	1653	2858	2734	2.13	1.28
	Namuesse D	1312	2928	2852	1.74	1.34
	85-867	1947	2473	2273	2.69	1.07
	Inhaca-E	1280	2799	2725	1.77	1.28
	INIA-11C	1651	2574	2438	2.31	1.14
	Sh-50	133	3305	3303	0.17	1.55
	UC-524B	78	3292	3292	0.11	1.54
Moderate	IT99K-407-8	261	1925	1920	0.60	0.90
	97K-813-35	127	1991	1989	0.27	0.93
	Melak	351	1884	1874	0.80	0.88
	99k-205-9	121	1979	1977	0.26	0.93
	IT86D-1048	744	1619	1574	1.77	0.74
	Namuesse	73	1931	1931	0.16	0.90
	98k-2058	6	1971	1971	0.02	0.92
	INIA-5E	82	1928	1927	0.18	0.90
	INIA-71C	11	1961	1961	0.03	0.92
	Namuesse-F	192	1843	1840	0.47	0.86
	IT93K-2046	229	1829	1823	0.54	0.85
	IT83S-990	677	1545	1505	2.07	0.71
	97k-819-118	9	1877	1877	0.02	0.88
	Inhaca I	6	1891	1891	0.02	0.89
Low	INIA-25	12	1104	1104	0.05	0.52
	IT85F-2805	163	1034	1030	0.68	0.48
	Yacine	13	1035	1035	0.06	0.49
	IT86D-396	8	1029	1029	0.04	0.48
	INIA-36H	18	1027	1027	0.08	0.48
	97K-110-687	16	972	972	0.08	0.46
	INIA-67B	8	976	976	0.04	0.46
	IT86D-612	11	890	890	0.06	0.42
	IT95K-181-9	107	816	814	0.54	0.38
	Apagbaala	6	862	862	0.03	0.40
	IT86D-1035	14	846	846	0.08	0.40
	IT85F-1517	11	558	558	0.08	0.26
	IT93K-693-2	132	465	460	1.17	0.22
	IT83D-338-1	7	382	382	0.01	0.18

Correlation analysis between quantitative indices of stress tolerance and stressed and non-stressed yield are presented in Table 3.6. The results indicated that the stress tolerance index was strongly and positively correlated with non-stressed yield, stressed yield, mean productivity and geometric mean productivity. The correlation between stress tolerance index and geometric mean productivity was one. Stress susceptibility index was correlated with tolerance index and non-stressed yield. The correlation between stressed and non-stressed yield was 0.71.

Table 3.6: Correlation among stressed (Ys) and non-stressed yield (Yp), mean productivity (MP), tolerance index (TOL), geometric mean productivity (GMP), stress susceptibility index (SSI) and stress intensity (STI) of 136 early maturing genotypes

	Ys	Yp	MP	TOL	GMP	SSI	STI
Ys	1.00						
Yp	0.71**	1.00					
MP	0.89**	0.95**	1.00				
TOL	0.07	0.75**	0.52	1.00			
GMP	0.92**	0.93**	0.99**	0.45	1.00		
SSI	-0.09	0.60**	0.35	0.94**	0.28	1.00	
STI	0.92**	0.93**	0.99**	0.45	1.00**	0.28	1.00

Principal component analysis and biplot displays of 136x7 data matrix is illustrated in Figures 3.1. The PC1 explained 83.93% of the total variation in the data matrix and had high correlation among non-stressed yield (Yp), stress tolerance index (STI), geometric mean productivity (GMP) and mean productivity (MP). This dimension can be named as the yield potential-mean productivity component, which separates the high yielding from the low yielding genotypes. Because the angles and the directions between the attribute vectors indicate the strength and the direction of the correlation between two attributes, the biplot indicates that there was significant and positive correlation between stress tolerance index and geometric mean productivity, stress tolerance index and mean productivity, stress tolerance index and stressed yield, and stress tolerance index and yield potential. The PC2 explained 16.05% of the total variation and had positive correlation with stressed yield and negative correlation with tolerance index and stress susceptibility index. Thus, this dimension can be called stress tolerance dimension and it separates stress tolerant from stress susceptible genotypes. In relation to the two components of the biplot, the genotypes fell into distinct clusters that corresponded to their yield potentials and stress-tolerance. Stress tolerant attributes STI, GMP, MP and Ys were correlated with genotypes FAEF-14-Inhaca-H, INIA-24, INIA-51A, IT85K-2205, Sh-50, UCR-739 and UC-524B which represent the cluster of higher yielding and stress tolerant genotypes. The stress tolerant attributes SSI and TOL were correlated with high yielding and stress susceptible genotypes such as INIA-11C, INIA-11D, INIA-42F, INIA-51, IT85F-867, IT85F-3139 and Var50B. Genotypes were distributed over the biplot space according to their yielding ability and adaptation to stress or non-stress environments.

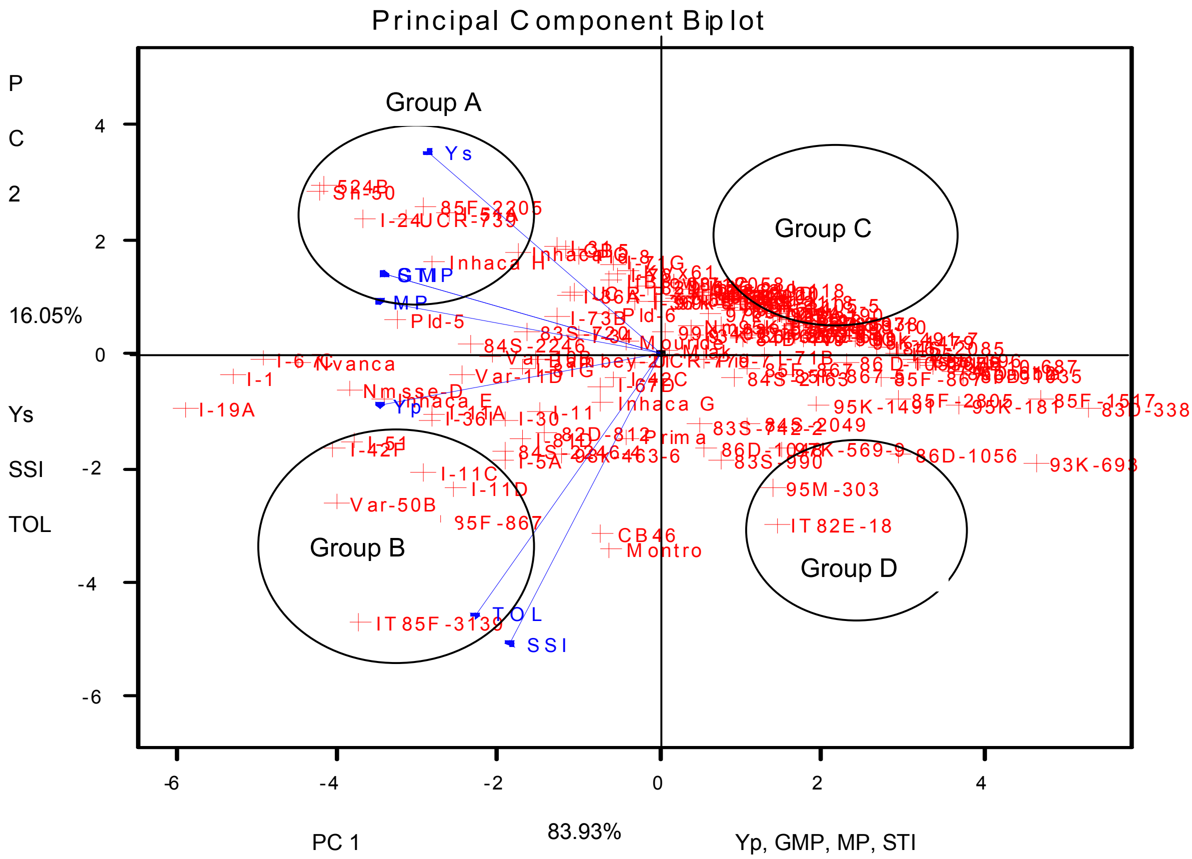

Figure 3.1: Biplot display of mean productivity (MP), geometric mean productivity (GMP), tolerance index (TOL), stress susceptibility index (SSI), stress intensity (STI) and yields of 136 genotypes grown under stressed and non-stressed conditions.

3.3.2 Results of 80 late maturing cowpea genotypes

3.3.2.1 Analysis of variance for yield and yield components

The analysis of variance (ANOVA) results of 80 late maturing genotypes are shown in Table 3.7. The genotypes, water regime and genotype × water regime interaction were highly significant ($p<0.01$) for all parameters studied (yield, number of pods per plants, number of seeds per pod and hundred seed weight). The linear adjustment for rows was not significant for all parameters studied (data not shown). The linear adjustment for columns was significant for yield, number of pods per plant and number of seeds per pod. Water regime explained a greater proportion of the variation observed in all parameters than genotypes and genotype × water regime interaction (Table 3.7).

Table 3.7: Analysis of variance for yield, number of pods per plant, number of seeds per pod and hundred seed weight of 80 late maturing cowpea genotypes grown under water stressed and non-stressed conditions at Chókwè

		Wald statistics/DF			
Source	DF	Yield	Number of pods per plant	Number of seeds per pod	100-Seed weight
Replications	2				
Genotypes	79	39.91**	25.09**	15.09**	171.80**
Water regime	1	564.89**	285.41**	32.78**	3095.18**
Genotype × water regime	79	13.60**	7.68**	2.84**	36.35**
Adjusted for columns	1	13.30**	7.89**	3.71**	0.21ns
Error	316				

Note: *,** = Significant at 5% and 1%, respectively; ns = not significant

3.3.2.2 Performance of cowpea genotypes under drought-stress and non-stress conditions

The yield and yield components of genotypes varied in both stress and non-stress conditions (Table 3.8). The mean yields of genotypes under non-stressed and stressed were 2219 and 1567 kgha^{-1}, respectively. The yield of genotypes ranged between 800 and 4300 kgha^{-1} and 400 and 3300 kgha^{-1} under non-stressed and stressed conditions, respectively. Under non-stressed conditions, genotypes N'diambour, FN-3-13-04, IT83D-442, Timbawene moteado, Zimbabwe, INIA-120, Massava-5, IT97K-556-6, Xingove, 24-125B-1, IT96D-610, INIA-72 and Tete-2 were high yielding and produced more than 3000 kgha^{-1}, while genotypes INIA-19C, KVx403, Suvita-2, IT89KD-288, 98K-1382, CC-27, IT98K-317-2, CP-2, Petite-n-green, IT90K-284-2, IT00K-901-6, IT98K-698-2, KVx525 and FN-2-14-04 were low yielding and produced less than 1300 kgha^{-1} (Table 3.7). Under drought-stressed conditions, genotypes INIA-120, IT96D-610, Tete-2, Massava-14 and Var-3A were high yielding and produced more than 2500 kgha^{-1} while genotypes INIA-19C, KVx403, Suvita-2, IT89KD-288, 98K-1382, CC-27, IT98K-317-2, CP-2, Petite-n-green, IT90K-284-2, IT00K-901-6, IT98K-698-2, KVx525 and FN-2-14-04 were low yielding and produced less than 1300 kgha^{-1} (Table 3.8).

Drought stress reduced yield and yield components but genotypes responded differently to drought stress. The yield of genotypes Zimbabwe, Xingove, IT83D-442, N'diambour, Massava-5 and Massava-11 was reduced by more than 50% while that of genotypes INIA-120, IT96D-610, Tete-2, IT95K-201-15, CC-36, Ecute, KVx403 and FN-2-14-04 was not affected (Table 3.8). The genotypes with severe yield reduction also registered severe reduction in number of pods per plant. In general, severe yield reduction was recorded on high yielding genotypes than in low yielding ones. The number of seeds per pod and hundred seed weight were in general less affected by drought stress.

Table 3.8: Yield, number of pods per plant, number of seeds per pod and 100-seed weight of a sub-set of 80 cowpea genotypes grown under stressed and non-stressed conditions at Chókwè

Yielding		Yield			Number of pods per plant			Number of seeds per pod			Hundred seed weight		
ability	Genotype	Non-stressed	Stressed	Reduction (%)	Non-stressed	Stressed	Reduction (%)	Non-stressed	Stressed	Reduction (%)	Non-stressed	Stressed	Reduction (%)
High	N'diambour	4300.0	1719.0	60.0	67	31	54.3	10	10	-0.1	18.5	16.5	10.8
	FN-2-13-04	3964.0	2037.0	48.6	61	28	54.6	14	15	-6.7	21.9	18.7	14.7
	IT83D-442	3918.0	1294.0	67.0	54	19	65.7	15	12	16.3	15.3	13.7	10.4
	Timbawene moteado	3740.0	2142.0	42.7	34	26	22.7	15	14	3.5	20.8	18.5	11.1
	Zimbabwe	3636.0	709.0	80.5	38	9	77.1	16	15	10.0	18.9	16.5	13.1
	INIA-120	3507.0	3118.0	11.1	49	45	7.7	10	11	-2.7	19.0	16.0	15.5
	Massava-5	3445.0	1467.0	57.4	51	18	63.7	14	14	0.8	26.7	22.7	14.8
	IT97K-556-6	3435.0	1774.0	48.4	34	22	34.0	10	10	1.1	24.3	21.2	12.6
	Xingove	3353.0	905.0	73.0	45	17	62.1	13	12	8.3	22.6	20.5	9.2
	24-125B-1	3186.0	1758.0	44.8	37	24	34.8	13	10	27.0	18.3	16.7	9.0
	IT96D-610	3105.0	3066.0	1.3	43	45	-4.3	12	11	9.2	19.9	20.1	-1.0
	INIA-72	2946.0	2444.0	17.0	48	44	9.5	14	13	6.3	12.1	11.1	8.2
	Tete-2	2924.0	2890.0	1.2	33	31	3.8	12	11	6.7	20.1	20.8	-3.3
Moderate	INIA 17G	2278.0	2360.0	-3.6	36	37	-1.0	15	13	10.5	11.6	12.6	-8.5
	IT95K-207-15	2269.0	2238.0	1.4	36	33	7.9	10	11	-9.1	19.4	20.4	-5.2
	EP2-Kunde 2	2263.0	1473.0	34.9	27	18	32.7	12	11	6.2	19.0	20.7	-8.8
	INIA 19F	2262.0	2288.0	-1.1	26	24	8.2	16	15	3.9	14.6	13.5	7.8
	KVx396-4-4	2240.0	1404.0	37.3	38	15	61.4	12	11	13.8	15.7	16.8	-7.3
	IT84D-460	2222.0	1911.0	14.0	37	27	25.9	11	12	-8.5	14.4	16.4	-13.9
	Massava-11	2187.0	910.0	58.4	36	16	55.6	14	13	8.4	20.9	18.3	12.8
	Maputo	2182.0	1356.0	37.9	20	16	21.0	14	15	-6.4	20.3	19.8	2.3
	CC-36	2112.0	2063.0	2.3	29	30	-3.4	14	10	25.4	17.1	15.3	10.6
	Ecute	2083.0	2194.0	-5.3	15	17	-9.4	16	15	3.4	17.8	18.8	-5.6
	58-57	2052.0	1490.0	27.4	31	25	20.8	11	11	3.1	12.3	12.3	0.0
	IT98K-498-1	2025.0	1410.0	30.4	23	19	17.0	10	11	-8.4	18.3	18.2	0.8
	IT81D-1137	1998.0	1193.0	40.3	24	17	28.9	14	13	3.0	25.2	22.8	9.5
	INIA-41	1989.0	1666.0	16.2	22	21	8.7	11	11	1.6	24.3	24.1	0.9
Low	INIA 19C	1262.0	1359.0	-7.7	15	16	-4.7	15	16	-7.3	14.3	13.1	8.3
	KVx403	1223.0	1184.0	3.2	14	13	2.0	13	13	-2.1	19.1	18.0	5.5
	SuVita2	1117.0	1228.0	-9.9	14	16	-13.6	12	12	0.9	21.0	19.7	6.1
	IT89KD-288	1044.0	1127.0	-8.0	18	16	11.9	9	8	10.1	19.5	20.2	-3.4
	98k-1382	1041.0	642.0	38.3	19	8	56.0	13	12	2.4	18.7	16.9	9.7
	CC-27	1039.0	1159.0	-11.5	19	18	6.9	10	10	-3.6	20.1	17.1	15.1
	IT98K-317-2	1012.0	1021.0	-0.9	15	15	-0.1	12	12	3.1	16.6	16.7	-0.4
	CP2	982.0	529.0	46.1	14	10	31.0	12	10	14.5	14.1	15.1	-7.1
	Petite-n-green	976.0	1096.0	-12.3	12	12	2.4	14	13	8.0	16.0	15.8	1.4
	IT90K-284-2	968.0	1082.0	-11.8	13	13	-5.2	9	10	-14.6	20.6	20.6	0.0
	IT00K-901-6	916.0	1039.0	-13.4	14	16	-12.4	10	12	-12.6	19.6	18.5	5.3
	IT98K-698-2	900.0	968.0	-7.6	11	13	-14.6	10	11	-12.4	18.7	18.3	1.8
	KVx525	858.0	946.0	-10.3	9	11	-19.0	12	12	0.5	20.0	20.7	-3.4
	FN-2-14-04	828.0	801.0	3.3	10	10	1.5	15	14	5.6	21.6	19.5	9.8
Mean		2219.0	1567.0		27	21		13	12		22.2	18.1	
LSD		338.9	338.9	331.2	6	6	6.1	2	2	1.6	1.1	1.1	1.09
CV (%)		9.6	12.4		14	18		8	9		2.9	3.7	

Correlation analysis indicated that yield was only significantly correlated with number of pods per plant in both stressed and non-stressed conditions (r=0.83, p<0.01; r=0.74, p<0.01), respectively (Table 3.9 and 3.10).

Table 3.9: Correlations among yield, number of pods per plant, number of seeds per pod and 100-seed weight of 80 late maturing genotypes grown under non-stress conditions

	Yield	Pods per plant	Seeds per pod	100-seed weight
Yield	1.00			
Pods per plant	0.8335**	1.00		
Seeds per pod	0.1383	0.0024	1.00	
100-seed weight	0.1217	-0.0170	-0.0507	1.00

Table 3.10: Correlations among yield, number of pods per plant, number of seeds per pod and 100-seed weight of 80 late maturing genotypes grown under drought-stressed conditions

	Yield	Pods per plant	Seeds per pod	100-seed weight
Yield	1.00			
Pods per plant	0.7394**	1.00		
Seeds per pod	0.1452	0.0474	1.00	
100-seed weight	0.0380	-0.1745	-0.1101	1.00

The stress tolerance indices of a sub-set of 80 late genotypes are indicated in Table 3.11. Genotypes that combined lower tolerance index and stress susceptibility index and higher mean productivity and stress tolerance index were drought tolerant. Examples of these genotypes are INIA-120, IT96D-610, INIA-72, Tete-2, INIA-17G, INIA-19F and IT95K-207-15. In addition to drought tolerance, genotypes INIA-120, IT96D-610, INIA-72 and Tete-2 were high yielding. In contrast, genotypes that combined higher tolerance index and stress susceptibility index and lower mean productivity or stress tolerance index were susceptible. Examples of these genotypes are IT83D-442, Zimbabwe, Massava-5 and Xingove. Despite their drought susceptibility, IT83D-442, Zimbabwe, Massava-5 and Xingove were high yielding.

Table 3.11: Stress tolerance indices (TOL, MP, GMP, SSI and STI) of the sub-set of 80 late genotypes

Yielding ability	Genotype	Tolerance index (TOL)	Mean productivity (MP)	Geometric mean productivity (GMP)	Stress susceptibility index (SSI)	Stress tolerance index (STI)
High	Ndiambour	2766	3019	2683	2.13	1.21
	FN-2-13-04	2102	2995	2796	1.77	1.26
	IT83D-442	2785	2622	2212	2.36	1.00
	Timbawene moteado	1755	2953	2817	1.55	1.27
	Zimbabwe	3113	2164	1501	2.85	0.68
	INIA-120	568	3309	3289	0.51	1.48
	Massava-5	2166	2445	2178	2.10	0.98
	IT97K-556	1849	2600	2422	1.79	1.09
	Xingove	2608	2135	1687	2.58	0.76
	24-125B-1	1585	2492	2362	1.64	1.06
	IT96D-610	204	3076	3074	0.22	1.39
	INIA-72	687	2698	2669	0.76	1.20
	Tete-2	220	2898	2893	0.24	1.30
Moderate	INIA-17G	85	2325	2325	0.10	1.05
	INIA19F	142	2294	2293	0.20	1.03
	IT95K-207-15	196	2262	2258	0.26	1.02
	EP-Kunde-2	969	1847	1777	1.41	0.80
	KVx396-4-4	1015	1809	1734	1.47	0.78
	IT84D-460	496	2041	2006	0.66	0.90
	Massava-11	1451	1544	1348	2.14	0.61
	Maputo	1005	1755	1664	1.44	0.75
	Ecute	59	2157	2156	0.09	0.97
	CC-36	227	2072	2067	0.31	0.93
	58-57	736	1766	1724	1.15	0.78
	IT98K-498-1	801	1713	1649	1.20	0.74
	IT81D-1137	991	1590	1509	1.62	0.68
	INIA-41	502	1816	1790	0.87	0.81
Low	INIA19C	99	1327	1326	0.24	0.60
	KVx403	214	1206	1200	0.53	0.54
	SuVita2	50	1170	1169	0.14	0.53
	IT98k-1382	586	853	798	1.75	0.36
	IT89KD288	114	1083	1081	0.33	0.49
	CC-27	66	1087	1087	0.19	0.49
	98K317-2	158	1025	1020	0.42	0.46
	Petite-n-green	50	1057	1056	0.16	0.48
	IT90K-284-2	53	1034	1034	0.16	0.47
	CP2	649	731	654	2.07	0.29
	IT00K-901-6	57	980	979	0.17	0.44
	IT98K-698-2	116	927	924	0.38	0.42
	KVx525	80	908	907	0.27	0.41
	FN-2-14-04	215	799	786	0.82	0.35

Correlation analysis among drought tolerance indices and stressed and non-stressed yield are presented in Table 3.12. The results indicated that stress tolerance index correlated strongly and positively with non-stressed yield, stressed yield, mean productivity and geometric mean productivity. The correlation between stress tolerance index and geometric mean productivity was one. Stress susceptibility index was correlated with tolerance index and non-stressed yield. The correlations between non-stressed and stressed yield was 0.51.

Table 3.12: Correlation among mean productivity (MP), geometric mean productivity (GMP), tolerance index (TOL), stress susceptibility index (SSI), stress intensity (STI), stressed (Ys) and non-stressed yield (Yp) for 80 genotypes

	Ys	Yp	MP	TOL	GMP	SSI	STI
Ys	1.00						
Yp	0.51**	1.00					
MP	0.82**	0.91**	1.00				
TOL	-0.24	0.71**	0.36	1.00			
GMP	0.90**	0.83**	0.98**	0.20	1.00		
SSI	-0.47	0.46	0.08	0.90**	-0.07	1.00	
STI	0.90**	0.83**	0.98**	0.20	1.00**	-0.07	1.00

Principal component analysis and biplot displays of 80x7 data matrix are illustrated in Figures 3.2. In the 80x7 data matrix, the PC1 explained 72.32% of the total variation and had high correlation between yield potential, geometric mean productivity, mean productivity and stress tolerance index. This dimension can be named yield potential-mean productivity and separated genotypes with high yield potential-mean productivity from genotypes with low yield potential-mean productivity. Positive correlation was observed between stress tolerance index and geometric mean productivity, stress tolerance index and mean productivity, stress tolerance index and stressed yield and stress tolerance index and yield potential. The PC2 explained 27.52% of the total variation and had correlation with stressed yield, stress susceptibility index and tolerance index. This dimension can be named stress tolerance dimension and it separated stress tolerant genotypes from stress susceptible genotypes. In relation to the two components of the biplot, the genotypes fell into distinct clusters that corresponded to their yield potential and stress-tolerance. Stress tolerance attributes STI, GMP, MP and Ys were correlated with genotypes INIA72, INIA-120, IT96D-610, Massava-14, Tete-2 and Var3A which represent the high yielding and stress tolerant genotypes. Genotypes IT83D-442, Massava-5, N'diambour, Xingove, Zimbabwe were correlated with SSI and TOL. Genotypes were distributed over the four quadrants of the biplot space according to their yield potential and stress tolerance.

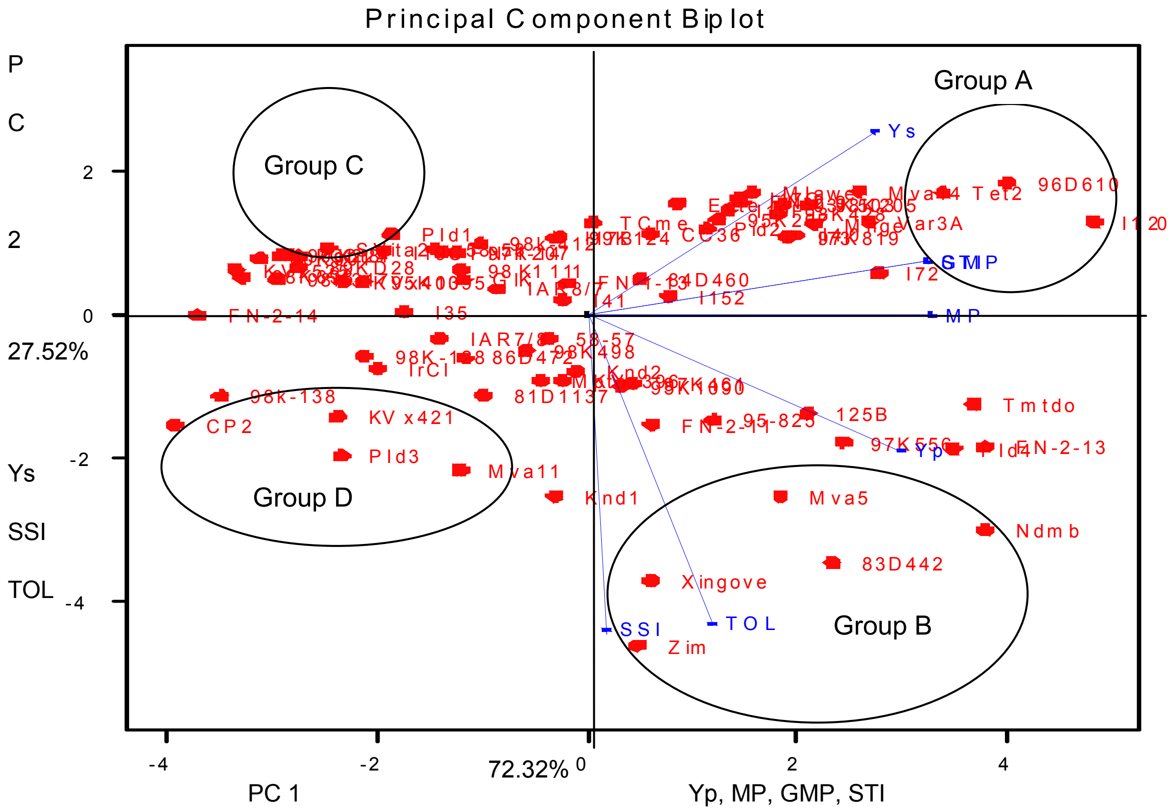

Figure 2: Biplot display of mean productivity (MP), geometric mean productivity (GMP), tolerance index (TOL), stress susceptibility index (SSI), stress intensity (STI) and genotype yields of 80 genotypes grown under moderate stress (SI=0.30) and non-stressed conditions.

3.4 Discussion

Genetic variation is an essential prerequisite for establishing any crop improvement programme. In this study, genotypic variation for yield and yield components was detected in both early and late genotypes grown under drought-stressed and non-stressed conditions suggesting that breeding for improved yield would be possible using the current germplasm. The strong and positive correlation between yield and number of pods per plant suggested that yield improvement would be achieved by selecting for the number of pods per plant. The high yielding genotypes produced three to five times higher yields than the low yielding ones but under drought-stressed conditions, some genotypes produced similar yield as the low yielding genotypes suggesting that some low yielding genotypes were stable across environments. The drought stress treatment applied was mild to moderate (SI=0.21 for early; SI=0.30 for late genotypes), but the yield of genotypes under stressed conditions was 21% and 30% lower compared to that of non-stressed conditions for the early and late maturing genotypes, respectively. The moderate stress suggested that the high water-holding capacity of soils at Chókwè was conducive for gradual drying. Furthermore, the low evaporation rate that took place during the winter season gave opportunity for physiological adaptation of cowpea genotypes.

The tested genotypes responded differently to drought stress imposed indicating that genetic variability for drought tolerance existed amongst the tested germplasm. For example, the yield of genotypes Namuesse, Zimbabwe, Timbawene-moteado, Massava-5, Massava-11, Xingove and FN-2-13-04 was severely reduced by drought while that of genotypes Sh-50, UC-524B and IT96D-610 from California and International Institute of Tropical Agriculture, was less affected. The reduction in yield was a result of reduction in number of pods per plant. These findings are in agreement with those of Turk *et al.* (1980) who indicated that the reduction in grain yield of cowpea was a result of reduction in number of pods and seed weight due to detrimental effects of drought on pod set and grain filling (Turk *et al.*, 1980). However, the seed weight was not affected by drought stress in this study. The difference in response of cowpea genotypes to drought is not surprising since the tested germplasm consisted of genotypes adapted to different growing conditions including the dry and hot areas of the Sahel and semi-arid and hot areas of California.

Correlations between stressed and non-stressed yield were 0.71 and 0.51 for early and late genotypes, respectively. These results suggested that selecting early genotypes based on yield potential would improve yield under stressed and non-stress environments while selecting for yield potential for late genotypes would increase yield only under non-stressed environments. Rosielle and Hamblin (1981) indicated that under most yield trials the correlation between stressed and non-stressed yield is smaller indicating that selection for yield potential would only increase yield under non-stressed environments while the selected genotypes would perform poorly under stressed conditions. The correlation among quantitative indices of drought tolerance and stressed and non-stressed yield indicated that stress tolerance index was correlated with stressed and non-stressed yield, mean productivity and geometric mean productivity suggesting that selection for this index would improve both stressed and non-stressed yield. In addition, stress tolerance index enabled identification of high yielding and stress tolerant genotypes, suggesting that this index was the best for selecting genotypes for drought tolerance. Fernandez (1992) also indicated that selecting for stress tolerance index would improve yield under both stressed and non-stressed environments.

Principal component analysis indicated that the PC1 explained most of the variation observed in yield. The PC1 was correlated with non-stressed yield and mean productivity while PC2 was correlated with stress tolerance suggesting that PC1 was a yield potential dimension while the PC2 stress tolerance dimension. Plotting the genotypes over the PC1 and PC2 with quantitative indices of stress tolerance and stressed and non-stressed yield, genotypes were distributed over the coordinate space indicating different drought adaptation and yielding ability. Different clusters of genotypes were identified; high yielding and drought tolerant (not reduced by drought) (group A), high yielding and drought susceptible genotypes (reduced by drought) (Group B), low yielding and drought tolerant genotypes (group C) and low yielding and drought susceptible genotypes (group D). Examples of genotypes in group A were early genotypes INIA-24, INIA-51A, IT85F-2205, Sh-50, UC-524B, UCR-739 and the late genotypes INIA-120, IT96D-610 and Tete-2; genotypes in group B were early genotypes INIA-42F, VAR-50B, IT85F-867, IT85F-3139 INIA-11C, INIA-11D, INIA-51 and the late genotypes Zimbabwe, Xingove, IT83D-442, Massava-5 and N'diambour; genotypes in group C were late genotypes IT98K-1111-1, IAR-8/7, KVx403 and KVx525; and genotypes in group D were early genotypes IT82E-18, IT95M-303 and late genotypes CP-2, KVx-421 and Massava-11. This biplot display was a clear indication that genetic variability for yield under drought conditions existed among the tested germplasm suggesting that improvement for yield under drought conditions would be possible. Fernandez (1992) indicated that the biplot analysis was a powerful tool for analyzing large data sets because it allows the visual appraisal of the structure of a large two-way data matrix.

The overall judgment of the results in this study is that genetic variability for cowpea drought tolerance existed. Genotypes were grouped according to their yielding ability and drought adaptation. Stress tolerance index was found to be a useful index for screening for drought tolerance because it enabled identification of drought tolerant and high yielding genotypes and multivariate analysis on stressed and non-stressed yield and quantitative indices of drought tolerance was useful for investigating the genetic variability of drought tolerance because it allowed the visual appraisal of the distribution of genotypes in the coordinate space showing the genotypes yielding ability and their tolerance to drought.

3.5 Conclusion

The objective of this study was to assess cowpea genotypes for variability in drought tolerance using stress intensity, mean productivity, tolerance index, stress susceptibility index, geometric mean productivity and stress tolerance index. Based on the results obtained it is concluded that:

(1) Genotypic variability for drought tolerance existed amongst the tested germplasm given that genotypes responded differently to drought stress

(A) Using a biplot display of yield and quantitative indices of stress tolerance, four groups of genotypes were identified based on yielding ability and drought tolerance; high yielding and drought tolerant genotypes (group A), high yielding and drought susceptible genotypes (group B), low yielding and drought tolerant genotypes (group C) and low yielding and drought susceptible genotypes (group D).

(B) Genotypes in group A were the best by combining high yield and low sensitivity to drought.

(C) Amongst the quantitative indices of drought tolerance, stress tolerance was the best because it enabled identification of group A genotypes.

(D) The number of pods per plant was strongly and positively correlated with yield. In general, drought tolerant genotypes did not show reduction in number of pods per plant

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Chapter Four

Gene Action Controlling Drought Tolerance, Yield and Yield Components Traits in Cowpea

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Abstract

Drought is a major abiotic constraint to cowpea production in Mozambique. A study was conducted to determine the gene action controlling drought tolerance, yield and yield components in cowpea using an 8×8 half-diallel mating design. The parents and their 28-F2 populations were evaluated under drought-stressed and non-stressed conditions in two sites (Umbeluzi and Chókwè) using a 9×4 α-lattice design with three replications at Umbeluzi and two at Chókwè. Drought stress was imposed from flower bud emergence to physiological maturity by withholding irrigation. The results indicated that there were genotypic differences in drought tolerance, yield, days to flowering, number of pods per plant, number of seeds per pod and hundred seed weight. Average yield across non-stressed conditions was about 1600kgha^{-1} and ranged between 1200 and 3000 kgha^{-1} while under severe drought stress it was about 300kgha^{-1} and ranged between 60 and 1500 kgha^{-1}. Both additive and non-additive gene action were involved in controlling cowpea drought tolerance, yield and yield components. Additive gene action was more important than non-additive for drought tolerance, days to flowering, number of pods per plant, number of seeds per pod and hundred seed weight. Non-additive gene action was more important than additive gene action for yield under severe drought. Selection for drought tolerance would be possible using the stay-green trait under drought stressed conditions and would be effective in early segregating generations. Direct selection for yield would be possible under non-stressed conditions while under drought stressed conditions, yield improvement would be done using the number of pods per plant and it would be effective in late segregating generations when the genes are fixed and fully expressed. The most desirable genotypes to use as parents in a breeding programme would be INIA-41 for drought tolerance and IT93K-503-1 for drought tolerance and yield.

4.1 Introduction

Cowpea is an important food legume crop in the drier regions of the tropics covering parts of Africa, Asia and Oceania, the Middle East, Southern Europe, Southern USA, and Central and South America (Singh *et al.* 2002). The crop is of major economic importance in Africa where more than 90% of the total world grain production of 5.7 million tonnes is produced in about 10 million hectares (FAOSTAT, 2008). The major world cowpea producers in Africa include Nigeria, Niger, Burkina Faso, Senegal and Mali (Fery, 2002; FAOSTAT, 2008). Cowpea is an important crop in Mozambique where its grain and leaves are important sources of food, protein and income particularly for the resource-poor households. However, despite such importance, yields have remained low (< 300 kgha^{-1}) (Heemskerk *et al.* 1988; INIA, 2003). The low yields have been attributed to a number of biotic and abiotic stresses, amongst which, drought is the most important. Currently, there are no drought tolerant cultivars amongst the cultivated genotypes. Therefore, the development of drought tolerant cowpea cultivars would be an effective and sustainable measure for ensuring increased cowpea production in the country.

To develop drought tolerant cultivars, knowledge of genetic variability of drought tolerance and its genetic control is necessary for identifying the best parents and selection strategy to use in breeding programmes. Several studies have indicated that genetic variability for drought tolerance exists in cowpea (Turk *et al.*, 1980; Turk and Hall, 1980a,b,c; Gwathmey and Hall, 1992; Watanabe, 1998; Watanabe and Terao, 1998; Mai-Kodomi *et al.*, 1999a, Singh *et al.*, 1999; Matsui and Singh, 2003; Muchero *et al*., 2008) implying that improvement of this trait is possible. However, information on gene action controlling drought tolerance, yield and its associated traits is scarce in cowpea in Mozambique. Studies conducted elsewhere in cowpea reported the prevalence of additive gene action over the non additive gene action in controlling yield, number of seeds per pod, pod length, hundred seed weight, pod width, pod wall thickness, inter-seed space, hundred seed weight and seediness in cowpea (Romanus *et al.*, 2008; Umaharan *et al.*, 1997). Nevertheless, combining ability and heritability estimates are specific to the germplasm being tested and the environment where the germplasm is being tested (Falconer, 1989). Such information would assist in devising an appropriate selection strategy to be used in cowpea breeding for improved yield and drought tolerance.

Different criteria of assessing cowpea for drought tolerance have been used and proved to be useful. Singh *et al*. (1999) and Muchero *et al*. (2008) used visual symptoms of wilting, plant death and recovery as criteria for assessing genotypic differences in drought tolerance. Plant water relations and solute accumulation (Turk and Hall, 1980a,b; Chiulele and Agenbag, 2004) as well as yield and yield related traits (Turk *et al.*, 1980) have also been used. The combination of visual symptoms for assessing genotypic variability of drought tolerance, yield and yield related traits would be useful for identifying genotypes and cross combinations carrying drought tolerant genes in cowpeas. In this study, variability in drought tolerance was assessed in different genotypes using visual symptoms of drought tolerance (stay-green).

The objective of this study was to determine the gene action controlling drought tolerance (stay-green), yield and components (days to flowering, number of pods per plant, number of seeds per pod and hundred seed weight) recorded under drought stressed and non-stressed conditions.

The hypothesis tested was that additive gene action is more important than non-additive gene action in controlling drought tolerance, yield and yield components.

4.2 Materials and methods

4.2.1 Site characteristics and environmental conditions during the experiments

The experiments were conducted at Chókwè Research Station (24º 32'S, 33º 00'E, 15m) and Umbeluzi (26º03'S, 32º 23'E, 15m) in Mozambique. At Chókwè the experiments were conducted between March and May while at Umbeluzi they were conducted between April and July 2010.

At Chókwè Research Station, minimum and maximum temperatures range between 12 and 25^{o}C and 22 and 34^{o}C in July and January, respectively. The station receives about 600mm per year; minimum and maximum rainfall takes place in July and January, respectively, with most of the rainfall occurring between November and March. The total evaporation measured using evaporation tank is about 1800mm per year; minimum and maximum evaporation takes place in May and January, respectively. The soils at the station are clay loam with high water retention capacity and the area is semi-arid. During the experimental period, minimum and maximum temperatures ranged between 17.8 and 29.6^{o}C and 22.2 and 33^{o}C in May and March, respectively. The total rainfall received was 317.4mm and minimum and maximum rainfall was 59.1 and 193.4mm in March and April, respectively. The total evaporation measured using the evaporation tank was 69.6mm and minimum and maximum evaporation took place in May and April with 8.9 and 60.7mm, respectively.

At Umbeluzi Research Station, minimum and maximum temperatures range between 11 and 26^{o}C and 22 and 32^{o}C in July and January, respectively. The station receives about 660mm per year; minimum and maximum rainfall take places in June and January, respectively, with most of the rainfall occurring between November and March. The total evaporation measured using the evaporation tank is about 1360mm per year; minimum and maximum evaporation takes place in April and October, respectively. The soils at the station are clay loam and the area is semi-arid. During the experimental period, minimum and maximum temperatures ranged between 12.2 and 27.8^{o}C and 20.2 and 29.8^{o}C in July and April, respectively. The total rainfall received was 295.2mm and minimum and maximum rainfall was 10 and 179.4mm in June and April, respectively. The total evaporation was 323.9mm and minimum and maximum evaporation took place in July and April with 42.6 and 79.7mm, respectively.

4.2.2 Cowpea germplasm

The important characteristics of eight (8) cowpea genotypes used in this study are presented in Table 4.1. Two genotypes were of Mozambican origin and were obtained from the National Gene-bank of the National Research Institute of Mozambique (IIAM) while the other six were of different origins and were obtained from the University of California Riverside in the United States of America. The genotypes comprised of two drought tolerant (INIA-41 and IT93K-503-1), two drought susceptible (INIA-152 and IT82E-18) and four others which had other desirable characteristics such as high yield, early maturity and large seed size. The drought tolerant and susceptible genotypes were selected from amongst 216 genotypes evaluated in an earlier experiment based on yield performance.

Table 4.1: Genotype name, origin and selection criteria of genotypes used in the diallel design

Genotype name	Origin	Selection criteria
IT82E-18	IITA	Drought susceptible, high yielding and early maturity
UCRP-24	UCR	Large seed size, farmers preference and early maturity
IT93K-503-1	IITA	Drought tolerant and high yielding
IT97K-499-39	IITA	High yield
IT84S-2246	IITA	High yield
Bambey-21	Senegal	Early maturity
INIA-152	Mozambique	Drought susceptible
INIA-41	Mozambique	Drought tolerant and large seed and pod size

Note: IITA = International Institute of tropical Agriculture; UCR = University of California Riverside

4.2.3 Diallel mating design, field evaluation and data collection

Eight (8) genotypes were grown in a crossing block at the Faculty of Agronomy and Forestry Engineering Experimental Farm (25º 58'S, 32º 35'E, 60m) in Maputo, Mozambique between January and June 2009 and cross-pollinated using a half diallel mating design. The 28-F1 progenies generated were advanced to the F2 generation between August and December 2009. The resulting 28-F2 populations plus the eight (8) parental genotypes were evaluated from March to July 2010 in two locations under drought stressed and non-stressed conditions in each of the sites. The eight parental genotypes included two checks. The experimental design was a 9×4 α-lattice with three replications at Umbeluzi and two at Chókwè.

At Chókwè, planting was done in the first week of March 2010 while at Umbeluzi it was done in the first week of April. The plot size for both parental genotypes and F2 populations in all experiments consisted of three rows of 6.5 meters long at inter-row spacing of 75cm and intra-row spacing of 20cm, making a plant population of 97 plants. Two seeds were planted per hill and 7 days after germination the weaker plants in each hill were removed leaving one plant per hill. Before planting soil fertility analyses was conducted and fertilizer applied at 6 kg N: 12 kg P: 6 kg K ha^{-1} using the fertilizer NPK12-24-12. Water stress treatment was imposed on the plots by withholding irrigation from flower bud emergence to physiological maturity while in non-stressed plots the plants were watered regularly to field capacity up to maturity. To avoid water seepage the non-stressed experiments were established 30 meters away from the water stressed. The field was maintained free from weeds and insect pests throughout the experiment through weeding and insecticide application.

Drought tolerance was assessed at Umbeluzi where severe drought stress was observed using the number of green plants (stay-green) as a percentage of total plants in a plot. This data was recorded at 5 days intervals in each plot from 30 days after stress imposition when the differences between genotypes were clear up to 45 days after stress imposition when the plants of susceptible genotype were completely dead. Data was also recorded in all environments on days to flowering (50% of plants with flowers), number of pods per plant, number of seeds per pod, 100-seed weight in g and yield in $kgha^{-1}$. The yield and yield components (number of pods per plant, number of seeds per pod, 100-seed weight) were recorded at physiological maturity.

4.2.4 Data analysis

4.2.4.1 Analysis of variance

Data on percentage of green plants was subjected to analysis of variance (ANOVA) per sampling date using Proc GLM procedure in SAS 9.1 software (SAS Institute, 2002). In a similar way, the yield, days to flowering, number of pods per plant and hundred seed weight were analysed per environment using the same procedure. In both analyses, the genotypes were considered as fixed effects and the replications as random effects. The linear model used for ANOVA per sampling date or per environment was as follows:

$$Y_{ijk} = \mu + r_i + g_{jk} + (gr)_{ijk} + e_{ijk} \quad \text{(Dabholkar, 1992);}$$

Where Y_{ijk} is the mean of *i*th or *j*th parental line or the F2 obtained by crossing *i*th and *j*th lines, μ is the grand mean, r_i is the effect of *i*th replication, g_{jk} is the effect of *ik*th genotype, $(gr)_{ijk}$ is the interaction of *jk*th genotype with r_i replication, e_{ijk} is the experimental error peculiar to *ijk*th observation.

The format of analysis of variance showing the sources of variation, the degrees of freedom, the mean squares and the expectations of mean squares for the fixed model are presented in Table 2.

Table 4.2: Format of analysis of variance table indicating the source of variation, degrees of freedom (DF), mean squares (MS) and expected mean squares for Griffing's (1956) diallel analysis, method 2 model 1

Source	DF	MS	Expected mean squares
Replications	$(r-1)$	Mr	$\sigma^2 + gc\frac{1}{(r-1)}\sum_k b_k^2$
Genotypes	$(g-1)$	Mg	$\sigma^2 + rc\frac{1}{(r-1)}\sum_i g_i^2$
Genotypes x Replications	$(g-1)(r-1)$	Mgr	$\sigma^2 + c\frac{1}{(g-1)(r-1)}\sum_i\sum_j\sum_k (gr)_{ijk}^2$
Error	$gr(c-1)$	Me	σ^2

4.2.4.2 Determination of gene action controlling drought tolerance, yield and yield components in cowpea

The gene action was determined by calculating the general combining ability (GCA) and specific combining ability (SCA) for the various traits following Griffing's (1956) Method 2 (parents and crosses), model I (fixed effects model) using the Diallel SAS-05 program (Zhang *et al*., 2005) in the SAS computer package (SAS Institute, 2002). The linear model for combining ability analysis was as follows:

$$Y_{ij} = \mu + g_i + g_j + S_{ij} + e_{ij} \qquad \text{(Dabholkar, 1992);}$$

Where Y_{ijk} is the mean phenotypic value, μ is the general mean, g_i and g_j are the general combining ability (GCA) effects of *i*th and *j*th lines, respectively, S_{ij} is the specific combining ability (SCA) effect of *ij*th crosses and e_{ij} is the environmental effect associated with *ij*th individual observation.

The expected mean squares for general and specific combining ability effects were obtained in the way presented in Table 4.3 according to Dabholkar (1992).

Table 4.3: Format of analysis of variance table indicating the source of variation, degrees of freedom (DF), sum of squares (SS), mean squares (MS) and expectations of mean squares for Griffing's (1956) diallel analysis, method 2 model 1

Source	*DF*	*SS*	*MS*	*Expected mean squares*
General combining ability	$p-1$	Sg	Mg	$\sigma^2 + (p+2)\left(\frac{1}{p-1}\right)\sum_i g_i^2$
Specific combining ability	$\frac{p(p-1)}{2}$	Ss	Ms	$\sigma^2 + \frac{2}{p(p-1)}\sum_i\sum_j S_{ij}^2$
Error	m		Me	σ^2

To make inferences on the type of gene action controlling drought tolerance, yield and yield related traits, the relative contribution of GCA to the total sums of squares was calculated using the formulae proposed by Baker (1978) as follows:

$$\frac{GCA}{SCA} = \frac{2 \times MSQ_{GCA}}{2 \times MSQ_{GCA} + MSQ_{SCA}}$$

Where MSQ_{GCA} is mean square for GCA, MSQ_{SCA} is mean square for SCA.

4.3 Results

4.3.1 Analysis of variance

The results of analysis of variance on stay-green, yield and yield components are presented in Table 4.4 and 4.5. Highly significant differences (p<0.01) were detected among genotypes with regard to stay-green recorded at 30, 35, 40 and 45 days after stress imposition. The replications were also significant at 30 and 35 days after stress imposition.

Highly significant differences (p<0.01) were also detected between genotypes for yield and all yield components (Table 4.5). Replications were significant for yield at Chókwè under stressed conditions, for days to flowering at Chókwè for both stressed and non-stressed conditions, for number of pods per plant at Umbeluzi for both stressed and non-stressed conditions and at Chókwè under stressed conditions, and for the number of seeds per pod at Umbeluzi under non-stressed conditions. Genotypes accounted for most of the variation observed in all traits.

Table 4.4: Mean squares for replications, genotypes and error for the percentage of green plants (stay-green) of 8 parents and their 28-F2 populations recorded at 30, 35, 40 and 45 days after stress imposition at Umbeluzi

		Days after stress imposition			
Source	DF	30	35	40	45
Replications	2	581.12*	543.59*	405.58ns	174.53ns
Genotypes	35	1139.54**	1300.83**	1122.58**	717.13**
Error	70	162.71	143.09	127.65	82.35

Note: *,** = Significant effects at 5% and 1%, respectively; ns = not significant

Table 4.5: Mean squares for replications, genotypes and error for yield, days to flowering, number of pods per plant, number of seeds per pod and hundred seed weight recorded in 8 parents and their 28-F2 populations grown under drought-stressed and non-stressed conditions at Umbeluzi and Chókwè

			Umbeluzi			Chókwè	
Trait	Source	DF	Non-stressed	Stressed	DF	Non-stressed	Stressed
Yield	Replications	2	33187.7ns	1598.3ns	1	24075.4ns	1442904.1*
	Genotypes	35	638329.3**	310948.2**	35	1627868.5**	1451686.7**
	Error	70	51533.08	2052.66	35	209858.17	245213.19
Days to flowering	Replications	2	8.90ns	6.48ns	1	14.22**	12.6**
	Genotypes	35	15.36**	17.96**	35	4.91**	4.89**
	Error	70	3.16	3.66	35	0.79	0.76
Number of pods per plant	Replications	2	6.48**	7.16*	1	33.35ns	177.35*
	Genotypes	35	16.43**	19.27**	35	172.95**	146.48**
	Error	70	1.26	1.98	35	71.38	37.89
Number of seeds per pod	Replications	2	4.45*	1.67ns	1	1.39ns	1.29ns
	Genotypes	35	1.95*	8.41**	35	7.46**	7.26**
	Error	70	1.14	0.93	35	0.79	0.77
Hundred seed weight	Replications	2	0.06ns	0.71ns	1	0.02ns	1.65ns
	Genotypes	35	20.04**	11.39**	35	14.51*	22.69**
	Error	70	0.99	1.22	35	7.05	5.78

Note: *,** = Significant effects at 5% and 1%, respectively; ns = not significant

4.3.2 Combining ability analyses

The mean squares for general combining ability (GCA) and specific combing ability (GCA) effects for the percentage of green plants, yield and components are presented in Table 4.6 and 4.7. The GCA effects for the percentage of green plants were highly significant ($p<0.01$) in all sampling dates (Table 4.6). The GCA mean squares were greater than SCA mean squares in all dates. The GCA mean squares accounted for 96, 94, 93 and 92% of the total variation on percentage of green plants recorded at 30, 35, 40 and 45 days after stress imposition, respectively.

Table 4.6: Mean squares for the number of green plants (%) recorded at 30, 35, 40 and 45 days after stress imposition in 8 parents and their 28-F2 populations under stressed conditions at Umbeluzi

		Number of green plants (%)			
Source	DF	30	35	40	45
GCA	7	3687.17**	4018.18**	3070.16**	1821.63**
SCA	28	342.82**	475.06**	484.86**	321.55**
Error	35	162.71	143.09	127.65	82.35
GCA:SCA ratio (%)		96	94	93	92

Note: *,** = Significant at 5 and 1%, respectively

The GCA mean squares for yield and all yield components (days to flowering, number of pods per plant, number of seeds per pod and hundred seed weight) were highly significant ($p<0.01$) in both sites and water regimes (Table 4.7). Specific combining ability (SCA) effects were also significant for all traits in almost all water regimes and sites except for the days to flowering at Umbeluzi under stressed conditions, number of seeds per pod at Umbeluzi under non-stressed conditions and hundred seed weight at Chókwè under non-stressed conditions. The GCA mean squares for yield were greater than SCA mean squares under non-stressed conditions or under moderate drought stress at Chókwè but lower than the SCA mean squares under severe drought stress at Umbeluzi. The GCA mean squares were also greater than SCA mean squares for yield components in both sites and water regimes.

The contribution of GCA mean squares to the total variation was 77, 59.6, 85.9 and 76.2% for yield; 94.8, 95.7, 91.8 and 91.9% for days to flowering; 90, 67.8, 74.4 and 75.5% for the number of pods per plant; 75.1, 87.2, 89.1 and 89% for the number of seeds per pod; and 96.3, 94.3, 92.2 and 92.1% for the hundred seed weight at Umbeluzi under non-stressed and stressed conditions and at Chókwè under non-stressed and stressed conditions, respectively. Overall, the GCA effects were closer to one for the days to flowering and hundred seed weight.

Table 4.7: General (GCA) and specific combining ability (SCA) mean squares for yield, days to flowering, number of pods per plant, number of seeds per pod and 100-seed weight of 8 parents and their 28-F2 populations grown under drought stressed and non-stressed conditions at Umbeluzi and Chókwè

			Mean squares per environment			
			Umbeluzi		Chókwè	
Trait	Source	DF	Non-stressed	Stressed	Non-stressed	Stressed
Yield	GCA	7	942966.5**	242849.3**	3364437.8**	1920896.0**
	SCA	28	564031.7**	329020.0**	1102372.7**	1202257.6**
	Error	35	51533.08	2052.66	209858.17	245213.19
	GCA:SCA ratio		77	59.6	85.9	76.2
Days to flowering	GCA	7	50.76**	61.46**	12.95**	12.97**
	SCA	28	5.62*	5.5ns	2.35**	2.33**
	Error	35	3.16	3.66	0.78	0.79
	GCA:SCA ratio		94.8	95.7	91.8	91.9
Number of pods per plant	GCA	7	42.69**	19.76**	222.96**	204.28**
	SCA	28	9.49**	18.76**	153.16**	132.8**
	Error	35	1.26	1.98	71.38	37.89
	GCA:SCA ratio		90	67.8	74.4	75.5
Number of seeds per pod	GCA	7	2.77*	20.71**	16.672**	21.13**
	SCA	28	1.84ns	6.08**	4.09**	5.17**
	Error	35	1.14	0.93	0.78	0.79
	GCA:SCA ratio		75.1	87.2	89.1	89
100-Seed weight	GCA	7	70.26**	34.75**	44.28**	61.29**
	SCA	28	5.46**	4.17**	7.52ns	10.49*
	Error	35	0.99	1.12	7.05	5.78
	GCA:SCA ratio		96.3	94.3	92.2	92.1

Note: *,** = Significant effects at 5% and 1%, respectively; ns = not significant

4.3.3 Performance of parents and F2 populations for stay-green under drought conditions at Umbeluzi

The performance of the 8 parental genotypes and 28-F2 populations for the number of green plants (stay-green) are shown in Figure 4.1 and Table 4.8. Genotypes IT93K-503-1, IT97K-499-39 and INIA41 had higher number of green plants than genotypes Bambey-21, INIA-152, UCR-P-24 and IT82E-18 in all sampling dates. Genotypes IT93K-503-1, IT97K-499-39 and INIA41 had more than 50% of green plants at 45 days after stress imposition when the most susceptible genotype IT82E-18 was completely dead (Figure 4.1). Genotypes IT93K-503-1 and INIA-41 also had the highest yields while INIA-152 and IT82E-18 had the lowest.

The number of green plants (stay-green) for the F2 populations was significantly different on different sampling dates. It varied between 29 and 93% at 30 days after stress imposition and between 14 and 58% at 45 days after stress imposition. The top twelve best performing populations involved the resistant parents INIA-41 or IT93K-503-1. On the other hand, the bottom twelve poor performing populations involved one or both susceptible parents INIA-152, UCR-P-24 or IT82E-18.

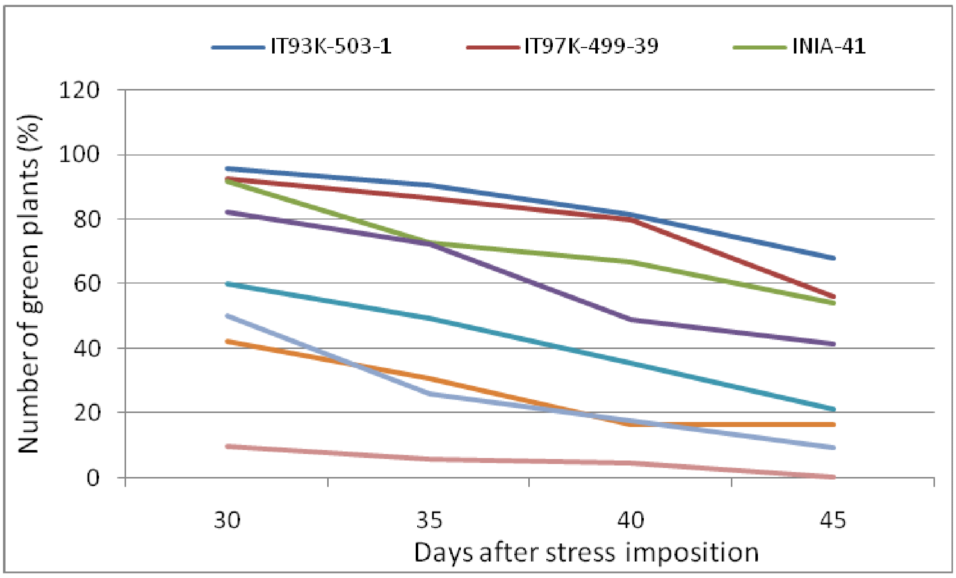

Figure 4.1: Number of green plants (%) of the 8 parental genotypes recorded at 30, 35, 40 and 45 days after stress imposition

Table 4.8: Number of green plants (%) of F2 populations recorded on drought stressed experiment at Umbeluzi at 30, 35, 40 and 45 days after stress imposition

	Number of green plants (%) on different sampling dates			
F2 populations	30	35	40	45
IT93K-503-1xIT84S-2246	92.3	84.0	73.0	57.7
IT84S-2246xINIA41	90.3	77.0	66.0	38.0
IT93K-503-1xINIA41	87.3	74.7	63.0	52.0
IT97K-499-39xINIA41	87.0	82.0	70.3	55.0
Bambey-21xINIA41	83.0	76.7	65.3	52.7
INIA-152xINIA41	82.3	70.0	61.7	38.7
IT93K-503-1xINIA152	72.0	60.7	45.3	32.3
IT82E-18xINIA41	71.7	61.3	53.7	42.7
IT93K-503-1xBambey-21	69.3	56.7	42.0	37.0
UCR-P-24xIT93K-503-1	68.7	32.7	27.0	20.3
IT93K-503-1xIT97K-499-39	66.0	55.3	37.7	26.0
UCR-P-24xINIA41	65.3	51.0	36.7	32.0
IT82E-18xBambey-21	62.3	53.7	48.7	31.0
IT82E-18xIT93K-503-1	62.3	27.7	22.7	20.3
IT97K-499-39xBambey-21	62.0	57.0	44.0	33.0
IT97K-499-39xIT84S-2246	61.0	45.3	34.7	20.7
IT82E-18xIT97K-499-39	60.3	54.7	41.0	42.7
IT82E-18xIT84S-2246	60.3	42.0	37.0	19.7
UCR-P-24xIT84S-2246	57.0	37.3	32.7	27.0
Bambey-21xINIA152	54.7	42.7	44.7	32.0
IT97K-499-39xINIA152	53.7	44.7	34.0	24.3
UCR-P-24xIT97K-499-39	52.0	39.3	33.7	25.7
IT84S-2246xBambey-21	52.0	39.7	32.3	22.0
IT82E-18xINIA152	47.7	40.3	27.3	18.0
IT84S-2246xINIA152	45.3	37.0	31.7	24.3
UCR-P-24xINIA152	43.0	28.0	23.0	21.7
IT82E-18xUCR-P-24	42.7	28.3	22.7	17.7
UCR-P-24xBambey-21	29.3	23.0	25.7	14.3
Mean	64.0	51.6	42.2	31.8
LSD0.05	4.3	4.1	3.8	3.1
CV (%)	19.9	23.2	26.8	28.5

4.3.4 Yield performance of parents and F2 populations

The grain yield of the 8 parental genotypes was significantly different in both sites and water regimes (Table 4.9). The genotypes IT93K-503-1, INIA-41 and UCR-P-24 were the highest yielding while IT82E-18 was the lowest yielding in most of the environments. The drought stress treatment reduced the yield by 75% at Umbeluzi and by 15% at Chókwè indicating that drought stress was severe at Umbeluzi. However, entries responded differently to the stress imposed. At Umbeluzi the grain yield of drought tolerant genotypes IT93K-503-1 and INIA-41 was not affected by the stress while that of susceptible genotypes IT82E-18 and INIA-152 was severely reduced.

The yield of the F2 populations varied in both sites and water regimes (Table 4.10). Drought stress caused severe yield reduction at Umbeluzi but not at Chókwè. The different populations responded differently to the drought stress imposed suggesting that there was variability for drought tolerance.

Table 4.9: Grain yield in Kgha^{-1} of 8 parental genotypes grown under drought-stressed and non-stressed conditions at Umbeluzi

	Umbeluzi			Chókwè		
Parental genotypes	Non-stressed	Stressed	Reduction (%)	Non-stressed	Stressed	Reduction (%)
IT93K-503-1	766	842	-9.9	4571	4476	2.1
INIA-41	464	491	-5.8	3397	2836	16.5
IT97K-499-39	997	323	67.6	2832	2809	0.8
UCR-P-24	889	392	55.9	2729	2366	13.3
INIA-152	1256	60	95.2	2199	2362	-7.4
IT82E-18	1715	169	90.1	1601	1729	-8.0
Bambey-21	1002	139	86.1	1656	1741	-5.1
IT84S-2246	969	84	91.3	1736	1394	19.7
Mean	1141	290	74.6	2320	1961	15.5
LSD0.05	77.3	15.4		194.5	210.3	
CV (%)	19.9	15.6		19.8	25.4	

Table 4.10: Grain yield in Kgha^{-1} of 28-F2 populations grown under drought-stressed and non-stressed conditions at Umbeluzi and Chókwè

	Umbeluzi			Chókwè		
F2 populations	Non-stressed	Stressed	Reduction (%)	Non-stressed	Stressed	Reduction (%)
IT82E-18xIT93K-503-1	1316	1522	-15.6	4514	4550	-0.8
Bambey-21xINIA152	1233	1390	-12.7	4533	2693	40.6
IT93K-503-1xBambey-21	1385	223	83.9	2766	2964	-7.2
IT93K-503-1xIT84S-2246	976	237	75.7	3431	1940	43.5
IT93K-503-1xINIA152	1598	186	88.4	3140	2689	14.4
IT97K-499-39xINIA41	1223	174	85.8	3392	1916	43.5
IT82E-18xUCR-P-24	2002	373	81.4	1769	1873	-5.9
UCR-P-24xINIA41	1216	199	83.6	1962	2528	-28.8
IT93K-503-1xINIA41	402	90	77.6	2744	1940	29.3
IT97K-499-39xINIA152	1722	442	74.3	1975	1463	25.9
UCR-P-24xIT97K-499-39	1006	323	67.9	1917	2358	-23
UCR-P-24xIT93K-503-1	1245	230	81.5	2526	1509	40.3
INIA-152xINIA41	1815	156	91.4	2216	1372	38.1
IT93K-503-1xIT97K-499-39	1047	287	72.6	2503	1347	46.2
IT82E-18xINIA152	1759	73	95.8	1577	1400	11.2
IT82E-18xBambey-21	1484	151	89.8	1760	1757	0.2
Bambey-21xINIA41	927	177	80.9	2547	1347	47.1
IT82E-18xIT84S-2246	1673	237	85.8	1606	1500	6.6
IT84S-2246xINIA41	1456	118	91.9	1136	1401	-23.3
IT97K-499-39xIT84S-2246	1046	115	89	2111	1551	26.5
IT82E-18xIT97K-499-39	1485	275	81.5	1471	1611	-9.5
IT84S-2246xINIA152	1320	120	90.9	1452	1630	-12.3
IT97K-499-39xBambey-21	1602	159	90.1	1944	1095	43.7
IT82E-18xINIA41	1368	171	87.5	1611	969	39.9
IT84S-2246xBambey-21	1062	75	92.9	1642	1728	-5.2
UCR-P-24xINIA152	982	88	91	1348	1616	-19.9
UCR-P-24xBambey-21	339	319	5.9	1542	1123	27.2
UCR-P-24xIT84S-2246	341	38	88.9	1662	1008	39.4
Mean	1141	290	74.6	2320	1961	15.5
LSD0.05	1141	290	74.6	2320	1961	
CV (%)	77.3	15.4		194.5	210.3	

4.3.5 General combining ability for stay-green, yield and yield components

The general combining ability estimates for stay green of the 8 parental genotypes are presented in Table 4.11. The general combining ability (GCA) estimates of the drought tolerant genotypes IT93K-503-1 and INIA-41 were high, positive and highly significant (p<0.01) in all dates while those of the susceptible genotypes IT82E-18, UCR-P-24 and INIA-152 were high, negative and highly significant (p<0.01). Overall, the genotypes IT93K-503-1, INIA-41 and IT97K-499-39 were superior in terms of frequency of favourable genes determining survival under drought conditions and divergent relative to the mean frequency of the diallel parental group while IT82E-18, UCR-P-24 and INIA-152 were in opposite side, inferior and divergent relative to the mean frequency of the diallel parents.

Table 4.11: General combining ability (GCA) estimates for number of green plants of 8 parental genotypes recorded at 30, 35, 40 and 45 days after stress imposition

	GCA estimates on different dates			
	30	35	40	45
IT93K-503-1	12.86**	9.06**	5.79**	7.59**
IT97K-499-39	2.98	6.89**	4.96*	3.79*
INIA-41	18.48**	19.43**	18.46**	14.01**
IT84S-2246	3.73	3.10	2.54	-0.29
Bambey-21	-4.77*	-1.4	0.29	-1.24
UCR-P-24	-13.81**	-17.44**	-14.75**	-9.74**
INIA-152	-7.77**	-7.61**	-6.29**	-6.54**
IT82E-18	-11.72**	-12.03**	-11.00**	-7.58**
V(gi)	4.75	4.17	3.72	2.4
V(gi-gj)	10.85	9.54	8.51	5.49

Note: *,** = Significant at 5 and 1%, respectively

The general combining ability (GCA) effects for yield and number of seeds per pod varied in different environments while those for days to flowering, number of pods per plant and hundred seed weight were consistently negative or positive in different environments (Table 4.12). Genotypes IT93K-503-1 and IT82E-18 had high and highly significant GCA effects in most of the environments. Parent IT93K-503-1 had positive GCA effects in three environments whereas IT82E-18 had positive GCA effects in two environments and negative in one environment. Another genotype with positive GCA effects for yield was INIA-152 with positive GCA in two environments but of moderate magnitude. Genotype UCR-P-24 had high negative significant GCA in two environments. Genotype IT93K-503-1 also had positive and significant GCA estimates for the number of pods per plant together with IT82E-18 and INIA-152. Genotype IT93K-503-1 had highly significant positive GCA effects in three environments for the number of seeds per pod. The GCA effects for days to flowering of IT93K-503-1 were associated with increase in days to flowering (positive) in all environments while for the hundred seed weight they were negative and significant in only one environment. Genotypes INIA-41 and UCR-P-24 had positive and significant GCA estimates in most of the environments for hundred seed weight but not for seed yield despite their high yield. The genotype UCR-P-24 apart from high hundred seed weight took fewer days to flower (data not shown). This genotype together with IT82E-18 and Bambey-21 had negative and significant combining ability estimates for days to flowering which were associated with early flowering. The drought susceptible genotype, INIA-152, had positive GCA effects for yield in two environments, and positive and significant GCA estimates in three environments for the number of pods per plant. Overall, IT93K-503-1 had GCA effects that were associated with increased yield and number of pods per plant together with genotype INIA-152. Genotype INIA-41 and UCR-P-24 had GCA effects which were associated with high hundred seed weight, UCR-P-24 apart from positive GCA effects for hundred seed weight also had GCA effects that were favourable for early flowering together with IT82E-18 and Bambey-21.

Table 4.12: General combining ability (GCA) estimates for yield, days to flowering, number of pods per plants, number of seeds per pod and hundred seed weight of eight parental genotypes grown under drought stressed and non-stressed conditions at Umbeluzi and Chókwè

		Environments			
		Umbeluzi		Chókwè	
Trait	Parents	Non-stressed	Stressed	Non-stressed	Stressed
Yield	IT82E-18	314.5**	80.9**	-309.4**	13.8
	UCR-P-24	-132.4**	-13	-315.9**	-43.9
	IT93K-503-1	-212.9**	149.8**	958.3**	749.4**
	IT97K-499-39	106.2*	-36.0**	-32.8	-174.7
	IT84S-2246	-31.5	-140.4**	-404.8**	-348.9**
	Bambey-21	-163.3**	34.6**	15.1	-86.5
	INIA-152	187.8**	24.2**	-5.1	-0.3
	INIA-41	-68.5	-100.1**	94.7	-108.8
Days to flowering	IT82E-18	-1.06**	-0.96**	-0.42*	-0.42*
	UCR-P-24	-1.81**	-2.54	-0.92**	-0.92**
	IT93K-503-1	1.44**	0.75*	1.14**	1.14**
	IT97K-499-39	-0.23	0.13	-0.86**	-0.86**
	IT84S-2246	0.1	0.21	0.2	0.2
	Bambey-21	-1.39**	-1.12**	-0.73**	-0.73**
	INIA-152	1.27**	1.5**	0.95**	0.95**
	INIA-41	1.69**	2.04**	0.64**	0.64**
Number of pods per plant	IT82E-18	1.68**	0.82**	-0.09	-0.84
	UCR-P-24	-1.36**	-0.07	-2.09	-2.96*
	IT93K-503-1	0.14**	1.61**	6.85**	4.98**
	IT97K-499-39	0.26	0.02	-1.77	-1.52
	IT84S-2246	-0.57**	-0.91**	-5.02*	-3.59*
	Bambey-21	0.22	-0.35	1.6	1.23
	INIA-152	1.51**	-0.25	1.48	4.79**
	INIA-41	-1.86**	-0.87**	-0.96	-2.09
Number of seeds per pod	IT82E-18	0.35	0.23	0.23	0.2
	UCR-P-24	-0.11	0.38*	-0.67**	-0.79**
	IT93K-503-1	-0.44*	-0.74**	0.66**	0.69**
	IT97K-499-39	0.14	-0.1	-0.71**	-0.75**
	IT84S-2246	0.43*	-0.99**	-0.39*	-0.49*
	Bambey-21	-0.15	0.48**	-1.27**	-1.37**
	INIA-152	0.14	1.61**	1.67**	1.60**
	INIA-41	-0.36	-0.86**	0.66**	0.58**
Hundred seed weight	IT82E-18	-0.12	-0.05	0.02	0.48
	UCR-P-24	1.38**	0.91**	0.49	1.48**
	IT93K-503-1	-0.33	0.29	0.32	-0.85
	IT97K-499-39	0.09	-0.17	-0.48	-1.43*
	IT84S-2246	0.34	0.24	0.76	0.81
	Bambey-21	-0.62**	-0.3	0.54	0.94
	INIA-152	-3.12**	-2.38**	-3.54**	-3.52**
	INIA-41	2.38**	1.45**	1.88**	2.08**

Note: *,** = significant at 5 and 1%

4.3.6 Phenotypic correlations between yield and yield related traits

Among the four yield-related traits studied, the number of pods per plant had strong positive and significant correlation with yield (Table 4.13, 4.14, 4.15). All other correlations estimates among traits were weak and not significant.

Table 4.13: Correlations among grain yield, days to flowering, 100-seed weight, number of pods per plant and number of seeds per pod under drought-stressed conditions at Umbeluzi

	Days to flowering	100-seed weight	Pods per plant	Seeds per pod	Grain yield
Days to flowering	1.000				
100-seed weight	-0.055	1.000			
Pods/plant	-0.178	-0.448	1.000		
Seeds per pod	-0.037	-0.106	0.185	1.000	
Grain yield	-0.097	-0.068	0.583**	0.321	1.000

Table 4.14: Correlations among grain yield, days to flowering, 100-seeds weight, number of pods per plant and number of seeds per pod under non-stressed conditions at Chókwè

	Days to flowering	100-seed weight	Pods per plant	Seeds per pod	Grain yield
Days to flowering	1.000				
100-seed weight	-0.251	1.000			
Pods per plant	0.256	-0.124	1.000		
Seeds per pod	0.353	-0.321	0.168	1.000	
Grain yield	0.446	-0.016	0.698**	0.194	1.000

Table 4.15: Correlations among grain yield, days to flowering, 100-seeds weight, number of pods per plant and number of seeds per pod under drought-stressed conditions at Chókwè

	Days to flowering	100-seed weight	Pods per plant	Seeds per pod	Grain yield
Days to flowering	1.000				
100-seed weight	-0.083	1.000			
Pods per plant	0.133	-0.210	1.000		
Seeds per pod	0.176	-0.393	0.156	1.000	
Grain yield	0.299	-0.158	0.680**	0.114	1.000

4.4 Discussion

4.4.1 Drought tolerance assessment using stay-green trait

Significant differences were detected among genotypes for stay-green (number of green plants) indicating that genetic variability for this trait existed amongst the genotypes used in the study. These results are in agreement with Gwathmey and Hall (1992) who found contrasting genotypic responses to stay-green in cowpea. The drought tolerant genotypes IT93K-503-1, IT97K-499-39 and INIA-41 had more than 50% green plants at 45 days after stress imposition when the susceptible genotypes INIA-152, UCR-P-24 and IT82E-18 were almost or completely dead. Both additive and non-additive gene effects accounted for the genetic determination of stay-green, but additive gene action was more important than the non-additive gene action since the GCA mean squares were greater than the SCA in all dates. This indicates that progeny performance for stay-green can be predicted based on general combining ability of the parents. This trait can easily be accessed visually and selection for it in the progeny could be conducted in early segregating generations. Ismail *et al.* (2000) indicated stay-green trait can be selected effectively beginning from the F3 families provided that a field nursery is available that has a senescence soil environment.

The general combining ability (GCA) estimates of the different genotypes were variable. The GCA estimates of genotypes IT93K-503-1, IT97K-499-39 and INIA-41 were high, positive and highly significant except those of IT97K-499-39 which were moderately high while those for genotypes IT82E-18, UCR-P-24 and INIA-152 were high negative and highly significant. According to Viana (2000) such variation in GCA values indicates strong differences in gene frequencies and genetic divergence among the population and the diallel parents for the trait under study. The high and positive GCA values of IT93K-503-1, INIA-41 and IT97K-499-39 were determined by genes that increased the ability of plants to survive under progressive drought conditions. These genotypes were also the highest yielding under severe drought conditions at Umbeluzi suggesting that the genes determining survival were also involved in determining yield performance under drought conditions.

The performance of the F2 populations generated from the different crosses was variable. However, populations generated from the crosses involving one of the genotypes with high and positive GCA effects (INIA-41 or IT93K-503-1) had high number of green plants in different sampling dates which confirm the role of additive gene effects in controlling stay-green trait in cowpea. Given the foregoing, for genetic improvement for drought tolerance using stay-green as a trait for selection, genotypes IT93K-503-1 and INIA-41 could be the most desirable to use as parents.

4.4.2 Performance of genotypes based on yield and yield components

Significant differences were detected among genotypes for yield, days to flowering, number of pods per plant, number of seeds per pod and hundred seed weight. Both additive and non-additive gene action accounted for the genetic determination of these traits, but additive gene action was more important than non-additive gene action for days to flowering, number of pods per plant, number of seeds per pod and hundred seed weight since the GCA mean squares were greater than the SCA mean squares in all environments. Romanus *et al.* (2008) reported the prevalence of additive gene action over the non-additive gene action for yield, number of seeds per pod, pod length, hundred seed weight and days to flowering. In their study, non-additive gene action was more important than additive gene action for the number of pods per plant. The difference in this findings may be explained by the differences in environmental conditions where the experiments were conducted as well as the differences in the genetic make-up of their germplasm compared to that was used in the present study because it has been suggested that combining ability and heritability estimates are specific to the germplasm and environmental conditions where the materials are evaluated. These results suggested that genetic improvement of cowpea yield using days to flowering, number of seeds per pod and hundred seed weight as indirect selection criteria would be possible and it could be predicted based on performance of the parents. However, results of phenotypic correlations between yield and yield related traits indicated that only the number of pods per plant would be useful for improving yield since the correlation between yield and number of pods per plant was high and positive.

Additive gene action appeared to be more important in determining yield under high or moderate moisture availability but not under severe drought conditions. The general combining ability effects of yield under severe drought at Umbeluzi were lower than the SCA effects. These results indicated that yield performance under drought conditions could not be predicted based on performance of the parents. This implies that selection for yield under severe drought would be difficult. However, given the higher GCA effects than SCA effects for the number of pods per plant under drought and strong correlation between yield and number of pods per plant, yield improvement under drought would be achieved using the number of pods per plant as indirect selection criterion for yield. Given the moderate magnitude of GCA:SCA ratio, selection for yield and number of pods per plant would be effective in late segregating generations when the genes are fixed.

Genotype IT93K-503-1 was found to be the best combiner for yield and number of pods per plant because it had higher yield and number of pods per plant and high positive GCA effects in most of the environments for yield and all environments for the number of pods per plant. This implies that this genotype might be the most desirable for yield improvement but under drought conditions, the number of pods per plant should be used as a selection criterion.

4.5 Conclusions

The objective of this study was to determine the gene action controlling stay-green, yield and components (days to flowering, number of pods per plant, number of seeds per pod and hundred seed weight) under drought stressed and non-stressed conditions. Based on the results obtained it is concluded that:

(1) The yield components (days to flowering, number of pods per plants, number of seeds per pod and hundred seed weight) were mostly controlled by additive gene action. Yield was mostly controlled by additive gene action under high moisture availability but under drought conditions non-additive gene action was more important.

A) Selection for stay-green would be effective in early segregating generation while for yield and number of pods per plant it would be effective in late segregating generations when the genes are fixed and fully expressed.

B) The genotypes IT93K-503-1 and INIA-41 would be the most desirable to use as parents in genetic improvement for drought tolerance using stay-green as a selection criterion while IT93K-503-1 would be the most desirable to use as a parent in genetic improvement for yield using yield as a selection criterion in high moisture availability and number of pods per plant in drought environments.

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Chapter Five

Genotype × Environment Interaction and Grain Yield Stability of Cowpea Genotypes under Drought-Stressed and Non-Stressed Environments in Southern Mozambique

Abstract

Studying genotype × environment interactions is crucial for designing recommendations about the best selection strategy in a breeding programme. This study was conducted to assess genotype × environment interactions and yield stability of 48 genotypes when grown under drought-stressed and non-stressed conditions. The GGE biplot method was used for quantifying the G×E interactions. Cross-over genotype × environment interactions were detected for yield indicating that genotypes responded differently to varying environmental conditions. Genotypes adapted to specific environmental conditions were identified. Genotypes IT-18, INIA-51, INIA-51A and Nhavanca were adapted to high yielding environments that were either drought stressed or non-stressed while VAR-11D was adapted to low yielding, stressful environments. Genotypes INIA-23A, INIA-81D, INIA-24, INIA-25, INIA-16 and INIA-76 were high yielding and the most stable while genotypes IT-18, INIA-51, INIA-51A, Nhavanca and VAR-11D were high yielding and most unstable. Genotypes Bambey-21, INIA-36, INIA-12 and Monteiro were consistently low yielding and stable except INIA-12 that was consistently unstable. The Chókwè site was a high yielding environment and adequate for identifying high yielding genotypes but not adequate for selection because it was not representative of an average environment while Umbeluzi was low yielding and not adequate for selection.

5.1 Introduction

Cowpea is a crop of major economic importance in Mozambique where it provides food and income particularly for the resource-poor households. The crop is produced under highly variable rainfall in amount and distribution over time and space which leads to low and unstable yields. Hence, high yield and yield stability should constitute major research and breeding objectives in the country.

Selecting genotypes for high yield and stability is generally complicated by genotype × environment interactions (G×E) caused by large and variable genotype by season and genotype by location interactions as a result of high variability in rainfall over seasons and locations and large differences in soil water-holding capacity and fertility across different agro-ecologies (Hall *et al.*, 1997). Ramagosa and Fox (1993) indicated that G×E interaction complicates selection and identification of superior genotypes because genotypes selected in one environment tend to perform poorly in other environments. In an attempt to solve the problem, plant breeders have adopted the multi-environmental trials (METs) for assessing several genotypes in several environments and the G×E interaction assessed. Yan and Hunt (1998) suggested that when the cross-over G×E interaction is present, the positive aspects of the G×E interaction have to be exploited to select for specifically adapted genotypes provided that the cross-over G×E interaction is repeatable over seasons or to select for yield stability and wide adaptation when the cross-over G×E interaction is not repeatable. Detecting the presence of G×E interaction can be done using the analysis of variance if the METs data is balanced. However, if the data is unbalanced, other methods for detecting and quantifying G×E interaction should be used because the analysis of variance will not be possible due to missing data (Yan and Hunt, 1998).

When G×E interaction is present, several methods can be used for quantifying it. The methods commonly used for quantifying G×E interaction include: contrasts (Yan and Hunt, 1998), linear regression (Finlay and Wilkinson, 1963; Eberhart and Russell, 1966), multivariate analysis such as principal component analysis (Zobel *et al*., 1988) and additive main effect and multiplicative interaction (AMMI) (Zobel *et al.*, 1988; Crossa, 1990; Gauch and Zobel, 1997). The merits and demerits of each one of these methods are discussed elsewhere (Kang and Miller, 1984). In recent years, the genotype plus the genotype by environment interaction, mostly known as GGE biplot has been proposed and widely adopted (Yan *et al.*, 2000; Yan *et al.*, 2001; Yan, 2002; Yan and Tinker, 2005; Gauch, 2006; Yan *et al.*, 2007; Burgueno *et al*., 2008). The GGE biplot has increasingly been used in mega-environment analysis (Yan and Rajcan, 2002; Casanoves *et al*., 2005; Sarmonte *et al.*, 2005; Yan and Tinker, 2005; Dardanelli *et al.*, 2006), genotype and test environment evaluation (Yan and Rajcan, 2002; Blanche and Myers, 2006), trait association (Yan and Rajcan, 2002) and heterotic pattern analysis (Yan and Hunt, 2002).

The GGE biplot is constructed by plotting the two principal components (PC1 and PC2) derived from the singular value decomposition (SVD) of environmental centred data (GGE matrix) such that three component matrices are generated; the singular value matrix (array), the genotype eigenvector matrix, and the environment eigenvector matrix. From the GGE biplot the information concerning the "which-won-where" patterns or best genotypes and their winning environments, the interrelationship among test environments and the ranking of genotypes based on both mean performance and stability can be visualized (Yan *et al.*, 2000; Yan *et al.*, 2001; Yan, 2002).

With G×E interaction being present and not repeatable, selection for yield stability and wide adaptation is recommended (Ramagosa and Fox, 1993; Yan and Hunt, 1998). Two concepts of stability have been reported, the static or biological and the dynamic or agronomic stability (Kang, 1998). Under the static concept, a genotype is indicated to be stable when its performance does not change with change in environmental conditions while under the dynamic concept a genotype is considered to be stable when it yields well relative to the productive potential of test environments (Ramagosa and Fox, 1993). Hill *et al.* (1998) indicated that the methods used for assessing the dynamic stability derive their stability estimates from the analysis of G×E interaction.

The objectives of this study were:

(1) to assess the G×E interactions, and

(2) to determine the stability for grain yield of 48 cowpea genotypes grown under drought-stressed and non-stressed conditions during three seasons in two sites.

The hypothesis tested was that cowpea germplasm in Mozambique is widely adapted.

5.2 Materials and methods

5.2.1 Site characterization and climatic conditions during the experimental period

The study was conducted during three seasons (2009 main season, 2009 off-season and 2010 main season) at Chókwè Research Station (24º 32'S, 33º 00'E, 15m above sea level) and Umbeluzi Research Station (26º 03'S, 32º 23'E, 15m above sea level). The characteristics of the sites are presented in Table 5.1. The two sites are located in a semi-arid area of Mozambique with an average annual rainfall of about 600 to 700mm. Most of the rain falls between November and April. The maximum temperatures in the two sites range between 24 and 34^{o}C and the minimum between 11 and 22^{o}C. The amount of water lost by evaporation measured with an evaporation tank is about two to three times higher than that received through rainfall indicating the need for supplementary irrigation to make up the soil water deficit. The soils in the two sites are clay loam.

Table 5.1: Characteristics of Chókwè and Umbeluzi Research Stations based on long term climatic data

Site	Type of data	Rainfall (mm)	Temperature maximum (^{o}C)	Temperature minimum (^{o}C)	Evaporation (mm)	Type of soils
Chókwè	Long term	600.0	24.0-34.0	12.0-22.0	1800.0	Clay loam
Umbeluzi	Long term	660.0	26.0-32.0	11.0-22.0	1360.0	Clay loam

During the experimental period the rainfall and evaporation were variable from season to season Table 5.2. Rainfall was higher in the 2010 season in the two sites than in the 2009 main and off-seasons. The 2009 off-season was the one with the lowest rainfall. During stress treatment, high rainfall was recorded at Chókwè during 2010 but not at Umbeluzi (data not shown). The minimum temperature varied from season to season with 2010 registering the lowest temperature in the two sites while at maximum temperature did not register considerable variation. The total evaporation measured using the evaporation tank also varied. It was higher in 2009 main season than in 2009 off-season and 2010 main season in the two sites. Among stations, the evaporation was higher at Umbeluzi than at Chókwè. The water deficit between the rainfall received and the evaporation was made up by supplementary irrigation. In addition to differences in environmental conditions, Umbeluzi registered high incidence of insects pests such as aphids, white fly and flower thrips in all seasons while at Chókwè only aphids were recorded at low population densities.

Table 5.2: Rainfall, maximum and minimum temperatures and evaporation at Chókwè and Umbeluzi Research Stations during three cropping seasons

Site	Type of data	Season	Rainfall (mm)	Temperature maximum (^{o}C)	Temperature minimum (^{o}C)	Evaporation (mm)
Chókwè	During the experiments	1	168.8	28.7-32.8	16.1-22.7	120.9
		2	120.7	27.4-31.9	12.6-20.5	50.7
		3	317.4	29.6-33.0	12.2-17.8	69.6
Umbeluzi	During experiments	1	155.8	29.0-31.3	14.9-21.8	646.3
		2	98.2	25.0-30.0	16.0-20.0	319.8
		3	295.2	27.8-29.8	12.2-20.2	323.9

Note: 1=2009 main season planting (February to May); 2=2009 off-season planting (August to November), 3=2010 main season planting (March to May) at Chókwè and (April to July) at Umbeluzi

5.2.2 Cowpea germplasm

Forty-eight (48) cowpea genotypes consisting of landraces and improved lines were used in this study. Amongst them, 24 genotypes were collected from farmers, 18 genotypes were sourced from the national gene-bank at National Research Institute of Mozambique (IIAM) and six (6) from the University of California Riverside in the United States of America. The names and origins of the different materials used in the study are presented in Table 5.3.

Table 5.3: Name of genotypes and origin of 48 genotypes evaluated for grain yield stability at Chókwè and Umbeluzi

Entry	Genotype	Origin	Entry	Genotype	Origin	Entry	Genotype	Origin
1	Bambey-21	Senegal	17	INIA-30	Mozambique	33	INIA-78A	Mozambique
2	Inhaca-D	Mozambique	18	INIA-31	Mozambique	34	INIA-81D	Mozambique
3	Inhaca-E	Mozambique	19	INIA-34	Mozambique	35	IT-18	Mozambique
4	Inhaca-G	Mozambique	20	INIA-36	Mozambique	36	IT82E-18	IITA
5	Inhaca-I	Mozambique	21	INIA-36I	Mozambique	37	IT97K-499-39	IITA
6	INIA-1	Mozambique	22	INIA-42C	Mozambique	38	Monteiro	Brazil
7	INIA-11	Mozambique	23	INIA-42F	Mozambique	39	Mounge	Senegal
8	INIA-11A	Mozambique	24	INIA-5	Mozambique	40	Namuesse	Mozambique
9	INIA-12	Mozambique	25	INIA-51	Mozambique	41	Namuesse-D	Mozambique
10	INIA-16	Mozambique	26	INIA-51A	Mozambique	42	Namurua	Mozambique
11	INIA-19	Mozambique	27	INIA-5A	Mozambique	43	Nhavanca	Mozambique
12	INIA-19A	Mozambique	28	INIA-5E	Mozambique	44	UCR-P-24	UCR
13	INIA-23A	Mozambique	29	INIA-67D	Mozambique	45	Var-3A	Mozambique
14	INIA-24	Mozambique	30	INIA-71G	Mozambique	46	Var-10B	Mozambique
15	INIA-25	Mozambique	31	INIA-73B	Mozambique	47	Var-11D	Mozambique
16	INIA-3	Mozambique	32	INIA-76	Mozambique	48	Var-50B	Mozambique

Note: IITA=International Institute of Tropical Agriculture; UCR=University of California Riverside

5.2.3 Experimental design, field evaluation and data collection

The forty-eight (48) genotypes were evaluated using a 12×4 α-lattice design. Three replications were used during the 2009 main season and 2009 off-season and two during the 2010 season at Umbeluzi. At Chókwè, two replications were used in all seasons. The genotypes were grown under drought-stressed and non-stressed conditions in all seasons in both sites. Water stress treatment was imposed by withholding irrigation from flower bud emergence (50% of plants with flower buds) to physiological maturity to the water stressed experiments while in non-stressed experiments the plants were watered regularly to field water capacity up to maturity. To avoid water seepage the non-stressed experiments were established thirty-meters away from the water stressed ones. The plot size consisted of four-rows of five meters long at inter- and intra-row spacing of 75cm and 20cm, respectively. Two seeds were planted per hill and thinned to one plant per hill at 7 days after germination. Recommended agronomic practices were followed in all experiments. Data on grain yield (kgha^{-1}) was recorded at physiological maturity in the two-centre rows of each plot.

5.2.4 Data analysis

The yield data was analyzed using GenStat 12.0 computer software (Payne *et al.,* 2009). The mixed models residual maximum likelihood (REML) was used to compute the variance components. Given the significant interactions, the analysis of genotype by environment interaction and genotypes yield stability were assessed using the GGE biplot method developed by Yan *et al.* (2000) using the GenStat 12.0 computer software (Payne *et al.,* 2009).

The model used for analysing the GGE biplot according to Yan *et al.* (2000) was as follows:

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

Where Y_{ij} is the measured mean yield of genotype *i* (=1, 2, ..., n) in environment *j* (=1, 2, ..., m); μ is the grand mean; B_j is the main effect of environment *j*; λ_1 and λ_2 are the singular values (SV) of 1st and 2nd principal component (PC1 and PC1, respectively), the square of which are the sum of squares explained by PC1 and PC2 for a two dimension biplot; ξ_{i1} and ξ_{i2} are the eigenvectors of genotype *i* for PC1 and PC2, respectively; η_{1j} and η_{2j} = the eigenvectors of environment *j* for PC1 and PC2, respectively; ε_{ij} is the residual error associated with genotype *i* in environment *j*.

Yan *et al.* (2001) referred to the model constructed from the decomposition of environment centred data as site regression and with two principal components as site regression two models (SREG2). Singular value partitioning is done using the following formula

$$g_{il} = \lambda_l^{f_1} \xi_{il} \quad \text{and} \quad e_{lj} = \lambda_l^{1-f_1} \eta_{lj}$$

Where f_l is the partition factor for PC_l. Theoretically, f_l can be a value between 0 and 1, but 0.5 is the most commonly used.

GGE biplot allows visualization of "which-won-where" patterns or the best genotypes and the environments where they won, the interrelationship among test environments and the ranking of genotypes based on both mean performance and stability (Yan, 2002). For the "which-won-where" patterns, a polygon view of the GGE biplot is drawn which indicates the best genotype or genotypes in each environment or group of environments (Yan, 2002). The polygon is formed by connecting the markers of genotypes that are farther away from the biplot origin such that all other genotypes are contained in the polygon. The rays perpendicular to the polygon sides or their extensions are drawn such that they divide the biplot into sectors such that some environments fall into some of the sections. The genotype or genotypes in the vertex of the sector has the highest yielding in all environments falling in that sector but if the sector does not have any environment it indicates that the genotype is poor yielding in all environments (Yan *et al.*, 2000).

Ranking of genotypes based on mean yield and stability, is done by drawing a line that passes through the biplot origin and average environment with the arrow pointing to the greater genotype main effect which represents the average environment coordination (AEC) axis or AEC abscissa. Perpendicular to this line is the ordinate of the AEC. Further away from the biplot origin in the direction of ordinate AEC indicates greater G×E and reduced stability (Yan, 2002). The genotypes projections onto the AEC abscissa are good approximations of the genotypes main effects. An ideal genotype should have the highest mean performance and be absolutely stable (perform the best in all environments). Such an ideal genotype is defined by having the highest vector length of the high-yielding genotypes and zero G×E. A genotype is more desirable if it is located closer to the ideal cultivar (Yan, 2002). Likewise, an ideal test environment should have large PC1 score (more discriminating of the cultivars) and near-zero PC2 scores (more representative of an average environment) (Yan *et al.*, 2001).

For determining the interrelationship among test environments, the lines connecting the biplot origin to the markers of environment are called environmental vectors (Yan, 2002). The angle between the vectors of two environments is related to the correlation coefficient between them. The smaller the angle between vectors, the higher the correlation among environments.

5.3 Results

5.3.1 Analysis of variance

The results of analysis of variance (ANOVA) indicated that the genotypes, sites, seasons and water regime were highly significant ($p<0.01$) (Table 5.4). Sites followed by water regimes and site × season were the major sources of variation while varieties, seasons and other interactions were minor sources of variation. The interactions among genotypes, sites, seasons and water regime were also highly significant except for the interaction of site × water regime that was not significant. The significant interactions indicated that genotypes responded differently to water regimes, seasons and sites and also to a combination of sites × seasons, sites × water regime and sites × seasons × water regimes. The seasons were not the same across sites as indicated by significant site × season interactions. Similarly, water regimes were not the same within seasons across sites.

Table 5.4: Analysis of variance for grain yield of 48 cowpea genotypes grown under water stressed and non-stressed conditions in two sites during 3 seasons in southern Mozambique

Sour of variation for fixed terms	D.F.	Wald statistic	Wald statistic/D.F.	chi pr
Genotypes	47	865.03	18.4	<0.001
Site	1	2612.02	2612.02	<0.001
Season	2	375.46	187.73	<0.001
Water regime	1	1493.29	1493.29	<0.001
Genotypes × Site	47	357.74	7.61	<0.001
Genotypes × Season	94	828.6	8.81	<0.001
Site × Season	2	970.78	485.39	<0.001
Genotypes × Water regime	47	194.18	4.13	<0.001
Site × Water regime	1	0.67	0.67	0.413
Season × Water regime	2	23.56	11.78	<0.001
Genotypes × Site × Season	94	766.06	8.15	<0.001
Genotypes × Site × Water regime	47	201.99	4.3	<0.001
Genotypes × Season × Water regime	94	414.52	4.41	<0.001
Site × Season × Water regime	2	302.49	151.25	<0.001
Genotypes × Site × Season × Water regime	94	423.39	4.5	<0.001

5.3.2 Yield performance of genotypes within sites, seasons and water regimes and season × site and season × water regime interaction

The genotypes × sites, genotypes × seasons, genotypes × water regimes interactions are presented in Table 5.5. The grain yield of all 48 genotypes was lower at Umbeluzi than at Chókwè. At Chókwè the grain yield of the genotypes ranged between 865 and 2879 compared to 371 and 1535 for Umbeluzi. Genotype Monteiro produced the lowest yield in both sites while the highest yield was produced by Nhavanca at Chókwè and INIA-51 at Umbeluzi. Genotypes Inhaca-I, INIA-12, INIA-5, INIA-5A, INIA-5E, INIA-42C, INIA-42F, INIA-67D, INIA-71B, IT-18, IT97K-499-39, Nhavanca, VAR-3A, VAR-10B and VAR-11B when grown at Umbeluzi produced less than 50% of the yields that they achieved at Chókwè, thus indicating that they were not stable. The grain yield of INIA-19A, INIA-34, INIA-71G and Inhaca-E although lower at Umbeluzi compared to Chókwè, was only 22% below that obtained at Chókwè, except for INIA-71G which was 28%, indicating that they were relatively stable. The high incidence of aphids, white-fly and thrips observed at Umbeluzi during all seasons despite insecticide applications, may have accounted for the lower yields. At Chókwè, aphids were observed at low population densities and no white-fly and flower thrips were observed during all seasons.

The grain yield of the 48 genotypes varied with season indicating different reaction of genotypes to change in seasons. The grain yield of the 48 genotypes was in general lower in the 2010 season than in 2009 main season and off-season. It ranged between 749 and 2655Kgha^{-1} in 2009 main season, between 0 and 2554Kgha^{-1} in 2009 off-season, and between 633 and 2123Kgha^{-1} in the 2010 main season. The lowest yielding genotypes were Monteiro, INIA-12 and Bambey-21 in 2009 main season, 2009 off-season and 2010, respectively, while the highest yielding genotypes were INIA-51A, VAR-11D and Nhavanca in 2009 main season, 2009 off-season and 2010, respectively. The genotypes that showed lower yield variation in different seasons were INIA-1, INIA-24, INIA-31, INIA-51, IT97K-499-39, Inhaca-E, Inhaca-I and Nhavanca while genotypes Bambey-21, INIA-12, INIA-3, INIA-16, INIA-34, INIA-36I, INIA-5A, INIA-71G, INIA-73B, INIA-76, IT-18, Monteiro, Namuesse-D, VAR-11D showed higher yield variation.

The grain yield of the 48 genotypes also varied with water regime, indicating that genotypes reacted differently to the change in water regime. The grain yield of the 48 genotypes varied between 707 and 2572 Kgha^{-1} in non-stressed conditions and between 529 and 1696 Kgha^{-1} in stressed conditions. Monteiro was the lowest yielding genotype in both stressed and non-stressed conditions while Nhavanca was the highest yielding under non-stressed conditions and INIA-81D the highest yielding under stressed conditions. Genotypes INIA-12, INIA-19, INIA-24 and IT82E-18 were less affected by water stress since their yields were reduced by less than 20%. In contrast, Inhaca-D, Inhaca-E, IT-18, INIA-5A, INIA-3, INIA-23A, INIA-30, INIA-34, INIA-42C, Mounge, Namurua, Namuesse-D and VAR-50B were very sensitive to water stress since their yields were reduced by more than 40%.

Table 5.5: Grain yield of 48 cowpea genotypes recorded at Chókwè and Umbeluzi during 2009 main and 2009 off-season and 2010 main season when grown under drought-stressed and non-stressed conditions

	Site				Season			Water regime			
Genotype	Chókwè	Umbeluzi	% Red.	Mean	Main-09	Off-09	Main-10	No-stress	Stress	% Red.	Mean
Nhavanca	2879	1276	55.7	2077.5	1977	2133	2123	2572	1583	38.5	2077.5
INIA-51	2477	1535	38.0	2006.0	2009	2151	1858	2454	1557	36.6	2005.5
INIA-5E	2798	1165	58.4	1981.5	2262	1917	1766	2267	1696	25.2	1981.5
IT-18	2670	1266	52.6	1968.0	2496	1999	1409	2471	1465	40.7	1968.0
INIA-51A	2538	1372	45.9	1955.0	2655	1572	1638	2407	1503	37.6	1955.0
I-81D	2447	1421	41.9	1934.0	2030	2053	1720	2172	1696	21.9	1934.0
VAR-11D	2594	1225	52.8	1909.5	1963	2554	1212	2172	1648	24.1	1910.0
INIA-42C	2636	1176	55.4	1906.0	2152	2144	1421	2388	1424	40.4	1906.0
INIA-25	2311	1417	38.7	1864.0	2018	1868	1706	2227	1501	32.6	1864.0
INIA-24	2406	1274	47.0	1840.0	1908	1895	1715	2007	1673	16.6	1840.0
INIA-5	2469	1097	55.6	1783.0	1658	1739	1953	2061	1505	27.0	1783.0
INIA-42F	2386	1167	51.1	1776.5	2108	1780	1441	2027	1526	24.7	1776.5
INIA-23A	2207	1313	40.5	1760.0	1973	2036	1271	2205	1316	40.3	1760.5
INIA-71G	2047	1471	28.1	1759.0	1885	2033	1360	2180	1339	38.6	1759.5
INIA-67D	2342	1147	51.0	1744.5	1828	1987	1420	2095	1394	33.5	1744.5
INIA-16	2160	1325	38.7	1742.5	2035	1723	1469	2110	1376	34.8	1743.0
INIA-11	2216	1263	43.0	1739.5	2045	1775	1399	2043	1435	29.8	1739.0
INIA-34	1941	1528	21.3	1734.5	1440	2260	1503	2244	1225	45.4	1734.5
INIA-73B	2332	1113	52.3	1722.5	1972	2161	1035	2027	1418	30.0	1722.5
INIA-76	2194	1241	43.4	1717.5	1800	2118	1235	2047	1389	32.1	1718.0
INIA-19A	1922	1507	21.6	1714.5	1938	1757	1449	2112	1317	37.6	1714.5
INIA-5A	2336	1061	54.6	1698.5	1686	2100	1310	2173	1225	43.6	1699.0
INIA-36I	2121	1243	41.4	1682.0	1636	2129	1282	2058	1307	36.5	1682.5
INIA-19	2181	1178	46.0	1679.5	1991	1946	1102	1812	1548	14.6	1680.0
IT97K-499-39	2339	1007	56.9	1673.0	1771	1693	1555	2061	1285	37.7	1673.0
Namuesse	2002	1318	34.2	1660.0	1763	1904	1314	2003	1317	34.2	1660.0
I-78A	2007	1285	36.0	1646.0	1912	1364	1663	2199	1094	50.3	1646.5
Inhaca-I	2223	1055	52.5	1639.0	1490	1683	1743	2040	1237	39.4	1638.5
VAR-50B	1927	1334	30.8	1630.5	1680	1865	1348	2063	1198	41.9	1630.5
Inhaca-E	1811	1441	20.4	1626.0	1686	1701	1491	2059	1193	42.1	1626.0
INIA-11A	2061	1118	45.8	1589.5	1686	1782	1300	1797	1381	23.1	1589.0
Namurua	1903	1196	37.2	1549.5	1612	1754	1283	2004	1096	45.3	1550.0
INIA-3	2075	1005	51.6	1540.0	2142	1428	1051	2126	954	55.1	1540.0
INIA-30	1714	1344	21.6	1529.0	1325	1533	1728	1935	1122	42.0	1528.5
IT82E-18	1908	1148	39.8	1528.0	1193	2240	1151	1688	1368	19.0	1528.0
Inhaca-D	1934	1097	43.3	1515.5	1913	1604	1029	1986	1044	47.4	1515.0
Mounge	2010	996	50.4	1503.0	1992	1152	1365	1905	1101	42.2	1503.0
INIA-31	1778	1226	31.0	1502.0	1427	1557	1522	1806	1199	33.6	1502.5
Namuesse-D	1866	1112	40.4	1489.0	2009	1466	991	1899	1078	43.2	1488.5
VAR-10B	1997	971	51.4	1484.0	1689	1381	1382	1729	1239	28.3	1484.0
UCR-P-24	1679	1271	24.3	1475.0	1281	1656	1489	1703	1248	26.7	1475.5
INIA-1	1909	1024	46.4	1466.5	1442	1594	1363	1667	1266	24.1	1466.5
Inhaca-G	1885	1025	45.6	1455.0	1686	1274	1406	1790	1120	37.4	1455.0
VAR-3A	2106	759	64	1432.5	1756	1515	1026	1711	1154	32.6	1432.5
INIA-36	1546	860	44.4	1203.0	1527	1017	1065	1404	1002	28.6	1203.0
Bambey-21	1500	888	40.8	1194.0	1476	1472	633	1402	986	29.7	1194.0
INIA-12	1558	519	66.7	1038.5	1807	0	1314	1072	1004	6.30	1038.0
Monteiro	865	371	57.1	618.0	743	301	810	707	529	25.2	618.0
Mean	2109	1170		1639.5	1802	1724	1392	1981	1298		1639.5
LSD0.05	197.8	197.8	197.3		242.1	242.1	242.1	197.6	197.6	197.3	
CV (%)	5.7	10.3			8.2	8.5	10.6	6.1	9.3		

Note: % Red. = percentage reduction; Main-09, Off-09 and Main-10 are 2009 main season, 2009 off-season and 2010 main season, respectively

The season × site and season × water regime interactions are presented in Table 5.5. The grain yield recorded in the three seasons varied within and between sites. It ranged between 1816 and 2430 at Chókwè and between 704 and 1633 at Umbeluzi (Table 5.6). The highest yield was recorded in 2009 main season at Chókwè and in 2009 off-season at Umbeluzi while the lowest yield was recorded in 2009 off-season at Chókwè and 2010 main season at Umbeluzi. The grain yields at Umbeluzi compared to Chókwè were 51.7 and 66.2% lower during the 2009 and 2010 main seasons, respectively.

The grain yield for the three seasons also varied with water regime. It ranged between 1743 and 2190 under non-stressed and between 1041 and 1438 under stressed conditions (Table 5.6). The highest grain yield under non-stressed conditions was recorded in 2009 main season while under non-stressed conditions it was recorded in 2009 off-season. The lowest yields were recorded in 2010 for both stressed and non-stressed conditions. Drought stress was more intense in 2010 followed by 2009 main season.

Table 5.6: Grain yield of three seasons in two sites and two water regimes

	Site			Water regime		
Season	Chókwè	Umbeluzi	% Reduction	Non-stressed	Stressed	% Reduction
2009-main season	2430	1173	51.7	2190	1413	35.5
2009-off-season	1816	1633	10.1	2010	1438	28.5
2010-main season	2080	704	66.2	1743	1041	40.3
Mean	2109	1170		1981	1298	
LSD0.05	49.9	49.9	50.6	49.7	49.7	49.4
CV (%)	1.5	2.6		1.5	2.3	

5.3.3 The GGE biplot

The GGE biplot was used to explore genotypes × sites × seasons, genotypes × sites × water regime, genotypes × season × water regime and genotypes × site × season × water regime interactions presented in Figures 5.1A to 5.4D.

The GGE biplot of genotype × site × season interaction explained 60.84% of the total variation. The first principal component (PC1) explained 39.40% while the second principal component (PC2) explained 21.43% of the total variation. Figure 5.1A shows the best performing genotypes and their winning environments as well as the worst performing genotypes in different test environments. Genotype VAR-11D was the best performing at Chókwè during the 2009 off-season (A2) and at Umbeluzi in all three seasons (B1, B2 and B3). This genotype also yielded more than the average mean in the other two environments since the angles between the genotype and these two environments were less than 90^o. Genotypes INIA-51A and IT-18 were the best performing at Chókwè during 2009 main season (A1) and 2010 main season (A3). Genotypes Var-11D and IT-18 performed equally at Umbeluzi during the 2009 main season (B1) since the line perpendicular to the side defined by the two genotypes passed through this environment. Genotypes INIA-12, IT82E-18 and Monteiro were the worst performing genotypes in all environments since they were at the vertices of sections with no environments (Figure 5.1A).

Figures 5.1B and 5.1C show the relationships among the different combinations of sites and seasons. The two main seasons at Chókwè (2009 and 2010) were highly correlated since the angles between the vectors of these two environments were small. Likewise, all the three seasons at Umbeluzi plus the Chókwè 2009 off-season were also highly correlated. The environment Chókwè - 2009-off-season was more discriminating followed by Chokwe-2009-main season since the length of their vectors was higher than those of other environments. Chókwè and its main seasons were clearly different from the group of Umbeluzi and its three seasons plus the Chókwè off-season. The environments Umbeluzi–2009– main season and Umbeluzi-2010-main season were representative of Umbeluzi mega-environment since they had zero and near-zero PC2 scores, respectively (Figure 5.1C).

Figure 5.1D shows the ranking of 48 genotypes based on their mean yield and stability. Based on mean yield performance, genotype IT-18 was the highest yielding followed by INIA-5E, INIA-42C, Nhavanca and VAR-11D. Other high yielding genotypes included INIA-51, INIA-51A, INIA-67D, Inhaca-D, INIA-76, INIA-16, INIA-24, INIA-23A, IT97K-499-39, INIA-5, INIA-42F, INIA-5a, INIA-36I and INIA-34. The rest of the genotypes had lower yields than the average mean. The lowest yielding genotypes were Bambey-21, INIA-36, INIA-12 and Monteiro. The most stable genotypes at the upper side of the mean were INIA-81D, INIA-16, INIA-24, INIA-76 and INIA-23A while at the lower side they were INIA-36 and Monteiro. The most unstable genotypes at the upper side of the mean were IT-18, VAR-11D, INIA-51A, INIA-42F, INIA-34, INIA-36I and INIA-5A while at the lower side of the mean they were IT82E-18, Namuesse-D, UCR-P-24 and INIA-12.

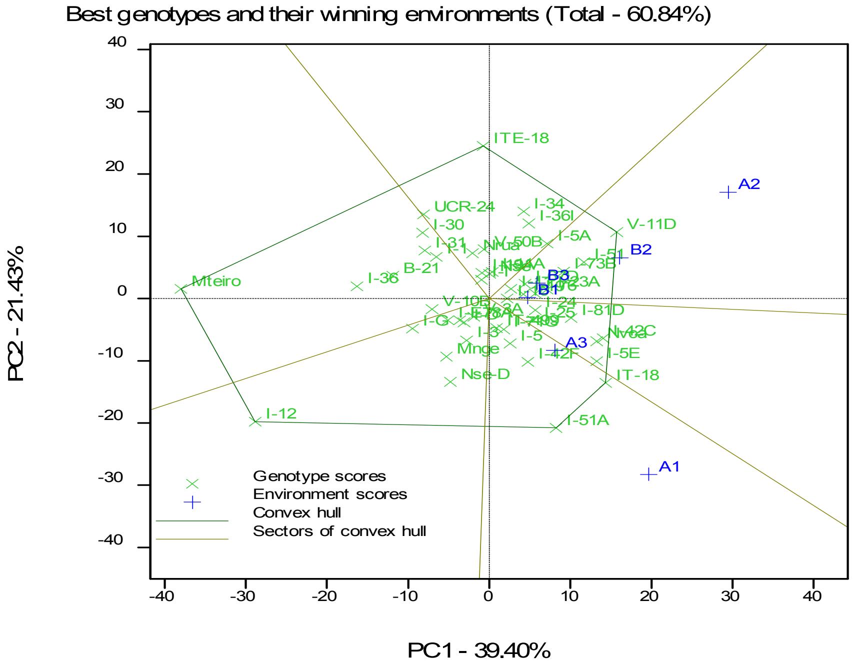

Figure 5.1A: Best performing genotypes in the combination of sites x seasons (A1=Chókwè × 2009 main season; A2=Chókwè × 2009 off-season; A3=Chókwè × 2010 main season; B1= Umbeluzi × 2009 main season; B2=Umbeluzi × 2009 off-season; B3=Umbeluzi × 2010 main season)

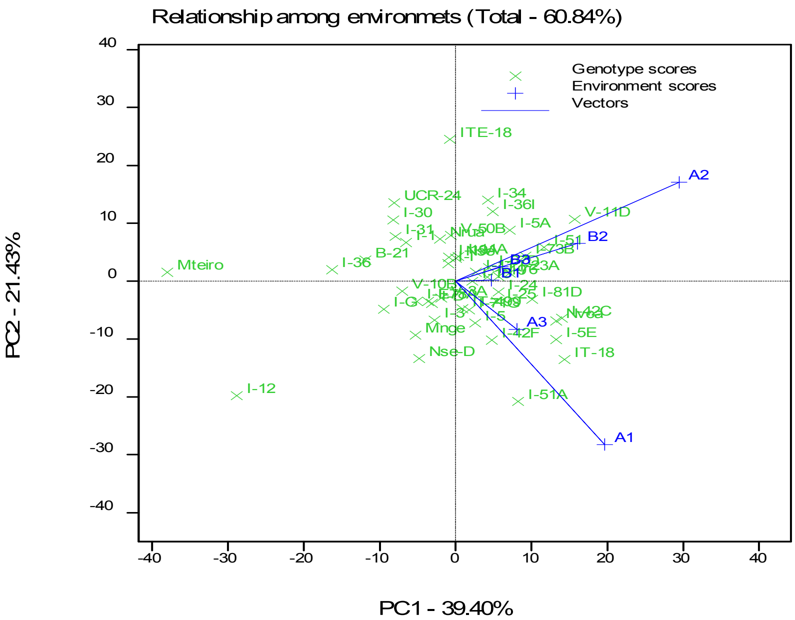

Figure 5.1B: Relationship among environments (sites x seasons) (A1=Chókwè × 2009 main season; A2=Chókwè × 2009 off-season; A3=Chókwè × 2010 main season; B1= Umbeluzi × 2009 main season; B2=Umbeluzi × 2009 off-season; B3=Umbeluzi × 2010 main season)

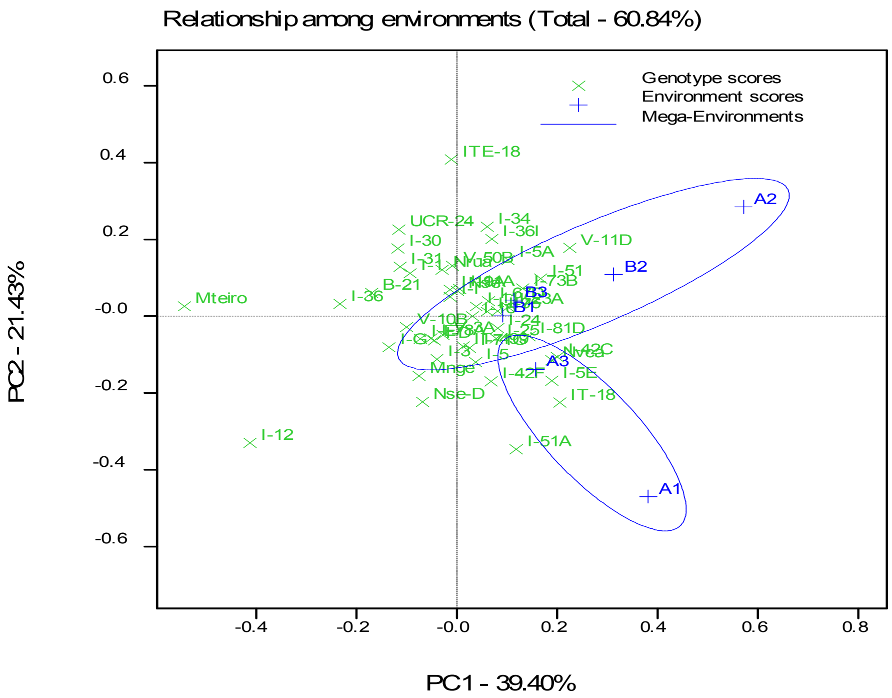

Figure 5.1C: Relationship among environments (sites x seasons) (A1=Chókwè × 2009 main season; A2=Chókwè × 2009 off-season; A3=Chókwè × 2010 main season; B1= Umbeluzi × 2009 main season; B2=Umbeluzi × 2009 off-season; B3=Umbeluzi × 2010 main season)

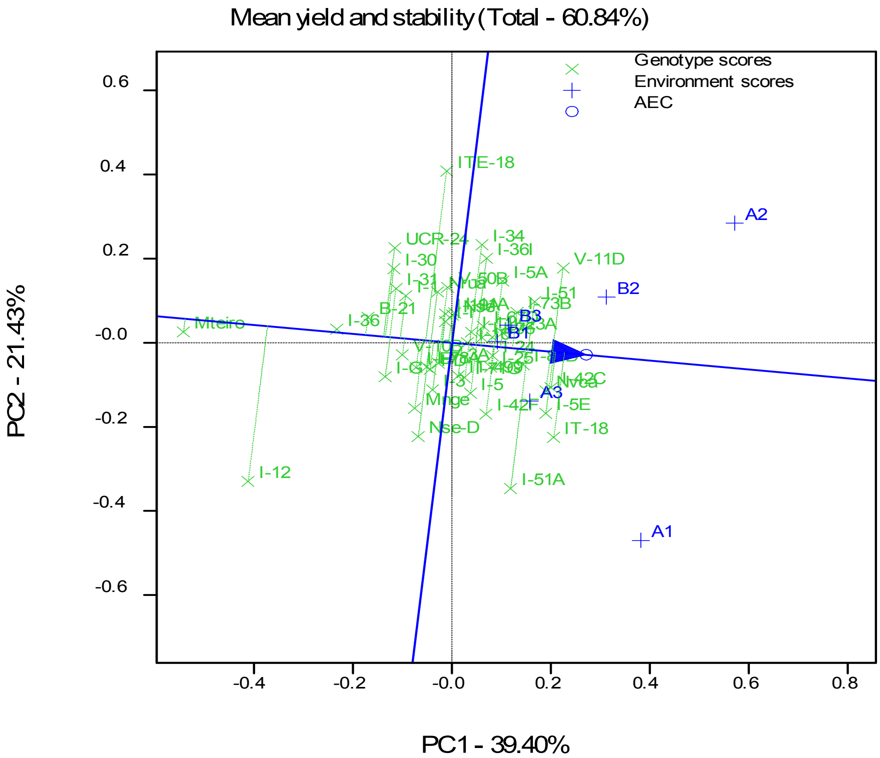

Figure 5.1D: Genotype mean and yield stability (A1=Chókwè × 2009 main season; A2=Chókwè × 2009 off-season; A3=Chókwè × 2010 main season; B1= Umbeluzi × 2009 main season; B2=Umbeluzi × 2009 off-season; B3=Umbeluzi × 2010 main season)

The biplot of genotype x site x water regime interaction explained 84.09% of the total variation (Figure 5.2A). The PC1 explained 64.74% of the total variation while the PC2 explained only 19.36%. Genotypes Nhavanca and IT-18 were the best performing in three of the four environments (Chókwè under stressed (A2) and Chókwè under non-stressed conditions (A1) plus the Umbeluzi under stressed conditions (B2)). Genotype Inhaca-E was the best performing only at Umbeluzi under non-stressed conditions (B1). Genotypes INIA-51, INIA-51A and INIA-71G were intermediate to Nhavanca and Inhaca-E at all sites since their marker scores were at the line connecting the two genotypes. Genotypes Inhaca-E, INIA-5E, INIA-12 and Monteiro were the worst genotypes in all environments since they were located at the vertices of sections with no environments.

The environments Chókwè-non-stressed and Chókwè-stressed were highly correlated (Figure 5.2B) but not with Umbeluzi under both water regimes. The environment Chókwè non-stressed was more discriminating followed by Umbeluzi non-stressed and Chókwè-stressed. Chókwè-stressed was more representative of the mega-environment consisting of Chókwè and its water regimes since its PC2 scores were smaller (Figure 5.2B and 5.2C).

Figure 5.2D shows the ranking of 48 genotypes based on their mean yield and stability. Based on mean performance, genotype Nhavanca was the highest yielding followed by IT-18, INIA-51 and INIA-51A. Other high yielding genotypes were INIA-5E, INIA-42C, VAR-11D, INIA-81D, INIA-76, INIA-24, INIA-23A, INIA-36I, INIA-73B, IT97K-499-39, INIA-5, INIA-67D, INIA-42F, INIA-16, INIA-25, INIA-24, Namuesse, INIA-71G, INIA-34, INIA19A and Inhaca-E. The lowest yielding genotypes were Bambey-21, INIA-36, INIA-12 and Monteiro. With regard to stability, the most stable genotypes at the upper side of the mean were INIA-51, INIA-51A, INIA-76, INIA-24, INIA-23A and INIA-36I while at the lower side of the mean the genotypes INIA-1 and INIA-36 were the most stable. The most unstable genotypes in the upper side of the mean were IT-18, Inhaca-E, INIA-5, INIA-71G, INIA-34 and INIA-19A while at the lower side of the mean the most unstable genotypes were INIA-30, VAR-3A, UCR-P-24 and INIA-12.

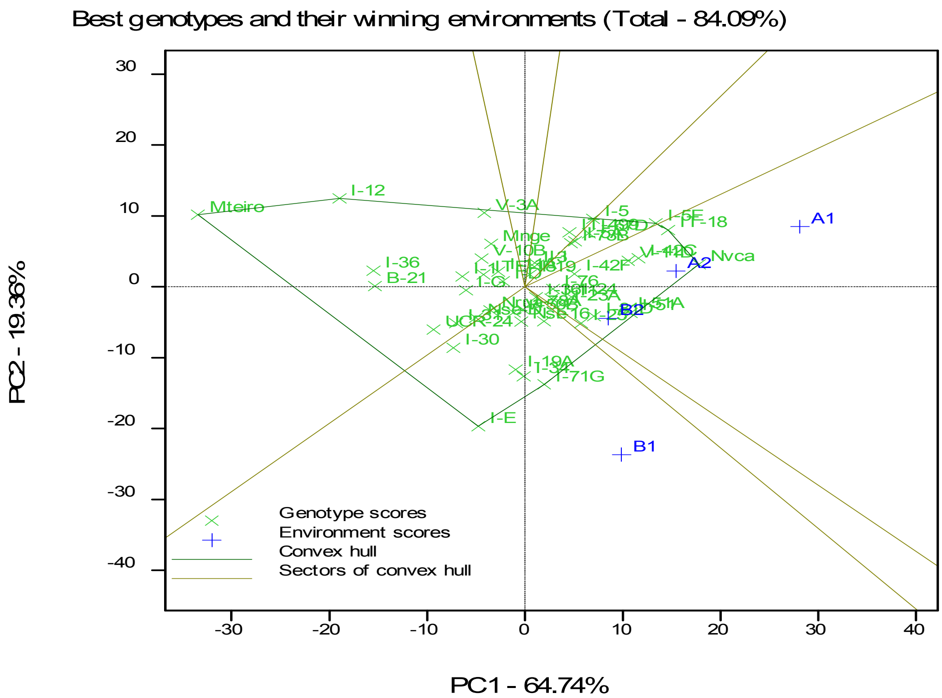

Figure 5.2A: Best performing genotypes in different sites and water regimes (A1=Chókwè × non-stressed; A2=Chókwè × stressed; B1= Umbeluzi × non-stressed; B2=Umbeluzi × stressed)

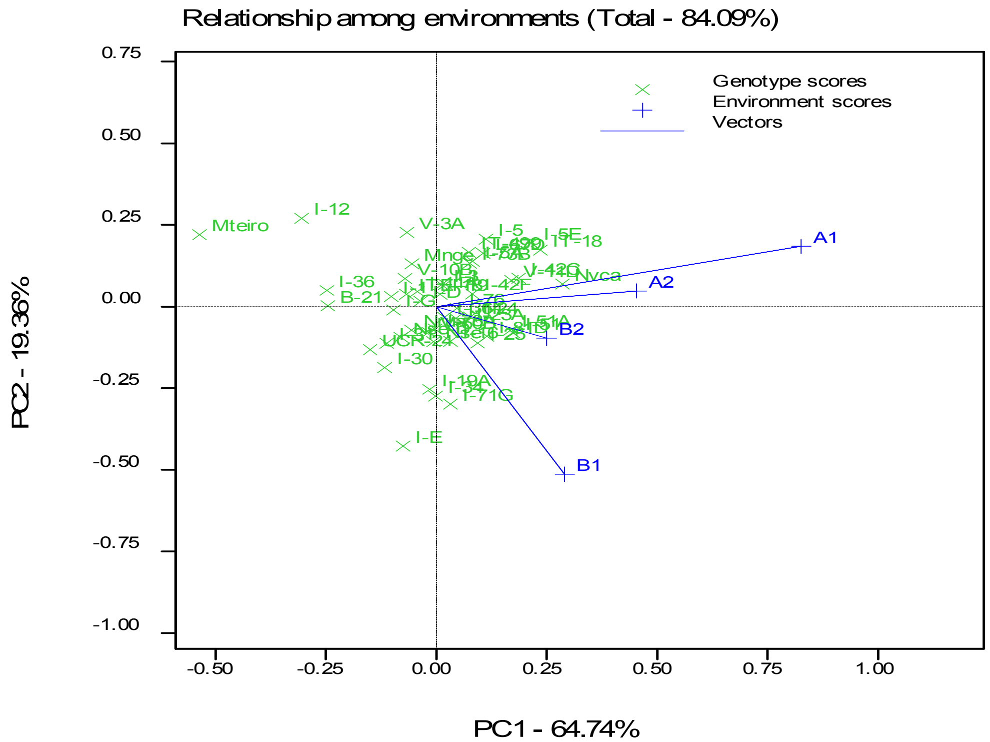

Figure 5.2B: Relationship among environments (site x water regime) (A1=Chókwè × non-stressed; A2=Chókwè × stressed; B1= Umbeluzi × non-stressed; B2=Umbeluzi × stressed)

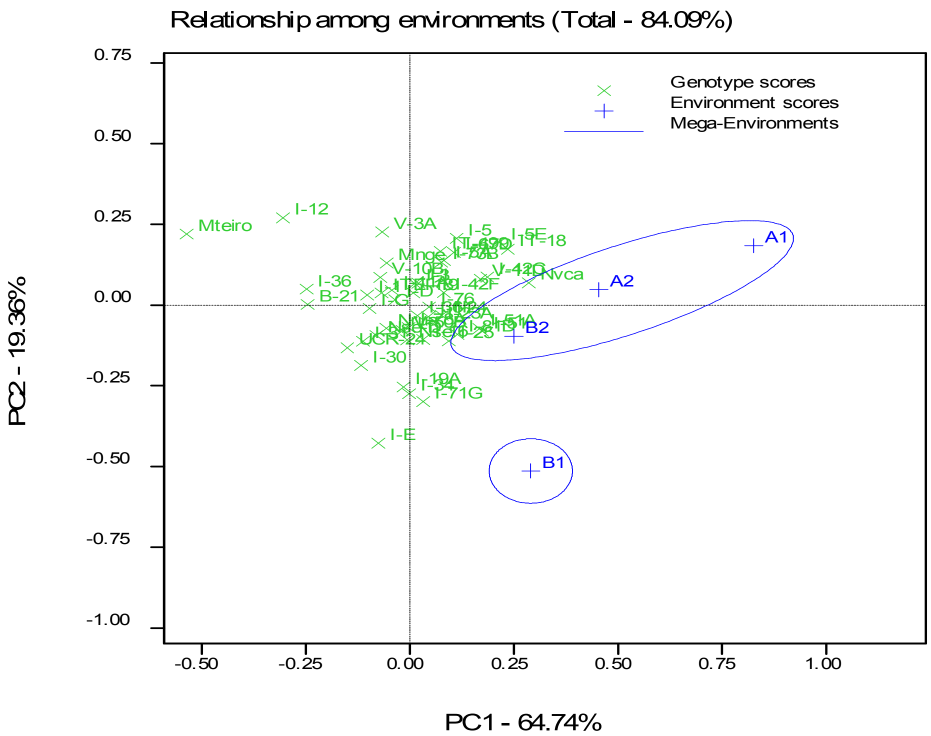

Figure 5.2C: Relationship among environments (site x water regime) (A1=Chókwè × non-stressed; A2=Chókwè × stressed; B1= Umbeluzi × non-stressed; B2=Umbeluzi × stressed)

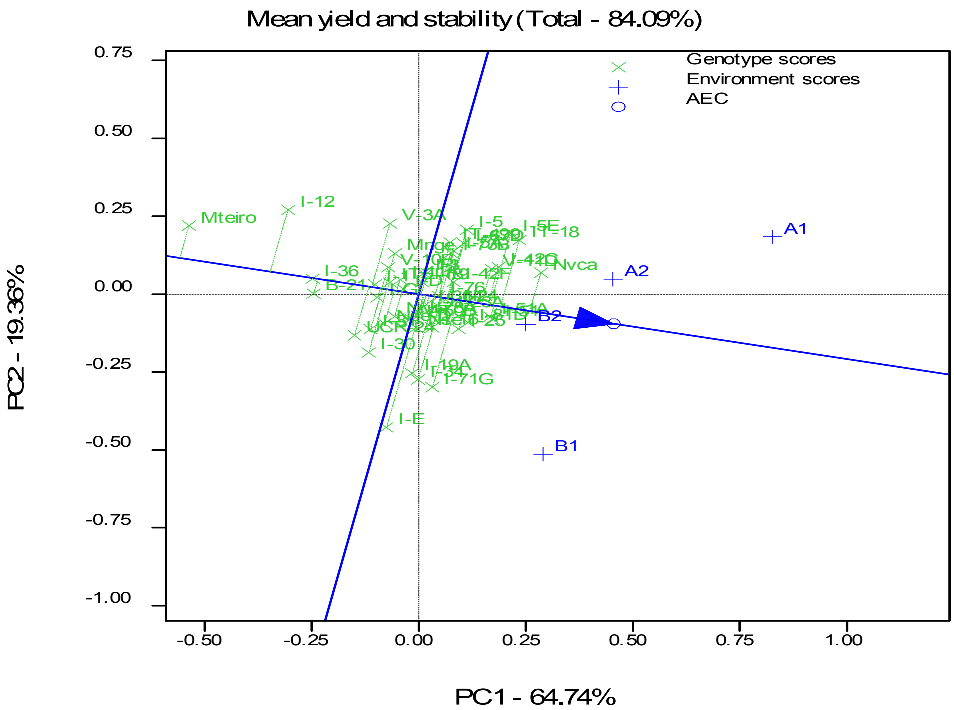

Figure 5.2D: Mean yield and yield stability of 48 genotypes in different site × water regimes (A1=Chókwè × non-stressed; A2=Chókwè × stressed; B1= Umbeluzi × non-stressed; B2=Umbeluzi × stressed)

The biplot of genotype x seasons x water regime interaction explained 66.17% of the total variation (Figure 5.3A). The PC1 explained 46.81% of the total variation while the PC2 explained only 19.37%. Genotype Nhavanca and INIA-51 were the best performing in four of the six environments (2009 main season under both stressed and non-stressed conditions (C1 and C2) plus the 2009-off-season under stressed conditions (D2) and 2010-main season under non-stressed conditions (E1)). Genotypes INIA-51A and VAR-11D were the best performing in one environment each, respectively, 2010 under stressed conditions and 2009 off-season non-stressed conditions. The worst genotypes in all environments were Bambey-21, INIA-12 and Monteiro.

Figures 5.3B and 5.3C show the relationship among different environments (combination of seasons and water regimes). The environment 2010-main season-non-stressed conditions (E1) was strongly correlated with 2009-main season for both stressed and nom-stressed conditions. The environment 2009-off-season-non-stressed (D1) was the most discriminating environment followed by the 2010 main season-non-stressed (E1) and 2009-off-season stress. The environment 2009-off-season-stress was more representative given its zero PC2 scores.

Figure 5.3D shows the ranking of 48 genotypes based on their mean yield and stability. Genotype INIA-51 was the highest yielding followed by Nhavanca, INIA-81D, INIA-5E and INIA-51A. Other high yielding genotypes were IT-18, INIA-16, INIA-19A, INIA-24, INIA-25, VAR-11D, INIA-34, INIA-42C, INIA-42F, INIA71G, INIA36I, INIA-67D, Inhaca-I, INIA-19, Namuesse-D, VAR-50B, INIA-78A, INIA-5, INIA-30, IT97K-499-39 and INIA-5A. The lowest yielding genotypes were VAR-3A, INIA-36, Bambey-21, INIA-12 and Monteiro. With regard to stability, the most stable genotypes at the upper side of the mean were IT-18 and INIA-42F while at the lower side of the mean they were INIA-1 and Monteiro. The most unstable genotypes in the upper side of the mean were INIA-51A, VAR-11D, INIA-5, INIA-5A, INIA-5E, INIA-71G, INIA-73B and INIA-78A while at the lower side of the mean the most unstable genotypes were Mounge, Namuesse-D, Bambey-21 and INIA-12.

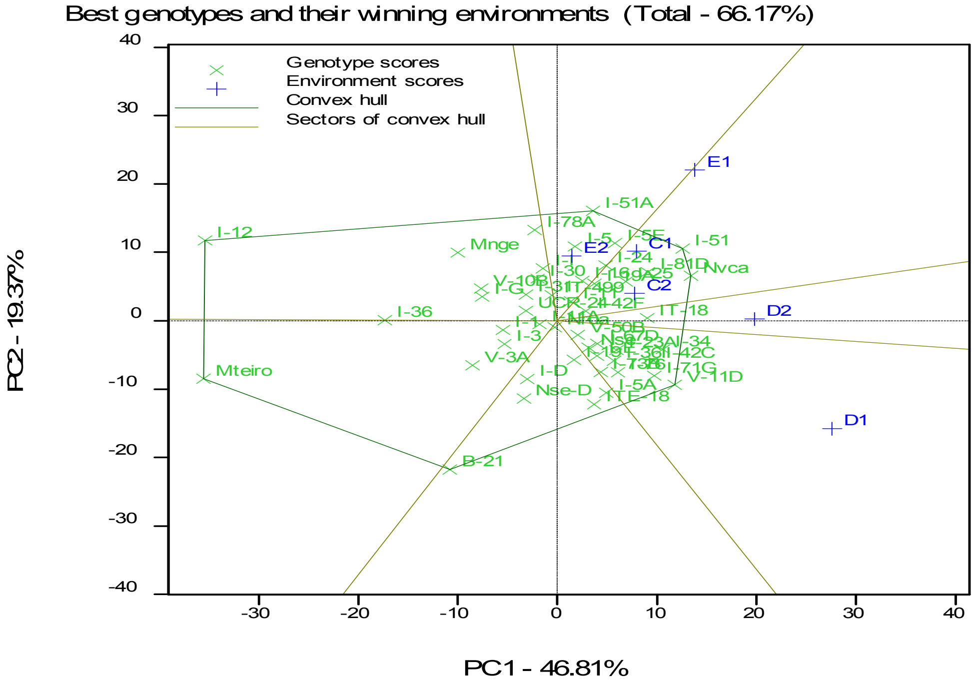

Figure 5.3A: Best performing genotypes in different seasons and water regimes (C1=2009-main season × non-stressed; C2=2009-main season × stressed; D1= 2009 off-season × non-stressed; D2=2009 off-season × stressed; E1=2010 main season × non-stressed; E2=2010 main-season × stressed)

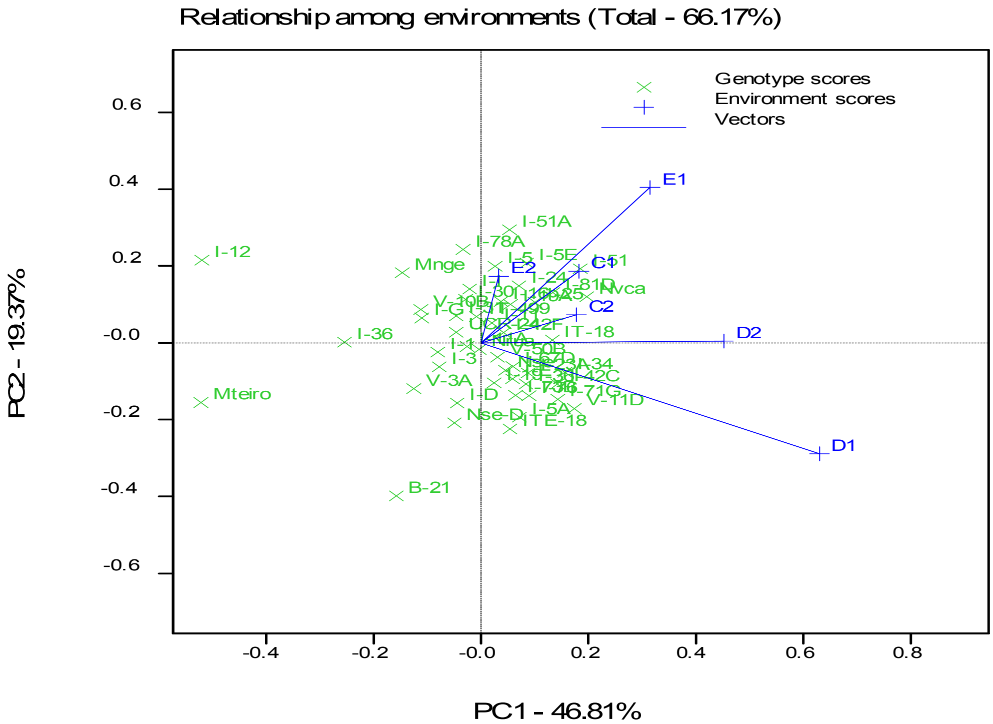

Figure 5.3B: Relationship among environments (seasons x water regimes) (C1=2009-main season × non-stressed; C2=2009-main season × stressed; D1= 2009 off-season × non-stressed; D2=2009 off-season × stressed; E1=2010 main season × non-stressed; E2=2010 main-season × stressed)

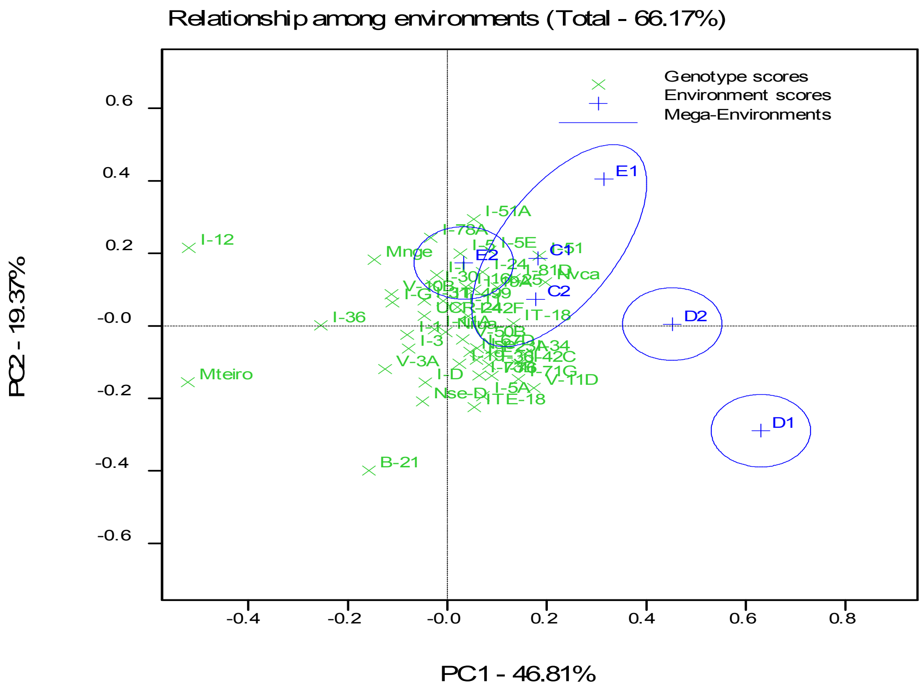

Figure 5.3C: Relationship among environments (seasons x water regimes) (C1=2009-main season × non-stressed; C2=2009-main season × stressed; D1= 2009 off-season × non-stressed; D2=2009 off-season × stressed; E1=2010 main season × non-stressed; E2=2010 main-season × stressed)

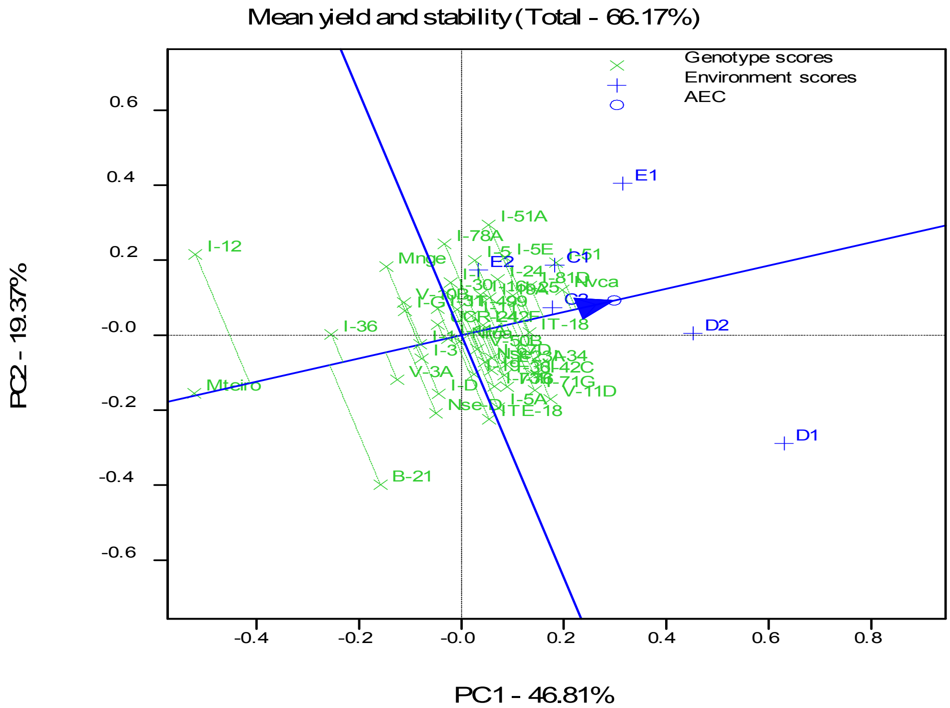

Figure 5.3D: Ranking of genotypes based on mean yield performance and stability in a combination of seasons and water regimes (C1=2009-main season × non-stressed; C2=2009-main season × stressed; D1= 2009 off-season × non-stressed; D2=2009 off-season × stressed; E1=2010 main season × non-stressed; E2=2010 main-season × stressed)

The biplot of genotype x site x season x water regime interaction explained 47.17% of the total variation (Figure 5.4A). The PC1 explained 29.93% of the total variation while the PC2 explained 17.08%. Genotype IT-18 was the best performing genotype in six environments (Chókwè- 2009 main season under both stressed and non-stressed conditions and 2010 -main season - non-stressed conditions and at Umbeluzi during the 2009 main season under non-stressed conditions, 2009 off-season under non-stressed conditions and 2010 main season stressed conditions) while genotype INIA-51 was the best performing genotype in five environments (Chókwè 2009 off-season under both stressed and non-stressed conditions and at Umbeluzi during 2009 main season stressed, 2009 off-season stressed and 2010 under non-stressed conditions). Genotype INIA-51A was the best performing genotype only in one environment (Chókwè during the 2010 main season under stressed conditions). The worst genotypes in all environments were IT82E-18, INIA-12 and Monteiro (Figure 5.4A).

Figures 5.4B and 5.4C show the relationship among environments. The correlation between the test environments indicates that there were two major groups of environments: group one consisting of Chókwè and its seasons and water regimes {Chokwe–2009 main season-stressed and non-stressed (A11, A12), Chokwe-2010 season-non-stressed and Umbeluzi 2009 main-season non-stressed and Chókwè 2010-stressed (A31) plus Umbeluzi environments (Umbeluzi-2009 main season–non-stressed (B11) and 2010-stressed (B32)}; group two consisting mainly of Umbeluzi and its seasons and water regimes {Umbeluzi 2009-mainseason stressed, 2009-off-seson stressed and 2010-non-stressed (B21, B22 and B31) plus Chókwè 2009-off-season stressed and non-stressed (A21 and A22)}. There was strong correlation among environments within groups but between groups the correlation was moderate to low. The environment Chókwè-2009-off-season-non-stressed was the most discriminating environment followed by Chókwè 2009-main season–non-stressed, but none of them were representative of the overall environment (large PC2 scores). The environments most representative of the two mega-environments were Umebluzi-2009-main-season-non-stressed (B11), Umbeluzi-2009-main-season-stressed (B12), Umbeluzi-2009-off-season-non-stressed (B21) and Umbeluzi-2010-main season-stressed (B32) while there was only one representative environment for Chókwè (Chokwe-2010-non-stressed - A31).

Figure 5.4D shows the ranking of 48 genotypes based on their mean yield and stability. Genotypes IT-18 and INIA-42C were the highest yielding followed by Nhavanca, INIA-5E, VAR-11D, INIA-51 and INIA-51A. Other high yielding genotypes were INIA-23A, INIA-81D, INIA-73B, INIA-25, INIA-24, INIA-76, INIA-67D, INIA-16, INIA-78A, INIA-5A, INIA-34, INIA-36I, INIA-5, INIA-42F, INIA-3, IT97K-499-39 and VAR-50B. The lowest yielding genotypes were Bambey-21, INIA-36, INIA-12 and Monteiro. The most stable genotypes at the upper side of the mean were INIA-23A, INIA-81D, INIA-24, INIA-25, INIA-78A, INIA-19 and Namuesse while at the lower side of the mean they were Bambey-21, INIA-36 and Monteiro. The most unstable genotypes at the upper side of the mean were IT-18, Nhavanca, INIA-51, INIA-51A, INIA-34 and INIA-36I while at the lower side of the mean the most unstable genotypes were IT82E-18, Namuesse-D, INIA-30, UCR-P-24 and INIA-12.

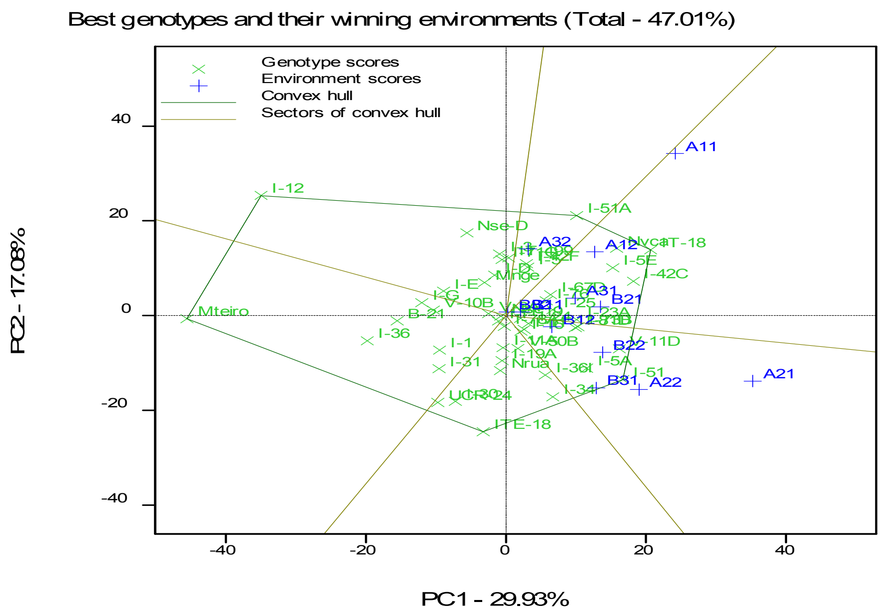

Figure 5.4A: Best performing genotypes in different sites, seasons and water regimes (A11 = Chókwè × 2009-main season × non-stressed; A12 = Chókwè × 2009-main season × stressed; A21 = Chókwè × 2009 off-season × non-stressed; A22 = Chókwè × 2009 off-season × stressed; A31 = Chókwè × 2010 main season × non-stressed; A32 = Chókwè × 2010 main-season × stressed; B11 = Umbeluzi × 2009-main season × non-stressed; B12 = Umbeluzi × 2009-main season × stressed; B21 = Umbeluzi × 2009 off-season × non-stressed; B22 = Umbeluzi × 2009 off-season × stressed; B31 = Umbeluzi × 2010 main season × non-stressed; B32 = Umbeluzi × 2010 main-season × stressed)

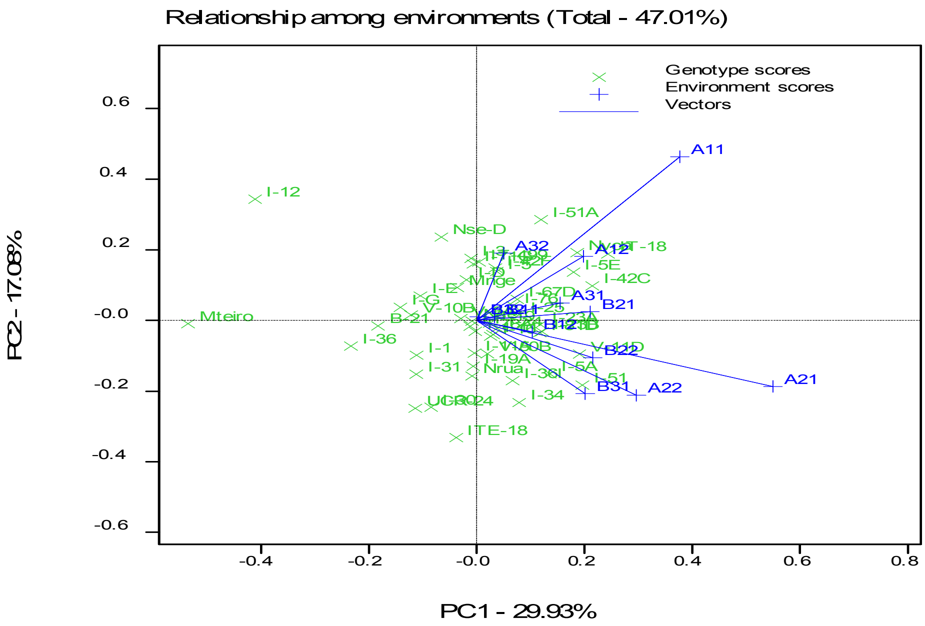

Figure 5.4B: Relationship among different sites, seasons and water regime (A11 = Chókwè × 2009-main season × non-stressed; A12 = Chókwè × 2009-main season × stressed; A21 = Chókwè × 2009 off-season × non-stressed; A22 = Chókwè × 2009 off-season × stressed; A31 = Chókwè × 2010 main season × non-stressed; A32 = Chókwè × 2010 main-season × stressed; B11 = Umbeluzi × 2009-main season × non-stressed; B12 = Umbeluzi × 2009-main season × stressed; B21 = Umbeluzi × 2009 off-season × non-stressed; B22 = Umbeluzi × 2009 off-season × stressed; B31 = Umbeluzi × 2010 main season × non-stressed; B32 = Umbeluzi × 2010 main-season × stressed)

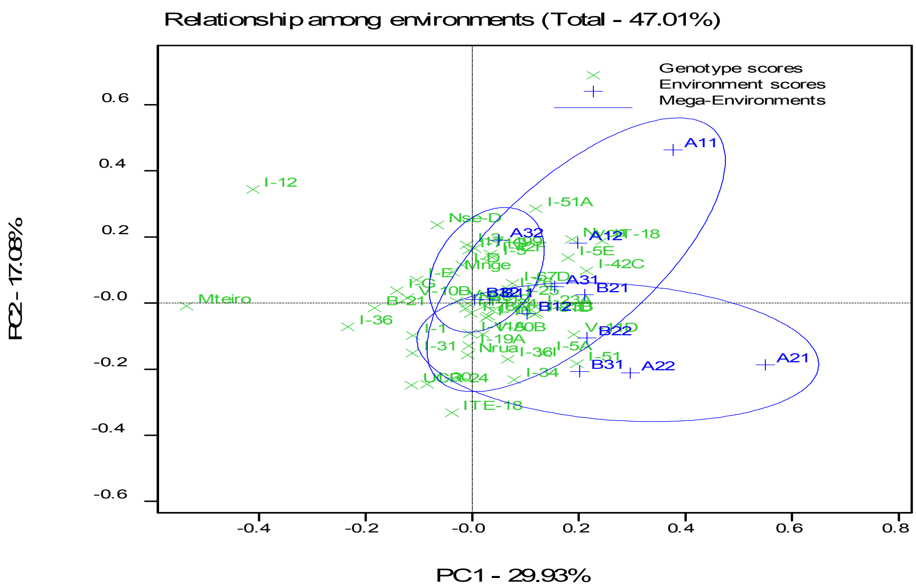

Figure 5.4C: Relationship among environments (A11 = Chókwè × 2009-main season × non-stressed; A12 = Chókwè × 2009-main season × stressed; A21 = Chókwè × 2009 off-season × non-stressed; A22 = Chókwè × 2009 off-season × stressed; A31 = Chókwè × 2010 main season × non-stressed; A32 = Chókwè × 2010 main-season × stressed; B11 = Umbeluzi × 2009-main season × non-stressed; B12 = Umbeluzi × 2009-main season × stressed; B21 = Umbeluzi × 2009 off-season × non-stressed; B22 = Umbeluzi × 2009 off-season × stressed; B31 = Umbeluzi × 2010 main season × non-stressed; B32 = Umbeluzi × 2010 main-season × stressed)

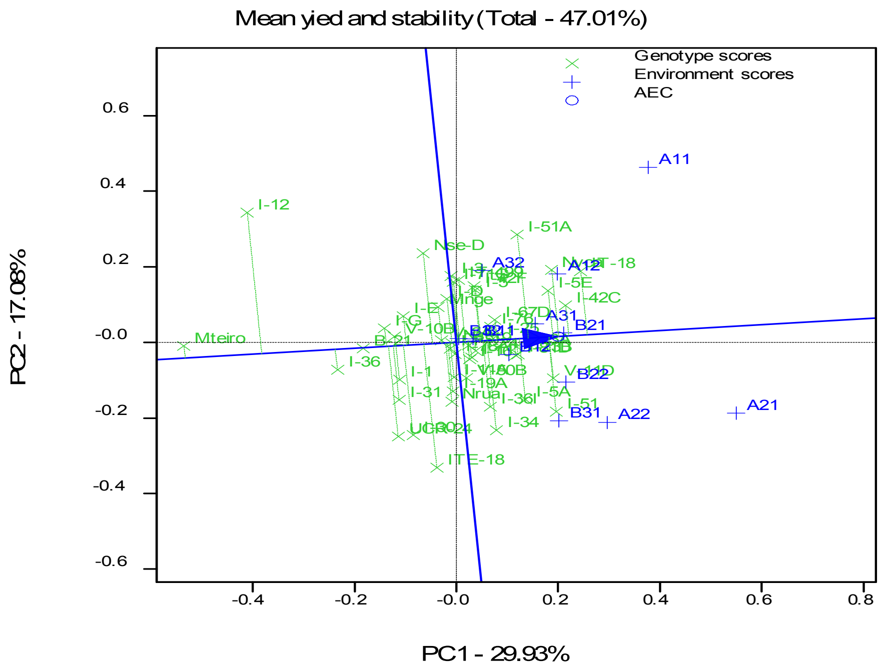

Figure 5.4D: Ranking of genotypes based on mean yield and stability (A11 = Chókwè × 2009-main season × non-stressed; A12 = Chókwè × 2009-main season × stressed; A21 = Chókwè × 2009 off-season × non-stressed; A22 = Chókwè × 2009 off-season × stressed; A31 = Chókwè × 2010 main season × non-stressed; A32 = Chókwè × 2010 main-season × stressed; B11 = Umbeluzi × 2009-main season × non-stressed; B12 = Umbeluzi × 2009-main season × stressed; B21 = Umbeluzi × 2009 off-season × non-stressed; B22 = Umbeluzi × 2009 off-season × stressed; B31 = Umbeluzi × 2010 main season × non-stressed; B32 = Umbeluzi × 2010 main-season × stressed)

5.4 Discussion

The tested genotypes were different with respect to yield data recorded in this study. The sites, seasons and water regimes were also significantly different. The sites accounted for most of the yield variation followed by water regimes and sites x season interaction. The large yield variation due to sites, which are not relevant for cultivar evaluation (Yan *et al.*, 2000; Yan *et al.*, 2001; Yan, 2002) justifies the use of site regression as the appropriate model for analysing the genotype and genotype x environment interaction. In addition, the use of the site regression model would help to identify the type of genotype x environment interaction present, the best genotypes, the most discriminating environments and the most stable genotypes (Yan *et al.*, 2000, Yan *et al.*, 2001; Yan, 2002, Yan *et al.*, 2007). The interaction between sites and water regimes was not significant indicating that the water regime applied was the same across sites. The interactions of genotypes x seasons, genotypes x sites, genotypes x water regimes, site x seasons, genotypes x site x season, genotype x site x water regime, genotype x season x water regime and genotype x site x season x water regime were highly significant. The significant interactions between genotypes and any of the environmental components indicated that genotypes responded differently to the change in each one of the environmental components. Variation in rainfall amount and distribution and biotic stresses such as insects between sites and seasons may have accounted for significant environmental differences and to different genotypic responses to environments. For example, at Umbeluzi the incidence of aphids, flower thrips and white fly was always high despite insecticide application. In addition, drought was more severe at Umbeluzi during the 2010 than other seasons while at Chókwè rainfall was received during drought stress imposition in 2009 and 2010 main seasons.

These interactions were of cross-over type since different genotypes were the best in different environments. That is an indication that the tested genotypes had adaptation to specific environmental conditions. The exploitation of genotype x sites interaction to breed for site specific adaptation and genotypes x water regime to breed for drought tolerance would be complicated by season variation as indicated by significant season and significant season x site and season x water regime interactions. Under these circumstances, Ramagosa and Fox (1993) recommend testing the genotypes over a representative range of conditions while Yan *et al.* (2007) suggests the selection of high yielding and stable genotypes over a range of target environments. Following the Yan *et al.* (2007) principle, genotypes performing above the environmental mean with yield stability as indicated by low projection from the average environmental coordination (AEC) axis would be considered stable and therefore, recommended for wide adaptation.

5.4.1 Performance of genotypes across sites, seasons and water regime

Drought stress caused most of the genotypes to perform poorly. However, genotypes INIA-12, INIA-19, INIA-24, IT82E-18, INIA-81D, INIA-11A, VAR-11D, INIA-1, INIA-42F, Monteiro, INIA-5E, UCR-P-24, INIA-5, VAR-10B, INIA-36, Bambey-21 and INIA-11 were able to withstand drought conditions and produce the same yield as the non-water stressed environment. However, despite their ability to withstand drought, these genotypes showed inconsistent yield with change in sites and seasons, with the exception of INIA-81D, INIA-24, INIA-5 that were consistent across season and UCR-P-24 that was consistent across sites. Given their ability to withstand drought and produce consistent yield over seasons, genotypes INIA-81D, INIA-24, INIA-5 and INIA-1 would be recommended for specific sites including those characterized by drought stress.

Lin and Bins (1988) indicated that a stable genotype should combine a high location mean yield and a small season variation because locations are predictable variations while seasons are unpredictable sources of variation. According to this principle, genotypes such as Nhavanca and INIA-51 would be considered stable followed by INIA-81D, INIA-24, INIA-25 and INIA-5 because they combined high mean yield across locations and water regimes and low yield variation across seasons. Genotypes such as IT82E-18, Namuesse-D, VAR-3A, INIA-36, INIA-12 and Monteiro would be considered the most unstable. Overall, genotypes INIA-81D, INIA-24 and INIA-5 would be recommended for wide adaptation given their drought tolerance combined with less yield variation from season to season and high mean site yield. Genotypes INIA-51 and Nhavanca, despite their sensitivity to drought would also be recommended for a wide range of locations given their low seasonal variation and high mean yield across sites and water regimes.

5.4.2 The GGE biplot

The first two principal components (PCs) of genotype × site × water regime interaction explained greater part of GGE variation (84.09%) than genotype × site × season (60.08%), genotype × season × water regime (66.17%) and genotype × site × season × water regime (47.01%). The large variation due to genotype × site × water regime could be associated with the large yield variation explained by sites and water regimes. In all interaction components, the PC1 had positive scores and explained most of the variation than the PC2. Yan *et al.* (2000) indicated that when the PC1 is positive and higher than PC2, it approximates the genotypes main effects or non-crossover interaction while the PC2 indicates the genotype × environment interaction.

5.4.2.1 Best performing genotypes

From the polygon view, the best genotypes in a set of environments and worst genotypes could be identified. The best genotypes are located at the vertex of the sector containing the environments in which they are winning while the worst genotypes are located at the vertex of sectors without environments (Yan *et al.*, 2000). Yan *et al.* (2000) indicated that when different environments fell into different sectors it implies that there are different highest yielding genotypes in those sectors and a cross-over G×E interaction exists. The authors further indicated that grouping the test environments into mega-environments would be possible provided that the genotype by location is consistent across years. In this study, a different environment grouping was observed which identified the winning genotypes in different G×E interaction components. Overall, genotypes Nhavanca, INIA-51, INIA-51A, IT-18 and VAR-11D were the best genotypes in different groups of environments and none of them was stable suggesting that they were specifically adapted to their winning environments. Genotypes IT-18, INIA-51A and Nhavanca were associated with the high yielding environments of Chókwè and main season suggesting that they were adapted to high yielding environments while INIA-51 and VAR-11D were associated with Umbeluzi suggesting that they were adapted to low yielding and stressful environments. Genotypes IT-18, INIA-51A, INIA-51 and Nhavanca showed high performance under drought stressed and non-stressed conditions indicating good adaptation to both drought-stressed and non-stressed environments.

5.4.2.2 Interrelationship among environments

Test environments can be characterized by being correlated, discriminating, representative of the mega-environment and ideal. Environments are indicated to be correlated when the angle between them is smaller; discriminating when the length of the vector from the biplot origin to the environmental marker is longer, representative of the mega-environment when its PC2 scores are near-zero and ideal for selecting superior genotypes when it is discriminating and representative (Yan *et al.,* 2000; Yan *et al.,* 2001; Yan, 2002; Yan *et al.,* 2007). Yan *et al.* (2007) indicated that environments with short vectors provide little information about genotypes and should not be used as test environments. In this study, Chókwè and its combinations of seasons and water regimes were correlated but uncorrelated or moderately correlated with Umbeluzi and its seasons and water regimes. In addition, Chókwè was the most discriminating environment (high yielding environment) but less representative suggesting that it would only be useful for identifying superior genotypes but not for selection. The main seasons were correlated but uncorrelated with the off-seasons. The lack of correlations between sites and seasons suggested that these sites were different and belonged to different mega-environments and the off-season would not be useful for selection or evaluation. The results show that genotypes selected at Umbeluzi should be recommended for the Umbeluzi mega-environment while the genotypes selected at Chókwè would also be recommended for the Chókwè mega-environment and Chókwè would be ideal for identifying high yielding genotypes. There representative environments for Chókwè as well as Umbeluzi mega-environments detected were not ideal for selection. However, the reduced number of seasons used in this study limits the drawing of final conclusions.

5.4.2.3 Ranking of genotypes based on mean yield and stability

Genotypes are considered high yielding when their yields are situated at the right side of the line perpendicular to the average environment coordination (AEC) axis while those situated at the left side are considered low yielding. With regard to stability, genotypes are considered stable when their projection from the average environment coordination (AEC) axis is smaller or zero while the genotypes showing higher projection from the AEC are considered unstable (Yan *et al.*, 2007). In this study, genotypes IT-18, Nhavanca, INIA-51, INIA-51A, VAR-11D, INIA-42C, INIA-81D were among the highest yielding across different G×E interaction components. The lowest yielding genotypes were Bambey-21, INIA-36, INIA-12 and Monteiro. Amongst the high yielding genotypes INIA-23A, INIA-81D, INIA-24, INIA-16, INIA-25 and INIA-76 were consistently stable. Genotypes INIA-51, INIA-51A and IT-18 showed stability but were not consistent across different G×E interaction components.

5.5 Conclusions

The objectives of this study were to: (1) assess the G×E interactions, and (2) determine grain yield stability of 48 genotypes when grown under water stressed and non-stressed conditions during three seasons in two sites with contrasting yield potential. Based on the results obtained it is concluded that:

(1) Genotype-by-environment interactions were present indicating that genotypes responded differently to the change in environments.

(2) Genotypes adapted to specific environments were identified. These included genotypes IT-18, INIA-51, INIA-51A and Nhavanca which were adapted to high yielding and drought stressed environments and VAR-11D which was adapted to low yielding and stressful environment. All these genotypes were highest yielding and unstable across environments.

(3) High yielding and stable genotypes included INIA-23A, INIA-81D, INIA-24, INIA-25, INIA-16 and INIA-76. These genotypes would be recommended for cultivation under different environments. The lowest yielding genotypes included Bambey-21, INIA-36, INIA-12 and Monteiro but INIA-12 was unstable.

(4) Chókwè was a high yielding environment and suitable for identifying high yielding genotypes but not suitable for selection while Umbeluzi was not high yielding nor suitable for selection.

(5) The GGE biplot was a suitable method to analyse the genotype × environment interaction and yield stability because it enabled an easy visual assessment of best performing genotypes and their winning environments, the relationship between environments and the raking of genotypes based on their yield performance and stability.

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Chapter Six: Overview

6.1 Introduction

Drought, manifested in the form of high variability in amount and distribution of rainfall over seasons and agro-ecologies, is a major constraint threatening cowpea production in Mozambique. Intermittent and terminal droughts take place, but terminal drought is most yield-limiting due to its direct negative effect on yield formation. Hence, drought-tolerant cultivars are needed to increase cowpea production in the country. This study is a step towards the development of farmers' preferred and drought tolerant cowpea cultivars in Mozambique. The study started with an attempt to understand farmers' perceptions about the major cowpea production constraits and preferences of cowpea varieties and traits. This information was to be considered during variety development in order to ensure varietal acceptance and adoption by farmers. Following that, the variability of cowpea genotypes for drought tolerance was investigated in order to identify sources of drought tolerance. Thereafter, the gene action controlling drought tolerance, yield and yield related traits were also investigated to determine the best selection strategy to be adopted in cowpea breeding for improved drought tolerance in the country. Lastly, genotype by environment interaction and grain yield stability of cowpea genotypes under drought-stressed and non-stressed conditions were investigated to identify desirable genotypes and screening sites. This chapter provides an overview of the research conducted, highlighting the objectives, major findings and implications of the results for future research.

Four interrelated objectives formed the focus of the research presented in this thesis. These were:

1. to determine farmers' perceptions on major constraints limiting cowpea production and identify preferences regarding cultivars and traits,
2. to determine the variability of selected cowpea germplasm collections for drought tolerance,
3. to determine the gene action controlling drought tolerance, yield and yield related traits, and

4. to assess the genotype × environment interactions and grain yield stability of cowpea genotypes when grown under drought-stressed and non-stressed conditions.

6.2 Summary of the Major Findings

Each of the four objectives was addressed through an independent study. The findings from each study are presented separately.

6.2.1 Participatory Plant Breeding: Assessment of Farmers' Perceptions and Preferences in Cowpea Varieties in Mozambique

Participatory rural appraisal and participatory varietal selection were carried out in Bilene, Boane and Chibuto districts and the market survey conducted in open markets and food stores in Maputo. The following information was obtained:

- Cowpea is an important crop produced for its leaves and grain for household consumption and the market.
- Accessibility to markets was the major driving force determining the aim of production and the relative importance of different cowpea products between districts.
- The major aim of production in districts located far away from the major markets was household consumption while in district located near major markets was income generation.
- Cowpea grain and leaves were important across districts but differed between districts; grain was the most important product for farmers located in districts that were far away from the major markets while leaves were more important for farmers located near the major markets.
- Drought was the most important production constraint indicated by farmers followed by aphids, bruchids and viral diseases.

- Farmers used various criteria to select a cowpea variety. High grain yield was indicated to be the most important selection criterion followed by high leaf yield, large seed size and earliness. Results indicated that high grain yield was not always the major criterion used by farmers to select cowpea varieties. Potential marketability of the variety was also an important criterion determining the selection of a variety.

6.2.2 Assessment of cowpea genotypes for variability in drought tolerance

Variability in drought tolerance among two-hundred sixteen (216) genotypes (136 early and 80 late) was studied by growing the genotypes under drought stressed and non-stressed conditions at Chókwè during the 2008 off-season (June – October). The following information was obtained:

- Genetic variability for drought tolerance existed amongst the tested germplasm.
- The two-hundred and sixteen genotypes were clustered into four groups according to their yielding ability under drought stressed and non-stressed conditions and their drought tolerance. These groups were: high yielding-drought tolerant genotypes (group A), high yielding-drought susceptible genotypes (group B), low yielding-drought tolerant genotypes (group C) and low yielding-drought susceptible genotypes (group D).
- Genotypes INIA-24, INIA-120, IT96D-610, Tete-2, Sh-50 and UC-524B were examples of high yielding-drought tolerant types; genotypes INIA-11C, INIA-11D, INIA-51, INIA-42F, IT85F-3139, VAR-50B, IT83D-442, Massava-5, N'diambour, Xingove and Zimbabwe were examples of high yielding-drought susceptible types; genotypes IT98K-1111-1, IAR-8/7, KVx403 and KVx525 were examples of low yielding-drought tolerant while IT82E-18, IT95M-303, CP-2, KVx-421 and Massava-11 were examples of low yielding-drought susceptible types.
- Stress tolerant index was strongly and positively correlated with drought-stressed and non-stressed yield, mean productivity and geometric mean productivity.
- Stress tolerance index was the best quantitative criterion for assessing cowpea genotypes for drought tolerance because it enabled identification of high yielding-drought tolerant genotypes.

- Multivariate analysis using drought-stressed and non-stressed yield and quantitative indices of stress tolerance was a useful method for assessing the variability of cowpea genotypes for drought tolerance.

6.2.3 Gene action controlling drought tolerance, yield and yield related traits

The gene action controlling drought tolerance, yield and yield related traits was studied using 28-F2 populations generated from an 8x8 half diallel and their parents grown under drought stressed and non-stressed conditions at Chókwè and Umbeluzi. Results from the study revealed that:

- Additive gene action was more important than non-additive in controlling drought tolerance (stay-green), days to flowering, number of pods per plant, number of seeds per pod and hundred seed weight.
- Additive gene action was more important than non-additive in controlling yield under non-stressed conditions while under drought-stressed conditions non-additive gene action was more important.
- The number of pods per plant was the only yield related trait that positively correlated with yield.
- Direct selection for yield would be possible under non-stress conditions while under drought conditions yield improvement would be possible by selecting for number of pods per plant
- Genotype IT93K-503-1 was the most desirable to use as a parent in genetic improvement for drought tolerance, yield and number of pods per plant while INIA-41 was the most desirable to use as a parent in genetic improvement for drought tolerance and hundred seed weight

6.2.4 Genotype × environment interaction and grain yield stability of cowpea genotypes when grown under drought stressed and non-stressed conditions in Sothern Mozambique

Genotype x Environment interaction and stability of grain yield of 48 cowpea genotypes was investigated in two locations (Chókwè and Umbeluzi) under drought-stressed and non-stressed conditions during three seasons (2009 main season, 2009 off-season and 2010 main season) in southern Mozambique. A 4×12 α-lattice design with three replications was used at Umbeluzi during 2009 main and off season while at Chókwè two replications were used in all seasons. The data was analyzed using the GGE biplot. Results from the study indicated that:

- Genotype-by-environment interactions were present.
- Genotypes adapted to specific and a wide range of environments existed.
- Genotypes IT-18, INIA-51, INIA-51A and Nhavanca were adapted to high yielding and drought stressed and non-stressed environments while VAR-11D was adapted to low yielding environment. All these genotypes produced the highest yields but were unstable across environments.
- High yielding and stable genotypes included INIA-23A, INIA-81D, INIA-24, INIA-25, INIA-16 and INIA-76.
- The lowest yielding genotypes included Bambey-21, INIA-36, INIA-12 and Monteiro. Genotype INIA-12 was unstable while the rest were stable.
- Chókwè was a high yielding environment and ideal for identifying high yielding genotypes but not adequate for selection since it was not representative of an average environment. Umbeluzi was a low yielding environment and was not ideal for selection.

6.3 Breeding Implications for the Findings

There were differences in aim of cowpea production as well as in importance of cowpea products between districts situated near major markets and those situated far from major markets. This information suggested that different types of cowpea varieties need to be developed. Varieties for grain production or dual-purpose (grain plus leaves) are necessary for districts situated far from the major market while varieties for leaf production would be suitable for districts situated near the major markets.

Drought, aphids and bruchids were the most important production constraints and high grain and leaf yield, large seed size, earliness and potential marketability of a variety were the most important traits determining the selection of a cultivar. This information suggested that a multiple of traits need to be considered in a cowpea breeding programme. To combine the different traits perceived or preferred by farmers a selection index needs to be developed and used to select genotypes amongst the segregating populations. In the calculation of selection index, grain yield will receive higher weighting for cultivars developed for districts located in rural areas while leaf yield would receive higher weighting for varieties developed for districts located near the markets.

The existence of genetic variability for drought tolerance implied that genetic improvement of cowpea for drought tolerance could be conducted using this germplasm.

The findings that additive gene effects were more important in controlling drought tolerance, grain yield under high moisture availability and yield related traits implied that breeding gain can be realised through selection. The fact that stay-green was mainly controlled by additive genes and is easy to assess, suggested that selection for this trait could be conducted in early segregation generations.

The fact that yield was controlled by additive genes under high moisture availability and non-additive genes under drought-stressed conditions suggested that direct selection for yield can be conducted under non-stress conditions while under drought stressed conditions indirect selection for yield should be conducted using the number of pods per plant and selection for yield and number of pods per plant should be conducted in late segregating generations when the genes are fixed and fully expressed.

The presence of cross-over G×E suggested that breeding for specific and wide adaptation is necessary.

6.4 Conclusions and the Way Forward

In this study, cowpea production constraints and farmers' preferences on cowpea cultivars and traits in the southern region of Mozambique were identified and ranked. The objective of cowpea production, the most important cowpea products and the factors determining production and importance of cowpea products identified. Efforts should be made to address the major production constraits through breeding to increase cowpea production in the region. During the breeding process farmers' preferences should be considered and farmers themselves should be involved to ensure varietal acceptance and adoption. Market aspects need to be considered to develop suitable varieties for farmers needs.

The genetic variability for drought tolerance was determined. Genotypes with high variability for grain yield and drought tolerance were identified. Genotypes with contrasting drought tolerance and yielding ability were used to gain more understanding on inheritance and gene action controlling drought tolerance, grain yield and yield related traits. High levels of drought tolerance using stay-green trait has been identified in the F2 generations. Best combiners for drought tolerance, high yield and number of pods per plant were identified. Breeding for drought tolerance and high yield needs to continue making crosses using identified parents and selection of high yielding and drought tolerant progeny conducted. In the selection process farmers will need to be involved. Selection for stay-green will have to be conducted in early segregating generation. Direct selection for yield under non-stress conditions and indirect selection for yield using the number of pods per plant under drought-stressed conditions will need to be conducted in late segregating generations.

Cross-over G×E was indentified. Genotypes adapted to specific environmental conditions and to a wide range of environments were identified. Low and high yielding environments were identified and genotypes adapted to them as well. Further studies need to be conducted using more sites and seasons for firm recommendations.