CHARACTERIZATION OF SORGHUM [*Sorghum bicolor* (L.) Moench] PARENTAL LINES AND PREDICTION OF THEIR HYBRID PERFORMANCE UNDER SIMULATED WATER AND POPULATION DENSITY STRESS

By

Clement Kamau Karari MSc. (Mississippi)

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African Centre for Crop Improvement

School of Biochemistry, Genetics, Microbiology and Plant Pathology

Faculty of Science and Agriculture

University of KwaZulu-Natal

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ABSTRACT

Sorghum breeders have not made much yield improvement in new sorghum varieties in Kenya since Serena in was released in the late 1960s. KARI Mtama-1 which was released in 1993 has no yield advantage over Serena. A yield plateau for sorghum in Kenya is apparent. A new breeding approach was adopted to break that yield barrier. Development of hybrid sorghum was proposed and is expected to break the yield barrier and also deriver cultivars that meet farmers' main requirements. The objectives of the study were to (1) identify farmers' requirements in sorghum cultivars, constraints to sorghum production and why improved cultivars from research are not being adopted, (2) characterize male and female parents and establish if genetic distance could identify superior parent populations for hybrid production (3) estimate genetic variance components and determine the possibility of using GCA and SCA estimates in choosing parents for use in hybrid production, (4) test hybrids and open pollinated variety (OPV) parental lines for stress tolerance and identify tolerant hybrids for further testing and, (5) compare single cross hybrids and OPV varieties in yield performance. Participatory rural appraisal in Kitengei and Nzambani areas of Kambu showed that sorghum was especially important in semi-arid parts of Kenya. Food, trade, feed, nursing food and thatching were the most important uses of sorghum. High grain and stover yield, large grain size, early maturity, drought tolerance, pest and disease resistance, coloured grain and intermediate plant height were the major requirements of farmers. Fifty-three pollinators and forty-one male sterile parents were introduced from four sources and screened together with 27 pollen parents from Kenya. Parents and hybrids were tested in 4 environments: high and low plant density, in high and low moisture regimes laid out in a triple square lattice design in Kenya, with parents having two additional tests in South Africa. Males, females, sexes and parental sources differed significantly in head weight. There were sex x country and sex x environment interactions for head weight. Genetically distant parents' populations had higher chances of superior heterosis. Parents showed significant additive genetic variance in head weight. The regression of non-additive to additive genetic variance was roughly one and significant. Three female and five male parents were suitable for production of hybrids adapted to multiple environments. Hybrids and OPV lines significantly varied in head weight. Hybrids were superior to OPV lines in most agronomic traits. Economic superiority of the hybrids was sufficient to cover cost of hybrid production and distribution in Kenya. Hybrids and OPV lines varied significantly for plant density stress. Hybrids were less sensitive to stress and more productive than OPV lines under population density stress. KARI varieties were sensitive to plant density stress. In general low sensitivity to stress was beneficial and hybrids had superior yield to inbred varieties.

DECLARATION

I hereby certify that this research is the result of my own investigation, which has not already been accepted in substance for any degree and is not being submitted in candidature for any other degree. Where use has been made of the work of others it is dully acknowledged in the text.

Signed...

Clement Kamau Karari

(Candidate)

Signed...

Professor Pangirayi Tongoona

(Supervisor)

Signed...

Dr John Derera

(Co-Supervisor)

Signed...

Professor Mark D. Laing

(Co-Supervisor)

Discipline of Plant Breeding

African Centre for Crop Improvement

School of Biochemistry, Genetics, Microbiology and Plant Pathology

University of KwaZulu-Natal

Pietermaritzburg

South Africa

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Clement Kamau Karari

DEDICATION

To individuals, groups, institutions, organizations and governments that continually struggle to feed the ever increasing population of mankind

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ABBREVIATIONS

ANOVA	Analysis of Variance
CGIAR	Consultative Group on International Agricultural Research
CMS	Cytoplasmic Male Sterility
DAO	District Agricultural Office (Officer)
FAO	Food and Agriculture Organization
FPB	Formal Plant Breeding
GCA	General Combining Ability
IBPGR	International Board for Plant Genetic Resources
ICRISAT	International Crops Research Institute for Semi-Arid Tropics
INTSORMILL	International Sorghum and millet
KARI	Kenya Agricultural Research Institute
Kes	Kenya shilling
PB	Plant Breeding
PPB	Participatory Plant Breeding
SCA	Specific Combining Ability
USA	United States of America
OPV	Open Pollinated Varieties
OPL	Open Pollinated Lines

GENERAL INTRODUCTION

Formal sorghum breeding has been undertaken in Kenya since 1938 (Hoskin, 1938; Humphrey, 1938; Doggett, 1953; Dowker, 1963; Majisu, 1971; KARI, 1993). However, breeders have not released many new high yielding sorghum varieties in Kenya since Serena was developed in the late 1960s. Seredo, released in 1972, has no yield advantage over Serena but it is adapted to a different production domain. A yield plateau is apparent. It has not been broken by many years of breeding for improved OPV varieties. A new breeding approach must be adopted to break that yield stalemate.

From his experience with the breeding of the sorghum varieties Serena and Seredo, and the hybrids; Hx57, Hx301 and Hx463, Majisu (1971) commented, "hybrids are the way to increase sorghum yields in the east African region". Majisu (1971), Jewett (1972) and Haussmann *et al.* (1998) found higher yield potential in hybrids than OPV lines. Hybrids and OPV varieties developed previously are unsuitable for Kenya since they were bred for higher potential areas of Uganda and Western Kenya, where the agronomic potential is much higher than most sorghum producing areas in eastern Kenya. When grown in eastern Kenya, the hybrids are highly vulnerable to drought. There is a clear need to develop sorghum hybrids specifically for the eastern parts of Kenya, which are semi-arid.

Traditionally, research in Kenya adopted a top-down research and extension approach whereby researchers decided what was best for farmers (Muthoka, 2002). For some time, methods that incorporated a bit of technology-user participation in technology development (Muthoka, 2002) such as Integrated Rural Development (IRD), Intermediate Technology Development (ITD) and Farming Systems Research and Extension (FSR/E) have been in use. However, the newer methods, though better than the top-down approach, are slow and farmers' needs change before technology development is complete. Past approaches have had a negative impact on sorghum production in Kenya. Farmers still maintain and grow their low yielding varieties instead of high yielding varieties developed in research. Farmer varieties are still more popular than research varieties (this publication, Chapter Two).

Past research did not address farmers' sorghum variety needs. Breeding efforts from 1938 to 2005 did not optimize on sorghum farmers' needs, because that research did not involve them in selecting varieties for their farming systems. Rapid methodologies that fully encompass rural participation and are abreast with rural situations (farmers' requirements) should be adopted in research and extension so that future research can benefit sorghum farmers. Participatory Rural Appraisal (PRA) methodologies can fill this gap and meet farmers' requirements in Kenya. Specifically, Participatory Plant Breeding (PPB) methodologies which are PRA methodologies in plant breeding (PB) (Sthapit *et al.*, 1996; Witcombe *et al.*, 1996) should be completely adopted to direct research effort so that research can benefit sorghum farmers. A Participatory Plant Breeding (PPB) assessment was integrated in this breeding research. Farmers described their needs to ensure their needs were met. This research should therefore improve farmers' adoption of new hybrids developed in the research. It was hoped that farmers would participate in the actual selection of superior hybrids, when hybrid numbers are reduced to farmer manageable levels.

A major challenge to sorghum production in Kenya is stress (Bebawi and Farah, 1981; House, 1985; KARI, 1993; Olabanji *et al.*, 1996). Abiotic stresses are physical stresses caused by environmental factors such as soil or weather. Examples are drought (low moisture availability), low soil fertility, physically poor soils and high temperature.

Biotic stresses are harmful interactions between biological organisms. In Kenya, they include:

1. Birds,
2. Insect pests, especially stem borers (*Chillo pertellus*, *Buseola fusca* and *Sesamia calamistis* genera of the family Lepidoptera),
3. Post-harvest weevils (*Sitophilus granarius, Sitophilus oryzae* and *Sitophilus zeamais in the* order Coleoptera and family Curculionidae),
4. Diseases such as covered kernel smut (*Sporisorium sorghi* (Link) Clinton) , head smuts (*Sphacelotheca sorghi* (Kuhn) Potter) and loose smut (*Sporisorium cruenta* (Kuhn) Potter) and,
5. Weeds such as striga (*Striga hermonthica* (Del) Benth and *Striga asiatica* (L.) Kuntze*)* (KARI, 1993).

The occurrence of one stress is not mutually exclusive of others. There is no limit to the number of stresses that can occur at any one time. The goal of breeding for stress tolerance must be realized if sorghum yields in semi-arid parts of Kenya are to be raised.

Plants are concurrently exposed to multiple stresses. Plant performance under stress is the result of the interaction of the plant with these stresses. Therefore, the best way to screen for stress is to expose the breeding crop to as many stresses as are likely to occur in a plant's natural growing environment. Plants that exhibit relatively high yield under stress are tolerant and should be selected.

As plant density is increased, resources available per plant decline and stress results. There is a range of densities over which a genotype's yield is constant and this varies with different genotypes (Harper, 1977). In the range of densities where yield is similar, yield is dependent on the most limiting resource (Donald, 1951). Yield becomes independent of plant density when more of the limiting resource is provided (Donald, 1951). Plant density not only simulates stress, it can also be used to quantify it. This principle was used to screen hybrids for tolerance to stress by evaluating them at different plant densities.

In dense crop stands, plants compete for resources such as moisture, nutrients, light and packing space (Harper, 1977). Therefore, population density simulated stress can screen for tolerance to abiotic stresses. When moisture is factored into plant density, the compounded stress will screen for both abiotic and biotic stresses. This is because by creating abiotic stress, high plant density causes biotic stress by creating an enabling environment for disease epidemics through bringing plants into closer contact (Harper, 1977). The few cases where density has not promoted epidemics are exceptions rather than the rule. Application of moisture (irrigation) encourages pathogens to proliferate and cause biotic stresses. Therefore plant density trials, combined with moisture trials, produce a comprehensive and powerful experimental environment that is able to bring all stresses together into a complex mixture, similar to natural environment.

Increasing plant density creates many interactions with the surrounding environments as a plant competes with neighbouring plants for moisture, space and nutrients. Some of these interactions have been investigated (Harper and McNaughton, 1962; Yoda *et al.*, 1963; Harper, 1977; Fasoulas and Fasoulas, 1997; Springer *et al.*, 2003; Krishnareddy and Stewart, 2004). Plants in dense stands assume a hierarchy whereby a few strong vigorous plants dominate many weak plants. They take up most of the resources and gain in yield. Their gain in yield does not compensate for the yield loss suffered by the weaker plants. Thus, overall resource productivity under dense stands is undermined (Fasoulas and Fasoulas, 1997). In most genotypes, there is an optimum plant density whereby resource productivity is maximized (Warren, 1963; Harper, 1977; Henderson *et. al.*, 2000; Springer *et al.,* 2003).

To summarize, high plant density tolerant plants are stress tolerant and they use resources efficiently. Single density yield trials do not quantify genotypic yield potential accurately because genotypes have different optimum plant density requirements. It follows, therefore, that for research to identify stress tolerant, resource use-efficient genotypes, trials at different plant densities are required. Such research would determine optimum planting density for genotypes used in the future. These approaches have not been combined in one research programme before, especially in Kenya. It appears to offer numerous benefits and should be tested.

The goal of this research was to increase productivity of sorghum in Kenya.

The specific objectives of the study were:

1 To identify farmers' requirements for sorghum cultivars, constraints to sorghum production and why improved cultivars from research are not adopted,

2 To characterize male and female parents and establish if genetic distance can identify superior parent populations for the production of hybrids,

3 To estimate genetic variance components of parents and determine the role of GCA and SCA estimates in predicting performance of parents in hybrids over environments,

4 To compare single cross hybrids and OPV varieties for yield performance, and

5 To test hybrids and OPV parents for tolerance to stress and to identify tolerant hybrids for further testing.

The hypotheses for each objective are listed according to objective numbers:

1. Failure of sorghum breeders to involve farmers in cultivar selection and identification of production constraints has lead to inappropriate cultivars that have been adopted by very few farmers.
2. Populations that are genetically distant give high yielding hybrids when hybridized;
3. Parental genetic variance components can be used to identify parental potential to produce high yielding hybrids
4. Hybrids are higher yielding than OPV varieties in semi-arid conditions, and
5. Sensitivity to different plant densities can be used to identify stress tolerant genotypes.

This investigation was conducted in phases, which are presented in the different chapters of this thesis: Investigation of available knowledge on sorghum with emphasis on sorghum hybrids is in Chapter One, on literature review. Farmers' requirements for grain sorghum cultivars were investigated via a Participatory Rural Appraisal (PRA) study, and are presented in Chapter Two. Chapter Three covers an investigation into the identification of sorghum populations containing the best parents for hybrids, prior to hybridization. In Chapter Four is the selection of the best parents for hybridization and estimation of parental genetic variance components (combining ability). Chapter six is on the identification of the best hybrids and an investigation of whether hybrids were advantageous over OPV varieties in Kenya. Chapter five covers the testing of hybrids and parents for stress tolerance. The pertinent findings of Chapters One to Six are discussed in an overview, contained in Chapter Seven.

This research is similar in focus to research conducted previously in east Africa on hybrid sorghum. However, it differs from past research in that the diversity of both parents and hybrids was much greater. In the study, 53 male sterile and 68 male fertile parents were used. In comparison, four to six male sterile and five to ten male fertile parents were used in previous studies. Hybrids were tested over simulated environments, contrary to the multiple natural environments which were used in previous studies. As covered in Chapter five, another difference was that genotypes were grown in two plant densities. Optimum density was estimated and genotypes were compared over multiple densities. Unlike past research, PRA breeding methods were used to ensure farmers' sorghum ideotypes were identified. Consequently on-farm requirements may have been better addressed. This research benefited from past research in that knowledge that was not available in previous studies was available to the study. The goal of the research was to raise sorghum grain yield in Kenya from the present static level of 3 t ha^{-1}.

Finally, the presentation of this research (thesis) is organized in the composite format, whereby each chapter is presented as a discrete, independent research paper. Consequently, there is a certain amount of repetition in Materials and Methods, and

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CHAPTER ONE

LITERATURE REVIEW

1.0 Introduction

Sorghum literature was reviewed in this chapter, with the aim of improving the quality of the proposed research. The review is organized into three broad sections. The first section deals with general sorghum plant traits and responses to broad environmental stimuli like day length. The second section deals with creating hybrids and the third section with selection of parents and hybrids. Section four identifies the way forward.

1.1 **General plant traits and responses to environmental stimuli**

1.1.0 Sorghum plant parts and traits

Hybrid performance has been associated with heterosis which can be expressed in various plant traits. The sorghum plant is comprised of the panicle, the peduncle, the stem, the leaves and the root system. It is important to review those traits that have influence on hybrid performance.

1.1.1 Plant height

Plant height in sorghum is a property of the stem. According to Doggett (1953), height is determined by the number of nodes and the internode lengths. Morgan and Finlayson (2000) have associated dwarfism with lower yield compared to height in similar genetic backgrounds. Extremely high yielding hybrids were generally very tall and very late maturing (Niehaus and Pickett, 1966). Rana *et al.* (1996) found high yielding hybrids in the height range of 175 to 180 cm. Plant height was positively correlated with yield and number of seeds on the head (Niehaus and Pickett, 1966; Kirby and Atkins, 1968; Kambal and Webster, 1966). Plant height, peduncle length and head length had insignificant association while peduncle and head lengths were significantly associated (Kambal and Webster, 1966). Kambal and Webster (1966) concluded that peduncle and head lengths were under similar genetic control. This genetic control was different from the genetic control for height. In similar genetic backgrounds, taller genotypes had higher yield than shorter genotypes (Casady, 1966; Hadley *et al.*, 1965). In a study of height involving gene mutants of isogenic sorghum lines, taller mutants had higher yield than shorter mutants. House (1985) associated height with higher stem lodging.

The genetics of height in sorghum were investigated by Quinby and Karper (1974. They found height to be under control of four genes which they symbolised as Dw_1 through Dw_4. Tall height was partially dominant to short height (dwarfness). The dwarfing effect of the alleles was brachytic and reduced the internode length with little effect on the number of nodes, peduncle length, head length, number of tillers or the number of leaves at maturity. According to Hadley *et al.* (1965), Casady (1966) and Morgan and Finlayson (2000), dwarfism in similar genetic backgrounds tends to lower yield compared to tallness. Zero dwarfs (Dw dominant at all four loci) could be as tall as four meters. The dwarfing genes did not affect root length or volume (Morgan and Finlayson, 2000). When genes at one or more of the loci were recessive, additional recessive loci had little impact in height reduction. The four-dwarf homozygous state was thought to be lethal and plants of that genetic complement were extremely rare.

From the preceding literature, this research should aim at a compromise between short and tall hybrids because of the strong association between height, yield and number of seeds per head. Plant lodging was associated with excessive plant height, while extreme late maturity and very tall height were also associated. Late maturity would not be ideal in the semi-arid conditions where this research was conducted.

1.1.2 Leaves, stems and uses in sorghum

According to Doggett (1970), well adapted sorghum cultivars have 14 to 17 leaves and unadapted cultivars may have up to 30 leaves. According to House *et al.* (1995), a well adapted sorghum plant has seven to eight leaves after dropping lower leaves. According to Rana *et al.* (1996), number of leaves may indicate yield potential of hybrids. High yielding hybrids had few leaves (Rana *et al.*, 1996; House *et al.*, 1995).

There are many brown midrib (bmr) genes in sorghum (House *et al.*, 1995). Brown midrib genes (bmr 6, 12 and 18*)* are important in reducing lignin content and improving digestibility in ruminants by 20 to 30% (House *et al.*, 1995). Inheritance was simple recessive and controlled by bmr genes. Studies indicated linkage between bmr 12 and 18 but independence in bmr 6. Brown midrib genes occur naturally in maize, millet and sorghum (House, 1995). According to Cherney *et al.* (1991), chemical mutagens induced bmr genes, reduced lignin in stem and leaves by 5 to 51%. Reduction was generally higher in the stem than leaves.

The taste of the stem (forage) may range from insipid to sweet and from dry to juicy (House *et al.*, 1995). Sweet forage is more palatable to livestock. Sugar content can be as high as in sugar cane. The sugar content has implications for sorghum uses such as chewing, production of sugar, syrup and bio-ethanol (House *et al.*, 1995; House *et al.*, 2000).

1.1.3 The sorghum grain traits and genetics

Inheritance of grain protein in sorghum is polygenic. Combining ability (both General Combining Ability (GCA) and Specific Combining Ability (SCA) for protein was significant. Heritability varied between 41 and 85% and depended on varieties, populations used and method of computation (Liang *et al.,* 1969: House *et al.*, 1995). Additive gene action was less important than non-additive gene action in inheritance of grain protein (House *et al,* 1995). Mid parent heterosis for grain protein was generally significantly negative. Genotypic effects were greater than environmental effects (Hulse *et al.*, 1980). Nanda and Rao (1975) found significant differences among hybrids in protein content, yield and amino acids; threonine, methionine, isoleucine, leucine and phenylalanine. Non-additive gene action was generally more important than additive gene action in all amino acids (Nanda and Rao, 1975; House *et al.*, 1995). There was significant negative correlation between protein content and yield in hybrids and OPV lines. Protein content was lower in hybrids than in OPV varieties but quantity per plot was higher in hybrids because of higher yield in hybrids (Collins and Pickett, 1972, House *et al.*, 1995). High lysine content sorghum was identified in Ethiopia in 1974 controlled by the high lysine gene *hl (*House *et al.*, 1995).

Carbohydrates in sorghum relate to the waxy and sugary endosperms. Waxy endosperm sorghum is important in determining which foods can be prepared. The endosperm ranges from corneous to floury. Floury endosperms stain blue with iodine while waxy endosperm stains red (House *et al.*, 1995). Waxy endosperm is inherited as a single recessive gene (Doggett, 1988). Variation in sugary endosperm ranges from 0.34 to 2.7% (House *et al.*, 1995). The sugary endosperm is inherited as a single recessive gene like waxy endosperm (House *et al.*, 1995). Grain colour occurs in the pericarp, in the testa or in the endosperm. Endosperm colour is visible only when the pericarp is colourless. Presence of the *Y* allele results in yellow colour and R in red pericarp in presence of Y. The R gene in presence of *I gene allele* augments intensity of *Y.* Genotypes that are R-Y-I- are brighter red than R-Y-ii. The gene *m* modifies the yellow colour due to Y (House *et al.* 1995). Grain colour and carbohydrates (wax and sugar) have been easy to manipulate but protein content was polygenically controlled and difficult to improve.

1.1.4 Grain quality

Grain Quality is difficult to define (Bramel-Cox *et al.* 1995). It varies with regions and end use. Bramel-Cox *et al.* (1995) has suggested that food, feed and beer, the end products of sorghum grain, be used as basis for grain quality determination. According to Andrews *et al.* (1996), flour yield after milling and flour starch, water absorption and retention properties were good quantifiers of grain quality. Andrews *et al.* (1996) discouraged the use of taste, grain and flour colour because they were based on people's opinion which in turn varied regionally and could not be standardized. Selection for grain quality based on tannin content, grain hardness and lack of surface colouring has been practised (Andrews *et al.*, 1996). Feed quality grain has not been selected for because food quality grain is assumed to be acceptable in quality feed (Andrews *et al.*, 1996). Determination of acceptable quality grain is a challenge in this research. Feed quality is also foreseen as a challenge.

1.1.5 Grain yield and yield components

According to House (1986) yield is a quantitative trait. Gene action is partitioned into additive and non-additive components. The additive component has been expressed as general combining ability and the non-additive component as specific combining ability (Falconer and Mackay, 1996; Simmonds and Smartt, 1999). Additive gene action was more important in yield of OPV plants than non-additive gene action (Niehaus and Pickett, 1966; Kambal and Webster, 1965; Beil and Atkins, 1967). Non-additive gene action is more important in hybrid vigour or heterosis. Both additive and non-additive gene action may contribute to yield of the germplasm being used in this research. Additive and non-additive gene action should be exploited in a similar approach to breed for yield in semi-arid parts of Kenya. Yield was composed of number of seeds per head and seed weight (Niehaus and Pickett, 1966; Kambal, 1965).

1.1.6 Maturity period in sorghum

Sorghum generally flowers in 55 to 70 days (House *et al.*, 1995). Productive hybrids flower in 68-70 days (Rana *et al.*, 1996). Sorghum varieties cultivated in semi-arid parts of

Kenya flower in 60 to 70 days (KARI, 1993). There is a general feeling that they are late maturing (PRA chapter two of this publication). Extremely high yielding hybrids were generally very tall and very late maturing (Niehaus and Pickett, 1966). In semi-arid parts of Kenya, seasonal rain is highly erratic in amount and distribution and most of it falls in the first six weeks of a three-month sorghum growing period. After those six weeks, the sorghum crop reaches maturity using residual soil moisture. According to Majisu (1971), Jewett (1972) and Haussmann *et al.* (1998), sorghum hybrids were higher yielding than OPV lines in the east African region and Kenya. Additionally, Niehaus and Pickett (1966) clearly established a linkage between late maturity and high yield. From these facts, the objectives of this research are to identify high yielding hybrids within a flowering period range of 55 and 60 days.

Quinby (1967, 1974), investigated sorghum maturity from a genetics standpoint. He attributed maturity control to interaction of four loci; Ma_1, Ma_2, Ma_3 and Ma_4. Lateness was dominant over earliness. According to Miller (1968) tropical lines are dominant at all four loci and also are adapted to tropical regions.

A recessive condition (ma_ma_) at any of the maturity loci give reduced maturity period and improved adaptation to temperate areas (reduced photoperiod requirement). From this revelation, Texas Agriculture Experiment Station, USA established a programme to convert tropical sorghum germplasm to temperate (germplasm) adaptation (Schuering and Miller, 1978) to enable utilization in temperate conditions. The conversion involved substituting one of the maturity loci with recessive alleles, thereby increasing earliness. During the conversion two or three of the height loci were replaced with recessive alleles converting the lines into dwarfs (Stephens *et al.*, 1967). Consequently temperate sorghum lines are recessive at one of the maturity loci and at least one of the height loci. Lines from the Texas conversion programme are exclusively recessive at maturity locus one and dominant at the other three maturity loci. This revelation clearly established linkage between maturity and photoperiod response in sorghum.

1.1.7 Photoperiod response in sorghum

Plant response to day length is called photoperiodism (FAO, 1972) and to temperature as thermoperiodism (Sweeney, 1987). Photoperiodism and thermoperiodism are compensatory (Sweeney, 1987). Miller *et al.* (1968) identified five photoperiodic sorghum groups and established that photoperiodism and maturity were linked.

Sorghum is photoperiod sensitive (Stephens *et al.*, 1967; Miller *et al.*, 1968) and is classified as a short day warm season plant (Miller, 1982). Varieties adapted to the tropics do not flower in temperate zones, because summer day length is never short enough. However, temperate varieties easily flower in the tropics (Rao and Rana, 1982). According to Miller (1982), temperate varieties and hybrids adapted to the tropics had higher yield at high altitude in temperate and tropical conditions than tropical varieties and hybrids.

Kenya lies between 5^0N and 4^0S (Macmillan education Ltd., 1999). Therefore, photoperiod is not a constraint to flowering in sorghum in Kenya. Sorghum could be grown throughout the year in Kenya.

1.1.8 Panicle traits and choice of good parents for hybrids

Dunlap and Morgan (1981a, 1981b) found sorghum floral initiation to be under the control of a balance between phytohormones. Doggett (1988), Chantereau and Nicou (1994), Pedersen *et al.* (1998) and Rosenthal and Gerik (1989) have studied the panicle morphology and pollination in sorghum. Panicles vary from loose to compact and from partially or fully exserted above the flag leaf. Spikelets flower from the top tip of the panicle downwards to the panicle base (Doggett, 1953). Spikelets have two florets, each of which contains two glumes, two lemmas, one palea and a lodicule. All the floret parts protect three anthers that surround two stigmas. One floret is insessile and infertile, while the other is sessile and fertile (Doggett, 1988; Chantereau and Nicou, 1994). Generally, florets produce single grains through twin grains are produced in some or all spikelets of some varieties (Doggett, 1953). Panicles are 11 to 32 cm long and can carry 200 to 3600 kernels weighing 20 to 59 g. The flowering period within a sorghum field takes 15 to 20 days and 3.2 to 5.8 days within a panicle. Outcrossing is high in dwarf and loose headed varieties. It is low in long glumed and compact panicles (Rao and Rachie, 1965). Sorghum florets are self pollinated but out crossing ranges between 2% and 25% (Doggett, 1953; Doggett, 1988; House, 1995). Pedersen *et al.* (1998) recorded 0.1 to 13% outcrossing in R-line rows, 0.5 to 9% in rows of B-lines and 0 to 100% in Sudan grass. Both genotype effects and isolation effects significantly influenced outcrossing. This behaviour can be exploited to maximize fertilization and grain production in the sorghum hybrids.

Rosenthal and Gerik (1989) evaluated genetic differences in the flowering process of grain sorghum with respect to ambient temperature, flowering duration and the period of flowering. These traits determine length of exposure to pollination and are likely to influence production of hybrids in the study. They found significant variation in the flowering duration but not in the flowering period among genotypes. Both traits were independent of panicle size and were fairly consistent in the temperature range of 25^{0}C to 35^{0}C. Extreme temperatures caused floral abortion, reduced seed set and lowered grain yield (ICRISAT, 1983). Flowering period was influenced by phenological age within the crop, uniformity of crop establishment, crop tillering and crop density (Rosenthal and Gerik, 1989). From this literature review, it appears hybrid production can be maximized in the temperature range of 25^{0}C to 35^{0}C.

1.2.0 Development of hybrid sorghum

1.2.1 The origin of sorghum and early cultivars and landraces

Highest sorghum yield reflects the maximum genetic expression and optimum growing conditions. In evolutionary terms, as sorghum evolved, biological stresses evolved too. Therefore, centres of origin and diversity are not only centres of origin for sorghum, but also centres of origin and diversity for sorghum pathogens. Consequently, they are an invaluable source of resistance and tolerance required for high yield (Yan and Wallace, 1995). Emulating conditions in the centres of origin, diversity and domestication is likely to maximize hybrids yield potential (Majisu, 1971; Miller, 1982). Early cultivars and landraces of sorghum constitute germplasm adapted to specific areas where they are found (IPBGR, 1987; Doggett, 1988). This research is likely to benefit from such locally adapted germplasm more than exotic germplasm. Consequently, exotic germplasm should only be used when local germplasm lacks certain desired traits.

1.2.2 Classification and races of sorghum

There are five races of sorghum: Bicolor, Guinea, Caudatum, Kafir and Durra races (House, 1985). Classification and races of sorghum are given (Snowden, 1936; Murty *et al.*, 1967; Harlan and de Wet, 1972; House, 1985; 1995). Hybrids in this research should be grouped according to races of the parents in accordance with their resemblance (Falconer and Mackay, 1996). Sorghum races have perhaps made the biggest contribution to hybrid sorghum in terms of traits (Harlan and de Wet, 1972). Distribution of cultivated sorghum shows a racial pattern whereby racial hybrids (intermediate races) occur at areas of intersection between pure races. Basic races contribute important traits to the hybrid (intermediate) races. Consequently, racial hybrids are important in agriculture (Harlan and de Wet 1972). The guinea-caudatum and guinea-Kafir intermediate races are very important in west and east Africa, India and China. Almost all American hybrids belong to Kafir-caudatum intermediate race. The yellow endosperm and large grain traits in American hybrids are from durra-caudatum (Harlan and de Wet, 1972).

According to Harlan and de Wet (1972), the cytoplasmic male sterility system used in production of hybrid grain sorghum, is derived from durra (milo) race. According to Andrews *et al.* (1996), when lines of the Kafir race cross with lines of the durra (milo) race, the hybrid is male sterile. The Kafir race carries nuclear genes that allow male sterility to be expressed when put in milo cytoplasm. The Milo race carries nuclear genes that restore male fertility in a Kafir nucleus (Andrews *et al.*, 1996). According to Andrews *et al.* (1996), cytoplasmic male sterility was developed by Stephens and Holland (1954). Perhaps the development was based on the reaction of the races pointed out by Harlan and de Wet (1972). Many more cytoplasms have been identified (Ross and Hackerott, 1972; Worstell at al., 1984; Kishan and Borikar, 1989; Elkonin *et al.*, 1996). However, commercial sorghum hybrids are still based on the "A1" genetic male sterile cytoplasm developed by Stephens and Holland (1954).

1.2.3 Cytoplasm male sterility in sorghum

A male sterility system controlled by cytoplasmic factors and organelle genes and therefore referred to as cytoplasmic male sterility *(cms)* is present in sorghum as described above. Cytoplasmic male sterility adversely affects development of specific cells in the anthers during some stage of microsporogenesis to cause male sterility. Its inheritance is non Mendelian in fashion. It is maternally inherited and causes complete male sterility under normal environmental conditions (Horner and Palmer, 1995). Some plants have *cms* systems that contain male nuclear restorer genes that override the *cms* condition. These systems are designated genic-cytoplasmic male sterility *(g-cms)*. Consequently, there are two types of cytoplasmic male sterile cytoplasms, a fertilizing cytoplasm designated *(F)msms* $_{\textit{(male fertile)}}$ and sterilizing one designated *(S)msms* $_{\textit{(male sterile)}}$ (Horner and Palmer, 1995).

1.2.4 Appraisal of sterility types in sorghum

Male sterility arising from physical and chemical emasculation is not practicable in a commercial setting because sorghum flowers are tiny and significant numbers cannot be emasculated by hand. The hot water technique (Stephens and Holland, 1937) and chemical emasculation (Robinson, 1987) can emasculate florets en masse, but they lack efficiency. Many fertile flowers always remain. Hybrids produced that way would be a mixture of OPV lines and hybrids (non-uniform) (Robinson, 1987). Bags used in the hot water technique pose increased cost of seed production. Cytoplasmic male sterility is the most useful way to produce commercial sorghum hybrids. Unlike genic male sterility, fertility restoration is not a problem. Commercially, cytoplasmic male sterility is superior to genic male sterility. It is efficient because all the plants and florets are male sterile unlike genic male sterility, causing pure hybrid seed to be produced.

1.2.5 Application of different types of sterility

Use of genic male sterility has been demonstrated (Majisu, 1971; House, 1985, 1986). In sorghum, it was used to make sorghum populations and sorghum genetic conservation (Majisu, 1971; House, 1985, 1986). The first sorghum hybrids were based on genic male sterility (Axtell *et al.*, 1999). In many crops, genic male sterility is the only male sterile system for hybrid seed production. In tomatoes, genic male sterility is used in the presence of a suitable morphological markers like stem colours to produce hybrid seed (Melis, 2003, personal communication.). Wide use of genic male sterility in hybrid seed production is hampered by maintenance problems (House, 1985). Consequently, hybrids produced using it, are relatively more expensive than those produced using cytoplasmic male sterile systems. Cytoplasmic male sterility has been widely used in commercial hybrids (House, 1985; Andrews *et al.*, 1996). Chemical and manually induced sterility has been used in self pollinated flowers to increase genetic recombination (Robinson, 1987; House 1985).

1.2.6 Genetic variability in male sterile cytoplasms

In the 1970's, a leaf blight epidemic in maize predisposed by a single male sterile cytoplasm stimulated sorghum breeders to diversify male sterile cytoplasms. Methods of developing cytoplasms included introgression of genes from wild relatives of sorghum into maintainers (Ross and Hackerott, 1972), use of isonuclear lines to screen existing sorghum germplasm for fertility restoration reactions (Worstell *et al.*, 1984), comparison of disease reaction and genetic marker techniques (Andrews *et al.*, 1996).

Ross and Hackerott (1972) released five grass type male sterile lines designated Kansas lines. Worstell *et al.* (1984) identified the A2 to A4 male sterile cytoplasms, while Kishan and Borikar (1989), identified the 9E male sterile cytoplasm. The "A1" male sterile cytoplasm, identified by Stephens and Holland (1954) is still the most widely used in commercial sorghum hybrids (Andrews *et al.*, 1996).

Research in the A2 CMS (Andrews *et al.*, 1996) indicated that most restorers in the A1 CMS were maintainers in A2 CMS and could be used as seed parents. The principle difference between A1 and A2 CMS is the degree of restoration. The A2 CMS is believed to possess genes that modify restoration of fertility by restorers in the A1 CMS (Worstell *et al.*, 1984). The newer cytoplasms have been found difficult to use (Andrews *et al.*, 1996). The 'A2' CMS has very few competent restorers, while A3 male steriles are indistinguishable from male fertiles. Both A4 and 9E systems have disadvantages that make them difficult to use for example the '9E' CMS lines have anomalous fertility reaction on identical male fertile testers (Elkonin *et al.*, 1996). The contemporary opinion is that it is easier to develop seed parents in the A2, A3 and A4 CMS than it is with A1 cytoplasm (Andrews *et al.*, 1996). A classification of the world sorghum collection into maintainer and restorers is available (Schuering and Miller, 1978), and breeding programmes may acquire maintainer and restorer germplasm for hybrids if international sorghum (IS) numbers are known.

From the foregoing, there is variation in cytoplasms. Developing A2 through A4 and 9E cytoplasms to the level of commercial viability like the A1 cytoplasm is a challenge to hybrid research. The proposed research is, therefore, restricted to the "A1" cytoplasmic male sterile system.

1.2.7 Development of cytoplasmic male sterile and male fertile lines

In section 1.2.3, it was explained how two lines; (S) *msms* $_{\text{(male sterile)}}$, (F) *msms* $_{\text{(male fertile)}}$ originate from cytoplasms; a third line (S) RfRf (male fertile) is also required (Horner and Palmer, 1995). The (S) msms $_{\text{(male sterile)}}$ line is cytoplasmic male sterile and referred to as A-line. The (F) msms $_{\text{(male fertile)}}$ line is fertile because it has a non-sterile cytoplasm and it has the same nuclear genotype as the A-line so it can increase seed on the A-line. It is called the B-line or maintainer. The third line (S) RfRf $_{\text{(male fertile)}}$ contains nuclear genes that override the expression of the male sterile cytoplasm and produces a fertile hybrid (Horner and Palmer, 1995). This line is called the R-line. Thus, it is possible to both maintain and perpetuate male sterility in the sterile line through crossing with a maintainer line to reproduce the sterile line and to restore fertility of a hybrid by using an R-line which restores fertility to the sterile cytoplasm. Sorghum hybrids are produced with three lines (Andrews *et al.*, 1996). According to Andrews *et al.* (1996), once a sterile cytoplasm is identified, it is used to identify maintainers and restores in sorghum populations. New A-lines are developed by introgression of the A-line into desired male sterile lines until the two lines are isogenic, differing only in cytoplasm. A cross of the sterile cytoplasm with a line that is fertile identifies a new restorer (R-lines).

1.2.8 Effect of cytoplasmic male sterility

The effects of male sterility inducing cytoplasms on agronomic traits has been investigated in sorghum (Quinby, 1970; Lenz and Atkins, 1981). Hybrids based on male sterile cytoplasm flowered later (0.5 d) and were taller by 3 cm compared to hybrids based on normal cytoplasm (Quinby, 1970). Quinby (1970) found no significant effect on grain yield, tillering ability and size of the largest leaf. Lenz and Atkins (1981), associated normal cytoplasm with slightly more vigorous and more productive plants, however they found no differences in productivity between milo and Kansas male sterile cytoplasms.

According to Quinby (1970), Lenz and Atkins (1981) and Rana *et al.* (1996), hybrids are superior in yield to OPV varieties. It follows therefore, that advantages of male sterile cytoplasm outweigh disadvantages. It is therefore, advantageous to use hybrids despite them having a male sterile cytoplasm. At present, it is not economical to make commercial hybrids seed from normal cytoplasm.

1.2.9 Hybrid vigour (heterosis)

Heterosis is a situation whereby the hybrid is superior to the OPV parents. It has been investigated in sorghum (Niehaus and Pickett, 1966; Kambal and Webster, 1966; Kirby and Atkins, 1968; Majisu, 1971; 1968; Haussmann *et al.*, 1998; Fasoulas, 2000). Two types of heterosis were reported (Niehaus and Pickett, 1966). In one type, plants were associated with gross changes in maturity, size and height but in the other type, plants were associated with general vigour without gross changes in size.

Heterosis varied with germplasm and plant traits (Niehaus and Pickett, 1966; Kambal and Webster, 1966; Kirby and Atkins, 1968; Haussmann *et al.*, 1998). Grain yield, number of seeds per head, plant height and days to 50% bloom had the highest heterosis (Niehaus and Pickett, 1966; Kambal and Webster, 1966; Kirby and Atkins, 1968; Haussmann *et al.*, 1998). Heterosis was displayed in stalk diameter and number of leaves (Kirby and Atkins, 1968), in number of sorghum heads per plot and seed size

(Kirby and Atkins, 1968; Haussmann *et al.*, 1998), in biomass, harvest index and stalk lodging (Haussmann *et al.*, 1998), in seed density, growth rate, head exsertion (Kambal and Webster, 1966) and in protein content (Collins and Pickett, 1972).

Grain yield heterosis ranged between 22% and 79.7%. Low performing parents generally had higher heterosis values than high performing parents (Miller and Lee, 1964; Kirby and Atkins, 1968). Haussmann *et al.* (1998) found higher heterosis under moisture stress than under favourable moisture conditions while Kirby and Atkins (1968) observed similar heterosis in varying environmental potential of the growing conditions. Within similar sets of females, average hybrid heterosis varied with the female sterile parents but not the male fertile parent (Kirby and Atkins, 1968).

1.2.10 Basis for hybrid vigour (heterosis)

The basis of heterosis is complementary heterotic parental groups (Pollack *et al.*, 1991; Andrews *et al.*, 1996). Various causes of heterosis have been proposed (Niehaus and Pickett, 1966; Fasoulas, 2000). They are allelic dominance, overdominance and epistatic gene action. According to Fasoulas, (2000) heterosis is caused by partial dominance. It increases with increased genetic diversity between parents (Majisu, 1971; Niehaus and Pickett, 1966). Heterosis in height is caused by increased head, peduncles and internode lengths (Niehaus and Pickett, 1966; Kambal and Webster, 1966).

1.2.11 Heterotic groups

While maize is divided into complementary heterotic groups (Pollack *et al.*, 1991); sorghum is grouped based on the Kafir and milo race cytoplasms (Andrews *et al.*, 1996). The Kafir race carries nuclear genes that allow expression of male sterility when put in milo cytoplasm. The Milo race carries nuclear genes that restore male fertility when placed on Kafir nucleus (Stephens and Holland, 1954; Andrews *et al.*, 1996).

Introduction of new genetic diversity in both the Kafir and milo pools of parents has disrupted original distinctness of the two pools (Schuering and Miller, 1978). To a lesser extent, they are still complementary (House, 1985; Andrews *et al.*, 1996; Gilbert, 1994). The Kafir-milo cytoplasm forms the A-B heterotic pool. The second pool is the restorer (R) pool. The maintainer (A-B pool) and restorer (R pool) are the only known heterotic groups in sorghum. According to Andrews *et al.* (1996), discovery of the A2, A3, A4 and 9E CMS is likely to open up new heterotic grouping in sorghum. To maintain high levels of genetic complementarity between heterotic groups, interbreeding between the A-B and the restorer pools should be avoided (Andrews *et al.*, 1996). Genetic variability should be manipulated within groups before hybridization (Andrews *et al.*, 1996). The proposed research will use the A-B and restorer pools. There is opportunity to identify members in the A-B and R pool by fertility reaction and heterosis of hybrids between A and R lines.

1.2.12 Characteristics of good hybrid parents

Andrews *et al.* (1996) have outlined traits of good hybrid parents. Seed (female) parents should have perfect male sterility that is stable under all environmental conditions and should have high yield and few tillers that ripen synchronously with the main heads. Heads should have good exsertion, good seed set, large seed and seedling vigour. Seed parents must possess traits that correlate well with good hybrid performance. They should be short, early maturing, disease, pest and lodging resistant (Andrews, 1987). The pollen (male) parents should completely restore male fertility in the hybrid, even in adverse conditions. Pollen parents should have many tillers that mature differently to provide a continuous and prolonged pollen supply.

Pollen parents that produce anthers on both the pedicellate and the sessile flowers are better since they have two successive phases of pollen shed from the same head (Andrews, 1987). They should be like male sterile parents in other traits. The recessive height genes should be as stable as possible to provide a uniform crop (Andrews, 1987). Pollen parents should contribute to hybrid seed germination and vigour (Maunder *et al.*, 1990). The male parent should consistently ‘nick’ with the seed parent to avoid staggered planting of either of the parents. Reduced plant density could be used to accentuate tillering and prolong the duration of pollen shed. In the long term, parents should be selected as described in this literature, for the time being selection must be according to reaction of lines herein.

1.2.13 Characteristics of good sorghum hybrids

Productive hybrids have been described (Rana *et al.*, 1996). Productive hybrids should have a wide environmental adaptation, high mean yield and a low coefficient of variation (CV %). An ideal sorghum hybrid is 175-180 cm tall and flowers in 68-70 days. Such hybrids generally yield 10-32% higher than OPV varieties. Across environments, hybrid yield should be more stable than yield of OPV varieties. Extremely high yielding hybrids are generally very tall, very late and unsuitable for combine harvesting (Niehaus and Pickett, 1966; Majisu, 1971). In Africa, where sorghum is grown in semi-arid areas, late maturity is a constraint to sorghum production, but plant size may not be. Good hybrids are usually associated with a reliable quality seed supply.

1.3 Selection of parents and hybrids

1.3.1 Field establishment

Field design is considered standard but a non-standard plot size was used and required reviewing. Plot size in sorghum was tested (Rasmusson and Lambert, 1962; Lessman and Atkins, 1963a and 1963b: Jensen and Robson, 1969). An optimum sorghum plot is a 4.5 m long row plot (60 plants) (Lessman and Atkins, 1963a). Lessman and Atkins (1963b) compared drilled and single-plant plots of sorghum spaced 7.6 cm (drill), 50 cm and 100 cm within rows and 100 cm between rows. Similarly, Jensen and Robson (1969) compared those of wheat. There was strong correlation ($p<0.01$) in yield ranking among the different sorghum arrangements. Jensen and Robson (1969) found close agreement between hill plots and rod (straight) row plots in ranking wheat varieties. Yield was proportional to plot size and rod row and linear hill plots had similar genotypic competitive pressure (Jensen and Robson, 1969). Two and a half as many replications were required to give precision of standard row plots (Jensen and Robson, 1969). Wider hill spacing was more accurate and required 2-3 hills (2-3 plants) to rank genotypes in yield (Lessman and Atkins, 1963b). Correlation between single plant plots and rod (straight) row plots was stronger between high and low yield genotypes and weak between intermediate yield genotypes. Large unguarded rod row plots or similar size plots guarded with common material ranked varieties as hill plots (Rasmusson and Lambert, 1962).

De Sousa-Vieira and Milligan, (1999) were successful in selecting high yield sugarcane genotypes and families using spaced hill plots. Wider spacing (82 cm) was more accurate than narrow spacing (60 cm).

1.3.2 Mating designs

Mating designs have been reviewed (Comstock and Robinson, 1948, 1952; Griffing 1956; Stuber, 1980; Pepper, 1983; Dupont-Nivet et al., 2000). Diallel and North Carolina designs I through III have been described (Stuber, 1980). Griffing (1956) identified four diallel analysis methods. According to Stuber (1980), partial diallel is similar to design III because parents are selfed. According to Pepper (1983), partial diallel is a nested design. Stuber (1980) restricts diallel mating designs to homozygous inbred lines, pure lines, and clones and to generating breeding populations. Details can be found (Stuber, 1980). Design II was both a factorial mating design and a modification of design I (Comstock and Robinson, 1948, 1952). Four female or four males form groups within the main group are mated (Comstock and Robinson, 1948, 1952; stuber, 1980) and analysis of variance over blocks is pooled in estimation of genetic variance components (Stuber, 1980). According to Stuber (1980), design III is inaccurate.

It is apparent in this literature that four crosses of a parent are required for genetic studies. However, the principle behind designs is not apparent. Therefore breeders are relegated to memorize the detailed descriptions. Pepper (1983) gives a superior account of designs. He is categorical that there are only three designs: Hierarchical, diallel and factorial mating designs. Within the three designs, there are allocations of male and female parents to produce a number of crosses from the many crosses possible (sampling). Therefore, apart from diallel and perhaps design II, many of what Stuber (1980) refers to as designs are sampling schemes. In each of the three designs (Pepper, 1983), there are two types of parents allocation usually referred to as nested allocation designs (Pepper, 1983; Dupont-Nivet et al., 2000). The two allocation (matings) designs are generally referred to as the (A/B) and (AB) nested mating designs (Pepper, 1983) (A represents males and B females). According to Pepper (1983) the best design is one that minimizes the error variance component in the total variance. Based on the error variance, he compared the A/B and the AB parental allocations. From the comparison, Pepper (1983), concluded that "regardless of the size of the experiment the AB allocation designs with equal number of males and females are optimal for simultaneous estimation of additive and dominance variances". He further observed; in the AB (factorial allocation) designs the ratio of males to females between 2:1 and 3:1 does not significantly reduce accuracy.

In a factorial design, AB may represent a sample or the full number of possible crosses (Dupont-Nivet et al., 2000). A factorial mating design is partial when a sample is represented and full factorial when AB represents all possible crosses (Dupont-Nivet et al., 2000). According to pepper (1983), one is not restricted to the four male and four females recommended (Comstock and Robinson, 1948, 1952); stuber, 1980). What matters is the male to female ratio.

1.3.3 Choice of parents by morphological traits

Andrews *et al.* (1996) and Andrews (1987) have outlined traits of good parents of hybrid. Both seed and pollen parent traits should correlate well with desirable hybrid performance. Parents should have good head exsertion, good seed set, seed size and seedling vigour that are transmissible to the hybrids (Andrews, 1987). Male and female parents should nick in flowering if possible and avoid staggered planting (Andrews, 1987) but this is not essential. Pollen parents should contribute to hybrid seed germination and vigour (Maunder *et al.*, 1990). According to Andrew *et al.* (1996), anthers in male sterile lines are infertile; therefore hybrid seed production must depend on cross pollination.

According to Niehaus and Pickett (1966) and Majisu (1971), geographically and genetically distant parent combinations produced hybrids that were high yielding. Haussmann *et al.* (1998) alluded to allelic impurity by referring to hybrids as heterozygotes when comparing hybrids and OPV lines. Fasoulas (2000) referred to hybrid vigour as a situation whereby the heterozygote was superior to the homozygote. Consequently parents with contrasting traits are likely to give high yielding hybrids. High yielding parents with different genetic contributions to heterosis should give high yielding hybrids (Collins and Pickett, 1972). Thus, even parents that have "good" per se yields could give high yielding hybrids. However, hybrid yield cannot be predicted from parental performance as low yielding parents might also show good heterosis in crosses. Therefore, parents must be selected on the basis of their performance when crossed onto OPV testers. The male parent should 'nick' with the seed parent if possible to avoid staggered planting of either of the parents (Andrews, 1987). However, crosses between lines that do not nick often show good heterosis such that staggered planting is sometimes necessary. House (1986) discouraged use of parents whose days to flowering differed by more than 10 days.

1.3.4 Choice of parent populations by genetic distance

The relationship between performance and genetic distance has been studied (Silverstein *et al.,* 2005; Kisha *et all.,* 1997; Hansen and Mensberg, 1998; Riday *et al.,* 2003). Methods of estimating genetic differences include microsatellite markers for polymorphic loci (Silverstein *et al.,* 2005), Random Fragment Length Polymorphism (RFLP) markers (Kisha *et al.,* 1997; Hansen and Mensberg, 1998; Riday *et al.,* 2003). Results indicated that genetic distance was significantly ($p < 0.05$) correlated with genetic variance for plant height. Yield variance was correlated with genetic distance estimates (Kisha *et al.,* 1997). When sorted according to population distances, the average genetic variance for yield of populations in the more distant populations was greater than for the less distant populations and genetic variation was correlated with performance (Kisha *et al.,* 1997). Kisha *et al.* (1997) concluded that although genetic distance cannot accurately predict genetic variance of individual crosses, it can on average identify populations of greater genetic variances. Silverstein *et al.* (2005), found inconsistent results, although weight of trout crosses between geographic populations was heterotic, the best performing progenies were from within one population. In a study of anadromous brown trout from four river systems/geographical regions using Restriction Fragment Length Polymorphic (RFLP) markers, Hansen and Mensberg (1998) found significant (*P*<0.001) correlation between geographical and genetic distance between population pairs whereas genetic distance correlations within geographic areas (river systems) were non-significant. Hansen and Mensberg (1998) also found a significant correlation between geographical distance and gene flow from one river system (geographic region) to another. Riday *et al.* (2003) found no significant correlation between genetic distance and heterosis between genotypes from two species (*Medicago sativa* sativa *and Medicago sativa* falcata) of luecern. In contrast, a morphological distance matrix based on seventeen agronomic and forage quality traits was significantly correlated with heterosis. Maturity period, midseason regrowth and autumn regrowth showed strong association with heterosis. Heterosis was also correlated with subspecies. They admitted that genetic distance *per se* between parental genotypes, based on neutral molecular markers, does not reflect the potential of individual genotypes to produce heterosis in their progeny (Riday *et al.,* 2003). There appears to be inconsistences in the relationship betweem genetic distance and performance. While some workers find a correlation between genetic distance and performance of populations, others do not. The available information is based on biotechnology methods. Only the work of Riday *et al.* (2003) has attempted to deal with morphological distance. There is need to investigate genetic distance using morphological traints and then relate this to heterosis.

1.3.5 Selection of hybrids by yield and heterosis

Heterosis in sorghum has been explored (Niehaus and Pickett, 1966; Kambal and Webster, 1966; Kirby and Atkins, 1968; Majisu, 1971; Haussmann *et al.*, 1998). It varied with germplasm (Niehaus and Pickett, 1966; Kirby and Atkins, 1968), with parental performance

(Kirby and Atkins, 1968) and with traits (Niehaus and Pickett, 1966; Kambal and Webster, 1966; Kirby and Atkins, 1968; Haussmann *et al.*, 1998).

Virtually all traits exhibited some heterosis (Kirby and Atkins, 1968; Haussmann *et al.*, 1998; Kambal and Webster, 1966). Number of seeds per head, grain yield, plant height and days to 50% flowering exhibited the most heterosis (Niehaus and Pickett, 1966; Kambal and Webster, 1966; Kirby and Atkins, 1968; Haussmann *et al.*, 1998). Single cross, F_1 hybrids, had better drought tolerance and higher yield than OPV lines (Reich and Atkins, 1970; Haussmann *et al.*, 1998). Second filial generation (F_2) hybrids were inferior to F_1 hybrids; they yielded 16% less and were heterogeneous (Moresan *et. al.,* 1977). Triple cross hybrids were inferior to F_1 hybrids, both triple and F_1 hybrids similarly yielded higher than OPV lines, but triple cross hybrids were heterogeneous and unacceptable to farmers (Jewett, 1972; Andrews *et al.*, 1996). Beside heterosis, cultivars should be selected on merit; triple cross hybrids should be investigated further and in many traits. Individual hybrids should be selected on their own merit and in important traits. Heterosis *per se*, is not enough reason to go with hybrids. Going for hybrids would only be warranted when the hybrids are superior to cultivars in use. The yield superiority arising from heterosis also sufficiently covers additional costs imposed on the farmer by hybrid technology.

1.3.6 The concept of combining ability

The concept of combining ability is predominantly applied to open pollinated crops, especially maize. According to Simmonds and Smartt (1999), it was first applied in maize by Sprague and Tatum (1942). It was untraditional in self pollinated crops like sorghum. From literature, express application of combining ability appears to be the work of Niehaus and Pickett (1966). Subsequently, it has been used (Kambal and Webster, 1965, 1966; Beil and Atkins, 1967) and is still in use (Ross and Kofoid, 1978; Rana *et al.,* 1996). It appears to have become important with the advent of male sterile systems like the cytoplasmic male sterile system in sorghum and sunflower. Inadvertently, when male sterility is applied, the self pollinated crops become cross pollinated, at least for the lines used. It is in use in the cytoplasmic male sterile system of sunflower where it was used to select parents for producing hybrids with a high oil content (Petakov, 1992; Fick and Miller, 1997). From the reports of (Niehaus and Pickett, 1966: Kambal and Webster, 1965, 1966; Rana *at al.,* 1996; Petakov, 1992), it has been fruitful. In this research combining ability analysis is used to identify parental lines which may combine well to give high yielding sorghum hybrids for semi-arid parts of Kenya.

1.3.7 Selection of parents by combining ability

When the parents have been used before, they can be compared by the number of competitive hybrids selected from crosses of a parental line (House, 1985). Generally parents are selected based on their combining ability for the traits of interest (House, 1985). Parents that have high genetic variance components have high breeding value and impart large effects on their hybrids (Falconer and Mackay, 1996 p. 114). Breeding value is quantified by heritability and combining ability (Falconer and Mackay, 1996; Simmonds and Smartt, 1999).

The concept of combining ability was first used by maize breeders in the USA in the 1930s to predict parental breeding value from their progenies (Simmonds and Smartt, 1999). General combining ability is the average performance of lines in hybrid combinations (Kambal and Webster, 1965). "It is the average value of all F_1's having a line as one parent expressed as a deviation from the overall mean of all crosses" (Falconer and Mackay, 1996). The deviation of a specific cross value from expected value is the specific combining ability of the two lines in the cross (Falconer and Mackay, 1996; Simmonds and Smartt, 1999). General combining ability is a measure of additive genetic variance and specific combining ability is a measure of non-additive genetic variance (Falconer and Mackay, 1996). Both additive and non-additive genetic variances can be estimated. Combining ability is necessary for efficiency in identification of good parental lines in hybrid breeding programs (Kambal and Webster, 1965). Variance of general combining ability was more important than variance of specific combining ability in grain sorghum yield (Kambal and Webster, 1965; Beil and Atkins, 1967). The ratio GCA: SCA was used to express the importance of GCA over SCA effects (Niehaus and Pickett, 1966). Kambal and Webster (1965), used the ratios of male GCA to the sum male GCA plus male GCA x location interaction and female GCA to the sum female GCA plus female GCA x location interaction to express stability of GCA of males and GCA of females over locations.

1.3.8 Selection of hybrids and OPV parents by stress tolerance

As plant density increases, resources per plant are reduced and a yield limit is set. High plant density therefore induces stresses. Density increases beyond the maximum limit are absorbed in plant stress adaptation responses. Genotypic adaptation to plant density therefore depends on morphological plasticity of plant traits (Harper, 1977). Genotypes exhibit variation in the range of densities where yield is the same and lowest density for maximum yield (Harper, 1977). According to Donald (1951), constant yield depends on the most limiting resource, not plant density because increases in the limiting resource increases yield. This observation is in support of the fact that density is a stressing factor. Sorghum exhibited differential reaction to plant density Yoda,1963). Yield and yield components were negatively associated with high plant density in beans (Yan and Wallace, 1995). Height, light and plant density have been associated (Morgan and Finlayson, 2000; Smith (1992). Therefore selection for tolerance to high plant density results in simultaneously selection for tolerance to low light intensity.

1.3.9 Selection of hybrids and OPV lines by participatory methods

Participatory Plant Breeding methods were developed to bring farmers (technology end users) on board in the variety selection process (Witcombe *et al.*, 1996) because there is no known substitute for farmers in the variety selection process. Generally, but not exclusively, plant breeders go for high yield. According to Johnson *et al.* (1968), Joshi *et al.* (1997) and Kitch *et al.* (1998), yield was not the most important farmer selection criterion. This does not mean that yield is not important in farmers' perception. For example, in Kitch *et al.* (1998) participants selected for high yield and yield components. The mystery is that yield, the focus of breeders is simply a moving target in farmers' selection criteria; sometimes it is very important at other times it is not so important. For this reason and the fact that other alternatives do not satisfactorily substitute for farmers' criterion, participatory plant breeding methods have become very important. In these approaches, farmers select from material grown in their localities or on-station (Maurya *et al.*, 1988; Joshi and Witcombe, 1995). They may select from among finished varieties or from segregating populations. Participatory plant breeding is a partnership; formal plant breeders contribute genetic variability and skills to manage it, while farmers contribute breeding goals and appropriate on-farm selection environments (Atlin *et al.*, 2001). Participatory plant breeding has evolved to fill gaps in crop breeding and to provide better service to farmers in marginal environments (Atlin *et al.*, 2001). Participatory plant breeding approach in this study was different from those highlighted in Sthapit *et al.* (1996) and Witcombe *et al.* (1996). Farmers described preferred traits in their sorghum crop and production constraints before the hybrids were created.

Participatory plant breeding methodologies have been successfully used to select and promote crop varieties (Joshi *et al.*, 1997; Kitch *et al.*, 1998; Witcombe *et al.* 1999). Little literature on participatory sorghum research was found; therefore, there is need for participatory research in sorghum to address poor adoption and social perception. Participatory approaches are reasonable and credible. They have become legitimate crop breeding and selection methods. Participatory plant breeding methodologies have worked in other crops and were also expected to work in this research.

1.4 Synthesis of literature review

In summary, the literature review indicated there is abundant knowledge on sorghum to support the objectives set forth in this research, but that is a short term outlook. In the long term, there are areas that require much more investment in research. For example the linkages between height and yield, high yield and late maturity, maturity and photoperiodism all require detailed study. The newer cytoplasms identified require development and deployment in new and probably more productive hybrids than the current ones. The area of sorghum origin and similar areas provided the most optimal sorghum production conditions. Those areas were invariably linked with sorghum pathogens and pests and could provide resistant germplasm to confer resistance in present production conditions. The search for resistances must continue. The association between light intensity and plant density requires research to identify genotypes that use light efficiently to fully exploit plant density which appears a lucrative perspective to maximise sorghum yield. Moisture use-efficient genotypes would provide a means to exploit the abundant agriculturally virgin semi-arid areas in the world, especially the semi-arid tropics (SAT), where insufficient food supply is a major problem. Research on sorghum must continue to better the livelihoods of mankind.

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CHAPTER TWO

THE PLACE OF SORGHUM, PRODUCTION CONSTRAINTS AND IDEAL PLANT AND VARIETY TRAITS, AS PERCEIVED BY FARMERS IN SEMI-ARID PARTS OF KENYA

2.0 **Abstract**

Farmers' perceptions have not been taken into account in developing sorghum varieties which probably explains the low adoption rates of improved varieties for farming systems in semi-arid parts of Kenya. A study was therefore conducted to assess farmer perceptions on the value of sorghum in the farming systems, production constraints and ideal variety characteristics. Participatory rural appraisal guides, questionnaires, group discussions, transect walks and facilitators were used in a participatory rural appraisal to collect data from farmers and their semi-arid farming systems. Sorghum had the lowest productivity and lowest market price compared to other crops but was very popular. Major production constraints included long maturity period, drought susceptibility, and low grain yield, low nutrient content, damage by birds and termites, chaffer grubs, head worms, stem borers, head smuts and marketing problems. Cultivars Kivila Kya Ivui, KARI Mtama-1 and Katengu were the most preferred by farmers. Low market price was a disincentive to expanding production. Sorghum had had the lowest productivity and price but was very popular (was unique) and reducing production constraints should increase sorghum production in the farming system. Cultivar improvement should target adding food, feed and thatching value and marketability. They should have high grain and stover yield potential, coloured large grain and medium height cultivars. Breeding germplasm should mimic Kivila Kya Ivui, KARI, Mtama-1 and Katengu in grain quality and plant morphology to increase adoption but should have higher yield to break the prevailing yield barrier. Farmers should be included in cultivar selection.

2.1 Introduction

Many agricultural technologies fail because researchers do not identify the real problems. They attempt to provide solutions to problems perceived independently of the farming communities they serve. Including farmers in problem conceptualisation and solution search may increase success in agricultural projects. In the past, research in Kenya adopted a top-down research and extension approach. Typically, the researchers decided what was best for farmers without consulting them. However, the failures of this approach lead to the development of participatory research processes, which engaged farmers directly in the research. Experience suggests that these processes are more effective than the top down methods, even if they are slower. Inappropriate research and extension methods have had a negative effect on sorghum production in Kenya.

Since 1938, considerable resources have been spent on sorghum research in the east African region to address sorghum farmers' needs for new varieties. However, early researchers did not use participatory processes, and therefore sorghum farmers generally did not accept the outcomes of these early research efforts. Farmers still maintain and grow their low yielding varieties instead of high yielding varieties developed by the national sorghum and millets research programmes. Had farmers adopted the new, high yielding sorghum varieties, then sorghum production would have been much higher and the frequency of food shortages experienced in semi-arid parts of Kenya would have been lessened.

Research methods that involve its farmer clientele in product development should be used to ensure that waste of resources is minimized in research. Specifically, sorghum farmers should benefit from sorghum research in Kenya. Rapid methodologies that ensure farmers' participation in the research processes, ensuring that farmer' sorghum requirements are recognized and incorporated into the research objectives should be adopted in research and extension so that future research can benefit sorghum farmers. Participatory Rural Appraisal (PRA) methodologies can tune research to address farmers' requirements in Kenya. Participatory Rural Appraisal (PRA) methodologies are a mix of approaches, methods, and theories that aim to speed up rural development. They include methods and approaches such as traditional research methodologies (Zazueta, 1988), consociation theories (Friere, 1970), agro-ecosystems analysis (Conway, 1990; Chambers, 1983) and district focus for rural development (Republic of Kenya, 1984). Subsequently, Participatory Plant Breeding methods should be adopted.

Participatory rural appraisal is founded on the assumptions that:

1. Participation of technology consumers enhances adoption of the technology;
2. Indigenous knowledge systems improve project conceptualization and implementation;
3. Participatory identification of needs, priorities and action plans minimizes conflict, enhances project ownership and partnerships among stakeholders;
4. Success of group activities triggers non-members to adopt the technology and/or initiate parallel projects;
5. Group activities strengthen linkages among communities, the administration and agents of change in development projects;

Self monitoring and evaluation properties of participatory methods keep projects timely, on course and productive (Muthoka, 2002).

Participatory Plant Breeding (PPB) involves participation of both farmers and scientists in plant breeding. In PPB, farmers can be involved in selecting new genotypes from material that is grown in their localities or on-station (Maurya *et al.*, 1988; Joshi and Witcombe, 1995). Farmers may select specific plants or varieties from among finished varieties or from segregating populations. In PPB, breeders contribute genetic variability and their scientific skills to manage the variability, whereas farmers contribute breeding goals and appropriate on-farm selection environments (Atlin *et al.*, 2001). Participatory plant breeding has evolved to ensure that breeders do not breed varieties which are inappropriate to farmers' requirements and perceptions in a particular production area.

Two strategies are used in PPB:

1. Selection from many crosses involving few progenies each, and
2. Selection from many progenies that are generated from one or two most potent crosses.

The former is applied when the potential of crosses is unknown, and the later when the potential is known. The latter strategy has been found to be more successful in PPB (Witcombe and Virk, 2001).

Participatory plant breeding methodologies have been used to select and promote crop varieties (Witcombe *et al.*, 1999; Kitch *et al.*, 1998; Joshi *et al.*, 1997). They have also been used to conserve crop biodiversity on farm (Sperling *et al.*, 1993; Witcombe and Joshi, 1996). Participatory plant breeding was not constrained by replication, number of environments or type of selecting groups (Kitch *et al.*, 1998). In addition, farmers and professional plant breeders showed similar selection intensity (Kitch *et al.*, 1998).

Participatory plant breeding methodologies have been successfully used in selecting for earliness, uniform maturity, high yield and yield components. Varieties developed by PPB were superior in germination, seedling growth rate and tiller production (Joshi *et al.*, 1997; Witcombe *et al.*, 1999). Plant height, milling recovery, grain and cooking traits were important cereal crops' selection criteria in PPB (Joshi *et al.*, 1997; Witcombe *et al.*, 1999), and yield was not the most important farmer criterion (Johnson *et al.*, 1968; Joshi *et al.*, 1997; Kitch *et al.*, 1998). Participatory plant breeding was never in conflict with farmer activities (Kitch *et al.*, 1998; Muthoka, 2002). Participatory plant breeding approaches were consistent, consensus building and democratic (Kitch *et al.*, 1998). They cost less and showed greater cultivar adoption than conventional breeding methods (Witcombe *et al.* 1999; Joshi *et al.*, 1997).

Farmers are almost as good in variety selection as formal breeders. They would critique the prevailing sorghum varieties and propose a practical model for their farming system. Potentially the strengths and weaknesses of new and farmers' varieties would be revealed in PRA meetings. The goal of the PRA meetings was to establish if hybrid technology would be viable in the farming system and the role of farmers a sorghum hybrid development process in ensuring that the hybrid technology developed was appropriate to their needs. The specific objectives of the study were to:

1. Find out the value of sorghum in a multiple-crop, semi-arid farming system and identify potential for expanding sorghum production;
2. Identify and prioritize sorghum production constraints in the farming system;
3. Identify traits preferred by farmers in desirable sorghum model cultivars, and
4. Conceive farmers concept of a desirable sorghum cultivar

The hypotheses tested were:

1. There is scope for expanding sorghum production in semi-arid Kenya, and
2. Farmers are aware of production constraints to sorghum production
3. Farmers know the traits they want in preferred sorghum cultivars for their environments and can describe the traits
4. Farmer popular cultivars are based on a predictable concept

2.2 Materials and methods

2.2.1 Description of study area

The PRA studies were conducted in Kambu area in semi-arid parts of Kenya, which is 280 km to the south east of the capital city, Nairobi, on the Nairobi-Mombasa road. Kambu is to the east of the Tsavo West Game Park and to the north of the Chyulu hills, which is the source of the Kibwezi River and many terrestrial springs that provide water for some time in the year before drying up. Within Kambu area, the PRA meetings were conducted in Kitengei and Nzambani. Kitengei is 15 km to the northern side and Nzambani 6 km to the southern side of the highway. Nzambani is near the Chyulu foothills, while Kitengei is about 30 km further north. Farmers of Kitengei and Nzambani have past experiences from higher potential areas of Kenya, where they originated from, before moving to this region due to population pressure. Kambu was chosen for the PRA meetings because it is situated in the heart of semi-arid parts of Kenya and sorghum was the second most important cereal crop in this area. According to Mololo (pers. com.) there are 2 000 households in Kambu. The survey component in the PRA indicated that a household had six members (children and adults), of which one was independent. Therefore, improving the farming system would benefit about one 120,000 lives.

Because one part of Kambu covers both agro- ecological Zones IV and V, Nzambani was chosen to represent Zone IV and Kitengei Zone V. Kambu area falls in agro-ecological Zones IV and V, with small portions falling into Zone VI, the driest limit of crop production in Kenya (Mololo, 2004). Agro-ecological Zones IV and V receive about the same rainfall (500-800 mm yr^{-1}). The basic difference between them is temperature; Agro-ecological Zone IV is cooler, with less evapotranspiration than Zone V. Consequently, there is more residual moisture available to crops after the rains in Zone IV than Zone V. Livelihood activities in Kambu, like all semi-arid areas in Kenya, include livestock keeping, husbandry of drought resistant crops and horticulture in the few irrigable areas, traditional bee keeping and charcoal burning. Harsh abiotic and biotic stresses cause low crop yield and there is a high frequency of crop failure. During periods of crop failure, farmers depend on relief food from the government for survival. Thus, promotion of an improved and drought tolerant cereal like sorghum may improve the frequency of crop success and lessen the effects of drought.

2.2.2 Participatory rural appraisal setting

The area agricultural officers (DAO) and area administrative chiefs were invited to participate in the PRA meetings. Based on reconnaissance visits of Kitengei and Nzambani with DAO officers, the necessary information to address the PRA meeting objectives was conceived, recorded and progressively developed into a draft PRA guide. The PRA guide (Appendix 11) covered strengths in the farming system, production system, constraints to sorghum production, consumption and commerce in agricultural commodities in the farming system, uses of sorghum, sorghum traits and cultivars most preferred by farmers in the farming system. Copies of the draft guide and PRA objectives were independently reviewed by social scientists based at KARI-Katumani research centre in Kenya. The major aim of the multiple reviews of the draft PRA guide was to create simple, accurate, quick and orderly communication with the PRA communities.

During the final visit, the research team, comprising principal investigator, social economists and DAO officers, pre-tested the improved PRA discussion guide in mock discussions and recordings using a sample of farmers from the area. This further improved the PRA guide and harmonized communication among group leaders and between each group leader and participant farmers. Seating and meeting logistics were planned. Kambu area agricultural office then invited farmers to PRA meetings on 29th September 2005 in Kitengei and on 30th September 2005 in Nzambani. Farmers from all villages in each of the two administrative areas were invited.

2.2.3 Participatory Rural Appraisal (PRA) meetings

Participatory Rural Appraisal (PRA) meetings started with plenary sessions. Chiefs called meetings to order and a chosen participating farmer led the session in prayer for the business of the day to be blessed, in line with farmers' custom in Kenya. Both attendance and meeting objectives were introduced. Group rules of interaction were collectively made and farmers were identified as the sorghum resource experts.

Farmers were then randomly divided into three groups to provide local control and greater opportunities to speak, given the scarcity of time. Three farmers were selected from random points in the seated group and asked to stand at different points about 10 m away from the main group and away from each other. Then, starting from a single common point in the main group, the rest of the farmers were sent alternately and cyclically to the standing farmers. Because, farmers from same localities tended to cluster together in the plenary session, this sampling tended to distribute farmers from the same village among all groups. Consequently, there was a fair representation of every village in each of the three discussion groups. Seven hundred and fifty-seven farmers attended the two meetings; 310 in Kitengei and 447 in Nzambani. Incidentally, 68% of the farmers in Kitengei and 70% in Nzambani were women. Farmers were registered in their respective groups of discussion and were not segregated by gender. On average a group comprised of 103 farmers at Kitengei and 149 farmers at Nzambani.

A social scientist from KARI who was competent in the local language (Kamba) was attached to each group to facilitate the discussions. Another officer drawn from either KARI or the area agricultural office recorded group discussions. Group leaders and recorders followed the discussion guide developed earlier (Appendix 11). Issues warranting further discussion were recorded on flip charts. Those topics that were covered well were recorded in notebooks. The principal investigator moved from group to group, consulting with group facilitators on difficult issues and guiding complimentary service crews comprising of a finance clerk, a representative from the area agricultural office, a representative from the chief's office and two representatives of the community.

Group meetings and discussions, questionnaires and facilitation constituted the basic procedures used to collect data on farmers' preferences. Surveys were used to collect crops and the farming system data. Techniques of data collection involved surveys, mind mapping and structured questions. At the field level appraisal was made by drives and transect walks (Pretty and Voudouche, 1994; Woodhill and Lisa, 1999). Farmers discussed issues until a topic was exhausted. Discussion facilitators probed them on the issue until they went silent. Farmers' responses to an item were read loudly twice, after the second reading the farmers voted by show of hands, which were counted and recorded. During the second reading of farmers' responses, farmers were allowed to add, remove or modify earlier responses. In the process, group leaders confirmed the accuracy of the recorders in capturing farmers' views during the discussion. Numbers of farmers who voted for or against a particular view were converted to percentages which were then analyzed following statistical procedures in Genstat 8 computer software (Lawes Agricultural Trust, 2006).

Variations between individual farmers do not show up in group discussions. As such, a small household survey was instituted to pursue specific household details, in an effort to understand the sorghum crop at household level. The survey was stratified according to areas of the PRA meetings (Kitengei and Nzambani). The sampling frames were the PRA meeting registers and had to be within budget allocation for the overall PRA research. Survey samples were constituted by the first 30 farmers picked from the register by two digit random numbers (Gomez and Gomez, 1984) from the Nzambani and Kitengei PRA meeting registers. The survey content covered farming aspects such as total area of land owned, proportion of cultivated and uncultivated land, crops and production estimates etc. After preliminary analysis, the farmers' three most preferred varieties were examined in terms of their agronomic traits and planting density by the researcher at the farm level. This stage had not been foreseen and was therefore not pre-planned. It involved measuring sampled sorghum crop row intervals, lengths and grain yield at the farm level. Plant constituting the sorghum crop were characterised by Plant height (mm), Head, exsertion (mm), maturity period (days), plant population (plants ha^{-1}) and grain yield (t ha^{-1}). Measurements were recorded as described in materials and methods in the biophysical Chapters Three through Six.

2.3 Results

The predominance of women farmers in the PRA at Kitengei and Nzambani agrees with prevailing observation that women dominate Kenyan subsistence agriculture. Literacy levels varied significantly among farmers and spanned from 1 to 18 years of education, that is from primary school to university education (Table 2.1). There was a mean of 7.8 school-going years in Nzambani and 7.1 years in Kitengei. Literacy levels among farmers varied significantly between gender ($p<0.05$) (Table 2.2). Male farmers spent more years in school than female farmers. The mean number of years in school was 8.2 for men and 6.8 years for women, in the Kambu area. Despite these differences in education level, both female and male farmers displayed free thinking, were cooperative, and were highly knowledgeable of the sorghum crop. The survey revealed that on average households cultivated 3.3 ha of land and had 1.1 ha under fallow.

Table 2.1: Distribution of education (schooling years) among farmers that attended PRA meetings at Nzambani and Kitengei meetings

Location	Number of farmers	1st quartile	2nd quartile	3rd quartile	4th quartile
Kitengei	310	4 school yrs	8 school yrs	10 school yrs	18 school yrs
Nzambani	447	6 school yrs	8 school yrs	9 school yrs	20 school yrs

[1] NB: Primary school should be completed in 8 years, high school in 4 years and university in 4 or more years

Table 2.2: Literacy (school-going years) of farmers according to gender and location

Gender	Kitengei	Nzambani	Overall Mean	Difference
Female	6.3	7.3	6.8	NS
Male	8.0	8.4	8.2	NS
Mean	7.1	7.8	7.5	NS
LSD (0.05)	1.2	1.2	0.9	

NS = non-significant.

Crop production, quantity sold and consumed, yield in kilogram per crop, land occupied per crop and price per kilogram of each crop were surveyed. The results are shown (Table 2.3). Maize and beans were consumed in the largest quantities followed by sorghum. In terms of land area cropped, sorghum was number two after maize, while beans took the third position (Table 2.3). Pumpkins and cotton were the significant ($p<0.05$) cash crops of Kambu (Table 2.3). Though not significantly different from the remaining crops, maize had reasonably high revenue (Table 2.3). More pumpkins, maize and cotton were sold than any other crops in the farming system in that order. Cowpea, maize and pumpkins were produced in greater quantity than the rest of the crops (Table, 2.3).

Table 2.3: Household production, consumption, quantity sold and consumed, price and revenue per crop in Nzambani during the long rainy season (data sorted by cropped area)

Crop	Cropped area (ha)	Consumption (kg/household)	Sold (kg)	Production (Kg)	Yield ($kgha^{-1}$)	Price (kes/Kg)	Sales revenue (kes)
Maize	1.4	684.6	745	1429.3	1021.0	5.84	5954.00
Sorghum	0.4	76.9	9	86	214.0	2.89	14.00
Beans	0.3	148.2	62	210	701.0	8.59	1094.00
Cotton	0.2	0.0	405	405	2025.0	23.00	9270.00
Cowpea	0.2	55.6	101	1567	783.5	15.39	2548.00
Green grams	0.2	55.7	98	155	768	21.60	2388.00
Millet	0.2	56.3	90	146	731.5	21.00	1890.00
Pigeon pea	0.2	92.7	112	205	1025	11.45	1732.00
Pumpkins	0.2	90.0	1125	1215	6075	8.89	10000.00
Mean	0.3	140.0	305	445	1484.0	13.18	3877.00
SED	0.2	117.9	378	496	2477.5	5.47	3506.00

NB: Cotton was grown for cash; sorghum is grown against the odds of poor price because it is the means of survival when seasons are extremely dry.

Percentages of farmers growing each of the 13 crops in the local farming system varied significantly ($p<0.01$), according to crops and locations but not seasons (Table 2.4). There were significant crops x seasons, locations x crops and locations x crops x seasons ($p<0.05$) interactions (Table 2.4). Percentages of farmers growing each crop differed significantly between locations ($P<0.05$) (Table 2.4).

Table 2.4: ANOVA for location, seasons, crop and percentage of farmers growing each crop in the Kitengei and Nzambani areas

Variable	Degrees of freedom	Wald/d.f.	Prob. of diff.
Locations	1	6.28	0.012
Crops	13	5.17	<0.001
Seasons	1	0.39	0.533
Locations x crops	12	2.60	0.002
Locations x seasons	1	2.28	0.131
Crops x seasons	13	11.07	< 0.001
Locations x crops x seasons	12	5.53	<0.001

*, ** significant 0.05 and 0.01 levels of probability

Though not significantly different, on average, more farmers grew each crop during the short rains than during long rainy season (Table 2.5). Pigeon pea, pumpkins, dolichos, cassava, cotton, groundnut were uniseasonal and grown during the short rainy seasons (Table 2.5). These results reflect resource (moisture) gradient between long and short rains season. Other than for the uniseasonal crops, the number of farmers growing each crop in each season did not significantly ($p<0.05$) differ (Table 2.5).

Table 2.5: Percentage of farmers growing each crop in the long and short rains seasons (ordered by means)

Crops	Long Rains	Short Rain	Mean	Difference
Maize	98.55	100.00	99.28	NS
Cowpea	87.99	91.74	89.86	NS
Green grams	87.35	89.92	88.63	NS
Sorghum	77.45	60.70	69.08	NS
Beans	57.25	65.97	61.61	NS
Pigeon pea	---	100.00	50.00	**
Pumpkins	---	90.65	45.32	**
Dolichos	---	69.38	34.69	**
Cassava	---	63.93	31.96	**
Finger millet	1.98	26.81	14.40	NS
Cotton	---	18.89	9.45	NS
Groundnut	-	16.81	8.40	NS
Pearl millet	4.38	10.24	7.32	NS
Sweet potato	1.80	11.99	6.89	NS
Mean	29.77	58.36	44.06	**
SED	13.33	13.33	13.37	

*, ** respectively significant at 0.05 and 0.01 levels of probability; --- crop data not available

Farmers were asked to rank the crops according to the level of tolerance to drought. The lowest rank being the most tolerant and the highest being the most affected by drought. Group scores were then averaged out to establish the most drought tolerant crop. The results are shown (Table 2.6). Cowpea and Maize ranked number one and two respectively. Sorghum was better ranked in the long rains than in the short rains but over the two seasons, the mean rank for sorghum was number three (Table 2.6).

Table 2.6: Crops ranking for survival in drought by seasons in Kitengei and Nzambani

	Long rains season		Short rains season	
Crops	Mean group rank	Final rank	Mean group rank	Final rank
Cowpea	2.3	1	3.2	1
Maize	4.2	4	3.7	2
Sorghum	2.3	1	4.2	3
Green grams	2.7	2	5	4
Pigeon pea	-	-	5.2	5
Dolichos	-		5.7	6
Cassava	-	-	7	7
Cotton	-	-	7	7
Beans	3.3	3	8	8
Pearl millet	4.5	5	8	8
Finger millet	5.7	6	8.3	9
Pumpkins	-	-	9.2	10
Sweet potato	7	7	9.4	11
Guard	-	-	11	12
Groundnut	-	-	14	13
Mean	4		7.2	
SED	0.3		0.4	

- Crop not grown in the season

Table 2.7: Drought survival ranks of the different crops assigned by farmers in the long and short rainy seasons at Kitengei and Nzambani areas

Crops	Long rainy season		Short rainy season	
	Mean group rank	Final rank	Mean group rank	Final rank
Beans	3.3	3	8.0	8
Cassava	-	-	7.0	7
Cotton	-	-	7.0	7
Cowpea	2.3	1	3.2	1
Dolichos	-		5.7	6
Finger millet	5.7	6	8.3	9
Green grams	2.7	2	5.0	4
Groundnut	-	-	14.0	13
Maize	4.2	4	3.7	2
Pearl millet	4.5	5	8.0	8
Pigeon pea	-	-	5.2	5
Pumpkins	-	-	9.2	10
Sorghum	2.3	1	4.2	3
Sweet potato	7.0	7	9.4	11
Guard	-	-	11.0	12
Mean	4.0		7.2	
SED	27.76		0.4	

Analyses of the different uses of sorghum among farmers showed significant differences ($p<0.01$) (Table 2.7). Food, sale, feed, and nursing food and thatching were the most important uses in that order (Table 2.7). Although uses did not differ significantly from site to site, the large differences in figures seem to suggest different uses for the two sites. While food was the most important utility in Kitengei, feed (chicken grain) may have been the main use in Nzambani. Likewise, grain sale was more important in Kitengei than in Nzambani.

Table 2.8: Sorghum utilities in Kitengei and Nzambani as indicated by percentage of farmers in each utility category

Uses of sorghum	Kitengei	Nzambani	Mean
Food	100.0	64.2	82.1
Sale	91.4	43.4	67.4
Feed	44.8	79.2	62.0
Thatching	33.3	1.8	17.6
Fodder	16.4	11.2	13.8
Brewing	0.0	1.0	0.5
Nursing food	17.9	*	*
Mean	43.4	33.5	27.76
SED	28.26	28.26	

* Data was not available therefore there was no mean

Cconstraints to sorghum production were classified into six classes; (a) pre-plant (b) growth stage (c) post harvest (d) cooking (e) consumption and, (f) marketing constraints. Farmers listed constraints sorghum constraints in each category and the ranked the constraint following pairwise ranking method (Woodhill and Lisa, 1999). Analysis of rank variation did not reveal any differences among the constraint (perhaps constraints were of equal weight). Farmer ranking was the only way to weigh the constraints and is presented (table 2.8). Many of the constraint listed cannot be overcome from the sorghum breeding approach. However, resistances to unreliable rainfall (drought), pests, diseases, chaffer grubs, aphids, smuts, termites, stem borer, head worms, bird damage, constipation (Red sorghum), low palatability, heartburns and incompatibility with stews (Table 2.8) are quite feasible within hybrid sorghum development research.

Table 2.9: Ranking of sorghum production constraints at different crop stages

Constraint	Mean Group Rank	Final Ranking
	Pre-Planting constraints	
Wrong seed	0.24	1
Unreliable rainfall (drought)	0.50	2
Expensive seed	0.95	3
Soil pests and diseases	1.17	4
Lack of knowledge to plant	1.20	5
Smut	1.41	6
Lack of draft animals	1.50	7
Lack of seed	1.67	8
Termites	1.67	9
	Growth Stage Constraints	
Lack of draft animals	0.33	1
Drought	0.72	2
Birds	1.83	3
Termites	1.94	4
Head worms	1.94	5
Pests and diseases	2.29	6
Smut	2.33	7
Chaffer grubs	2.54	8
Aphids	2.85	9
Stem borers	2.94	10
	Post Harvest Constraints	
Fake storage chemicals	1.0	1
Lack of storage chemicals	1.0	1
Storage pests (weevil)	1.4	2
Expensive chemicals	2.0	3
Poor market prices	2.0	3
Transport problems	2.0	3
	Cooking Constraints	
Low products prices	1.00	1
Few products	1.50	2
Few recipes	1.75	3
Lack of stews	2.00	4
	Consumption Constraints	
Constipation (red sorghum)	1	1
low palatability	2	2
Heartburns	2.1	3
Incompatible with stews	2.3	4
	Marketing constraints	
Low demand	1	1
Marketing problems	1	1
Lack of markets	1.5	2
Low market prices	1.5	2
Transportation to market	2.5	3
Variable prices	3	4

Analysis of the percentage of farmers showing preference for various traits and aspects in sorghum plants revealed significant differences among traits and aspects ($p<0.01$) (Table 2.9). Early maturity, tolerance to drought, resistance to borers and smuts, resistance to bird damage, grain yield and nutrient content were ranked high by farmers (Table 2.9).

Table 2.10: Percent farmers' preferences for specific traits and attributes of sorghum cultivars in Nzambani and Kitengei (combined)

Trait/aspect to improve	% Farmers proposing
Earliness	100.00
Drought tolerance	83.33
Borers and smuts resistance	66.67
Nutrient content	62.22
Grain yield	62.22
Resistance to birds	58.33
Markets	50.00
Digestibility (constipation)	33.33
Grain hardness (dehullability)	33.33
Processing and utilization	33.33
Grain size	22.22
Establishment of sorghum crop	19.79
Head shape	16.67
Plant height	16.67
Resistance to grain weevils	16.67
Mean	44.98
SED	24.52

Analysis of farmers' trait preferences revealed significant differences among traits ($p<0.01$) (Table 2.10). Farmers preferred high yield, large grain and early maturity and high stover yield.

Table 2.11: Percent farmer preferring specific sorghum plant traits in Kitengei and Nzambani

Plant trait	% Farmers Preference
Large grain size	100.0
High grain yield	100.0
Early maturity	95.0
Red grain colour	63.0
Brown grain colour	48.7
White grain colour	44.2
High stover yield	42.9
Medium height	41.2
Short height	36.4
Medium stover yield	35.7
Low stover yield	21.1
Medium grain size	20.0
Medium maturity	20.0
Medium grain yield	0.9
Small grain size	0.0
Late maturity	0.0
Low grain yield	0.0
Tall height	0.0
Mean	37.2
SED	20.87

Analysis of variety popularity among farmers revealed significant differences among varieties ($p<0.01$). There was significant variety by site interaction ($p<0.05$) (Table 2.11). “Kivila Kya Ivui” was popular in both Kitengei and Nzambani. Katengu and Gadam were popular in Kitengei, while “Kivila Kya Ivui and “KARI Mtama-1” were popular in Nzambani (Table 2.11).

Table 2.12: Percentage preference of sorghum varieties used in Kitengei and Nzambani the farming areas

Sorghum variety	Kitengei	Nzambani	Mean
Kivila Kya Ivui	40.60	60.04	50.32
KARI Mtama-1	0.84	53.29	27.07
Katengu	24.13	0.99	12.56
Gadam	12.69	0.00	6.35
Serena	4.29	0.00	2.14
Mwembe	0.00	1.46	0.73
Seredo	1.12	0.00	0.56
Mukenja	0.56	0.00	0.28
Muveta	-	2.03	-
Muvovi	-	0.22	-
Mean	10.53	12.14	15.63
SED	15.40	15.40	

Table 2.12: Sorghum plant populations and trait levels of the most preferred sorghum varieties under farmers' conditions in an extreme drought season (2006)

Variety	Grain yield (t ha^{-1})	Plant ht (mm)	Head exsert. (mm)	Maturity (d)	Plant population ha^{-1}
Katengu	0.89	848.0	36.7	105.5	30280
Katumani	1.25	1025.0	66.7	103.3	31374
Kivila Kya Ivui	1.44	1488.0	131.7	103.3	28005
Mean	1.19	1121.0	78.3	104.1	29886
SED	0.21	93.1	7.8	4.28	4522

Head exsert. = head exsertion

Table 2.13: Performance of the most farmer-preferred sorghum varieties for different traits under extreme drought conditions in Kitengei and Nzambani

Trait	Kitengei	Nzambani	Mean	SED	Prob. diff
Yield (t ha^{-1})	0.2	2.2	1.2	0.17	**
Maturity (d)	95.2	112.9	104.1	3.49	**
Plant height (mm)	1041	1200	1121	7.61	**
Head exsertion (mm)	89	68	78	0.64	**
Plant pop ha^{-1}	34836.0	24937.0	29886.0	3692.00	**

** Significant at 1% level of probability

2.4 Discussion and conclusions

The number of farmers growing maize, cowpeas, green grams and sorghum was higher than the number growing other crops across locations and seasons (Table 2.5). In a semi-arid setting where crop failure is frequent, consistency in growing a crop indicates consistent crop success over locations and seasons or other special attributes in the crops. The four major crops (Tables 2.5) must have had special attributes, for example, yield stability, dependability, economics, etc. This approach was supported by farmers' ranking (Table 2.6). Farmers' drought survival rank analysis across locations and seasons (rank summary) revealed significant survival differences among crops ($p<0.01$) (Table 2.6). In this analysis, sorghum was ranked high among other crops (Table 2.5) in both the long and short rainy seasons (Table 2.6). Farmers' ability to discussed locations and seasons clearly, is in agreement (Kitch *et al.*, 1998) that replications, environments and selecting groups are not a constraint to Participatory Plant Breeding (PPB).

As for energy sources, sorghum ranked second to maize. Sorghum occupied the second largest production area in the farms, had the lowest sales and the lowest proceeds from sales, as well as the lowest price per unit weight (Table 2.3). Furthermore, the bulk of sorghum production (77 kg) was consumed while very little (9 kg) was sold (Table 2.3). Therefore, sorghum was not grown for economic reasons but for survival and food security. Alternatively, there was not enough surplus production for sale which can be attributed to production constraints or the unavailability of high yielding sorghum varieties. It was concluded that sorghum occupied a unique place in the farming system.

Productivity of sorghum was very low at only 214 kg ha^{-1} (Table 2.3), versus estimated yield potential of 3 500 kg ha^{-1} in similar environments (KARI, 1997). Sorghum occupied the second biggest cropped land (Table 2.3) and had the lowest economic value (Table 2.3) but commanded high popularity across seasons (Table 2.5) and high production (Table 2.3). It was concluded that sorghum was grown as a matter of necessity and therefore has a unique value in food security in semi-arid mixed farming systems. It should be improved to enhance the important food security role. Furthermore, research should develop varieties that are suitable for processing and utilization to add value and profitability of sorghum farming.

On average farmers owned 3.3 ha of land, 2.2 ha were cultivated, while 1.1 ha was fallow, therefore, there was room for expansion. Farmers were literate, with a good mix of all literacy levels (Tables 2.1 and 2.2), and displayed a thorough understanding of the sorghum crop. Any farming technology could easily be implemented in the communities. Therefore, there was reasonable opportunity to expand sorghum production. However, the low price of sorghum (Table 2.3) was a disincentive to expanding production.

Having established that sorghum has a unique place in semi-arid, mixed farming systems, and as being worthy of improvement, farmers were engaged to discuss deficiencies and constraints in existing sorghum varieties. The constraints they identified could generally be classified as pre-planting, growth stage, post harvest, cooking, and consumption and marketing constraints (Table 2.8). Pest and diseases affected sorghum at all stages (Table 2.8), which is in agreement with Teete and Pendleton (2000). Drought occurrences impacted negatively on all growth stages (Table 2.8), which is in agreement with Rosenow *et al.* (1993). Scarcity of draft animals resulted in late planting and seedling drought which is in agreement with Rosenow *et al.* (1993). Competition from weeds (Bridges, 1994; KARI, 1997) is directly linked to yield reduction and quality loss (Stahlman, 2000). Other constraints were damage by birds, chaffer grubs, head worms and termites (Table 2.8). Without species identification, stalk borers and accompanying symptoms could have been confused with those of shootfly *(Atherigona socccata (*KARI, 1993). Smuts ("charcoal' as farmer described them) generally reflected head smut *(Sphacelotheca reiliana (*KARI, 1997), covered kernel smut *(Sporisorium sorghii (*KARI, 1993) and long smut (*Sporisorium ehrenbergii)* as identified by (KARI (1997) and Frederiksen (2000). All constraints are already recognized in KARI's, (1993) priority list of constraints in sorghum production.

Farmers' identification of narrow diversity in food recipes and sorghum products was in agreement with the goal of enhancing processing and utilization (KARI, 1997). Deficiencies in prevailing technology included fake seed, unavailability of good seed, and fake agro-chemicals (Table 2.8) which have not been registered. High costs of inputs, transportation and marketing were important constraints as well. Constipation due to consumption of red sorghum, heartburns and incompatibility with stews appeared new and peculiar to the Kambu area (Table 2.8). They are symptoms of grain quality constraints, which should be addressed during the breeding process and which have not been documented before in Kenya.

To further widen the horizon for sorghum utilization, recent uses of sorghum were examined. There were significant differences in number (percent) of farmers using sorghum in different ways (Table 2.7). Food, sale, feed, nursing food and thatching were farmers' most important uses, respectively (Table 2.7).

Cross examination of constraints and uses through farmers' preferred traits is shown (Table 2.9). Analysis of percent farmers preferring individual traits revealed significant differences among traits (Table 2.9). Early maturity, drought tolerance, resistance to borers and smuts, high yield, nutrient content, resistance to bird damage and marketing problems were ranked highest, in that order, among those traits farmers wanted to be improved (Table 2.9). Clearly, farmers would trade off yield for other traits that were perceived to be more important in semi-arid parts of Kenya, for example yield vs. earliness (Table 2.9).

In summary, farmers were looking for resistance to biotic and abiotic stresses in their sorghum crop. In addition, they wanted food quantity (yield) and food quality (nutrient content) improved in the sorghum crop. Based on percentage of farmers desiring each trait (Table 2.9), yield was not the most important farmer trait, as observed elsewhere (Johnson *et al.*, 1968; Joshi *et al.*, 1997; Kitch *et al.*, 1998). Breeders alone would not have identified this counter-intuitive situation, without engaging the farmers through a PRA process.

A deeper focus on the sorghum plant (Table 2.10) revealed significant differences among trait preference. High grain yield, large grain size, early maturity, red grain colour (coloured grain), medium plant height and high stover yield were the most important plant traits to farmers in Kambu (Table 2.10). Thatching was additionally important in the Kitengei area.

Analysis of preferences for the various sorghum varieties grown on-farm revealed significant differences ($p<0.05$) (Table 2.11). "Kivila Kya Ivui", KARI Mtama-1, and Katengu were most preferred, in that order. They should form the basis for future sorghum breeding for the semi-arid area. Because farmers could only offer a qualitative description of their varieties, further description was sought in a field survey. A survey on actual variety characteristic of the three most preferred farmer varieties provided description (Table 2.12), and actual performances in an extremely dry season (March-September, 2006) in the two PRA areas (Table 2.13). These three varieties may have defects, but to the farmers good traits overshadowed the defects, and hence provided good model varieties.

Putting the whole experience together (Tables 2.12 and 2.13), a picture of an ideal sorghum variety emerges: In dry seasons, the ideal variety should be high yielding (> 1.2 t ha^{-1}), food grain type, with a good amount of stover for livestock forage. It should possess abundant resistance to biotic and abiotic stresses. Specifically, it should be resistant to drought, stem borers, smuts, bird and grain weevil damage. The cultivar should complete its life cycle within 105 days. It should have coloured hard grain and be at most 1.5 m tall with an 80 mm long head exsertion. It should be most productive when grown in the population range of 28 000 to 30 000 plants ha^{-1} (Table 2.12). In addition, the variety should have acceptable forage for livestock, thatching sheds and grain quality widely accepted in the markets.

The position of sorghum in a semi-arid mixed crop farming system in Kenya was established and farmers' perceptions of the constraints to production were identified and ranked. There is considerable potential to expand sorghum production, if the low price of sorghum could be improved. Low productivity of currently grown sorghum varieties was revealed by low yield estimates (1.2 t ha^{-1}), compared to the yield potential (3.5 t ha^{-1}) for similar environments (KARI, 1997). There was need for improvement of sorghum production in semi-arid parts of Kenya farming systems in order to close the yield gap. Farmers perceived Kivila Kya Ivui, KARI Mtama-1 and Katengu cultivars as ideal model varieties. Varietal characteristics of Kivila Kya Ivui, KARI Mtama-1 and Katengu (Table 2.13) are a good guide for traits of prospective model cultivars. The model varieties and traits should be used to fine tune sorghum breeders' selection criteria in identifying traits and cultivars needed to address production constraints of semi-arid regions.

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CHAPTER THREE

THE USE OF GENETIC DISTANCE AMONG SORGHUM POPULATIONS TO PREDICT HYBRID PERFORMANCE

3.0 Abstract

Genetic relationships have been expressed by interclass correlation and genetic correlations. A study was conducted to characterize parents and express their genetic relationships (distances) based on agronomic data. Sixty eight R-lines, 53 A-lines and 27 pollen parents from five different sources were tested for agronomic trait performance over six environments in South Africa and Kenya. Population combinations were males of one source population paired with females from another source population without actual hybridization. Interpopulation correlations and the ratio of interpopulation correlation to a component of the genetic correlation for head weight, stem weight and total biomass were used as estimates of relative genetic distance and relative heterosis in hybrids, respectively. Results showed that the populations: all males x all females, Zimbabwe males x Purdue females, Kenya males x Purdue females, Kansas males x Purdue females showed the greatest distance in that order. The populations: Kenya males x Zimbabwe females, Zimbabwe males x Zimbabwe females had intermediate genetic distance and the populations: Texas males x Texas females, Texas males x Zimbabwe females had the least genetic distance of all population combinations in that order. Relative heterosis followed the same pattern and decreased as genetic distance was reduced. It appeared feasible to identify and rank potential of parental populations in production of hybrids by relative genetic distance. The ratio (r/t) tended to indicate relative heterosis. This result may help to reduce breeding time for high yielding hybrid. Parents showed significant variation in all traits studied. Male parents were variable in more traits than female parents.

3.1 Introduction

Breeders are confronted with the challenge of choosing source populations of parents most of the times. Initially source populations were landraces or farmer varieties. Today, most source populations are made up of progenies from crosses between OPV lines. Mean parental performance cannot help in selection because parent performance may not predict combining potential of populations. Normally, parents are chosen from different heterotic group such that one parent contributes a desirable trait that will be lacking in the other.

High yielding parents sometimes give high yielding hybrids (Collins and Pickett, 1972), especially in self-pollinated crops because the OPV varieties have undergone selection for high yield. Combinations of geographically distant and perhaps genetically distant parents sometimes give high yielding hybrids (Kambal and Webster, 1966; Niehaus and Pickett, 1966; Malm, 1968; Majisu, 1971). Geographical distance, however, can be discounted because germplasm has been exchanged across geographical areas. Biotechnology has demonstrated that genes are universal in all living things. The role that geographical distance may have played in creating (allelomorphs) allelic gene forms cannot be discounted. Genetic distance is more important than geographical distance in selecting parents from source populations. Mating genetically correlated individuals results in inbreeding and inbreeding reduces performance of genotypes (Falconer and Mackay, 1996).

According to the Hardy-Weinberg equilibrium (Falconer and Mackay, 1996), allelic frequency remains the same from generation to generation in absence of mutation and migration provided that population size is large and populations are random mating. Therefore, allelic frequency of hybrid is similar to the combined allelic frequencies of the mating parental populations if the populations are is large enough and have not been selected, undergone mutation, or non-random mating, which is very rare in nature. Populations are described by their mean and variances. When the means are similar, the distance between populations is the difference of their variances. According to Niehaus and Pickett (1966) and Majisu (1971), populations of distant origin generally give high yielding hybrids. Because of developing in different environments, they are likely to have different alleles and therefore are distant genetically. Population combinations having the highest difference of variances have the highest spread around the mean. The extreme on the higher side would be very high yielding whereas the extreme on the lower side would be very low yielding. Because the gene frequency in the combined population and the hybrids are the same (Hardy-Weinberg equilibrium), their hybrids have similar spread plus the non-additive component. Consequently, the highest yielding hybrids are likely to be found in populations with the highest variances than those with smaller variances.

Favourable gene alignments whether additive or non-additive, are exhibited in trait (yield) expression. Therefore, even low yielding parents can have good combing. How low-yielding a parent can be, and yet remain worthwhile in hybrids. As long as a parent can produce selfed seed economically and cross with another parent, then it should be suitable as a parent.

Heterosis is caused by non-additive genetic variance (Fasoulas, 2000). Superior sorghum hybrid heterosis and performance has been attributed to genetic and geographic distances between parents (populations) (Kambal and Webster, 1966; Niehaus and Pickett, 1966; Malm, 1968; Majisu, 1971). Geographical distances between parents used in the study are unknown. Numerous germplasm exchanges have taken place such that places of introduction, for example, USA are new sources of germplasm today. Many breeding programmes do not keep records on sources of germplasm. Origins of some parents were however traceable. It is feasible to estimate genetic distance between male and female populations.

According to Kisha *et al.* (1997) genetic distance was highly significantly correlated with genetic variance for plant height, and variance of yield was correlated with genetic distance estimates. When sorted according to population distances, the average genetic variance for yield of populations in the more distant populations was greater than for the less distant population and genetic variation was correlated with performance (Kisha *et al.,* 1997). They concluded that although genetic distance can not accurately predict genetic variance of individual crosses, groups of crosses that produced populations with greater genetic variance and performance could be identified. In Silverstein *et al. (*2005), crosses of trout (fish) originating from different geographic populations were heterotic. However, the best performing progenies came from within one population. Their findings pointed out that they could not correlate genetic distance between mating parents and performance of progenies. In a study of anadromous brown trout from four river systems/geographical regions, Hansen and Mensberg (1998) found highly significant correlation between geographical and genetic distances between population pairs. Whereas, genetic distance correlated insignificantly within geographic areas (river systems), however, genetic distance and geographic distance correlated significantly between different geographic regions (river systems). A significant correlation between geographical distances (isolation) from one river system (geographic region) to another was found. Riday, *et al.* (2003) found no significant correlation between genetic distance and heterosis between *Medicago sativa subspecies* sativa *and Medicago sativa subspecies f*alcata in luecern. In contrast, a morphological distance matrix based on seventeen agronomic and forage quality traits significantly correlated with heterosis. Large genetic distances of Maturity, midseason regrowth, and autumn regrowth showed strong association with heterosis. Nei (1972) and Nei and Roychoudhury (1974) have established a method of estimating genetic distance between populations based on number of gene loci substitution and large sample statistical theory. Such a method was very expensive for a large number of samples (Nei, 1989). According to Nei (1989), there was scepticism and criticism about scientists who used small samples.

From the foregoing, it is possible to estimate genetic distances between populations. Method of estimation need not necessarily be hightech, such as by using microsatellite or RFLP markers as has been the case in some sections of literature (Nei, 1972, 1989; Nei and Roychoudhury, 1974; Gorman and Reid, 1979; Kisha *et al.,* 1997; Hansen and Mensberg, 1998; Riday *et al.,* 2003; Silverstein *et al.,* 2005). There are numerous cases where genetic variances have been estimated in field trials (Kambal and Webster, 1966; Niehaus and Pickett, 1966; Beil and Atkins, 1968). Population variances in the study were estimated from field tests of parents in Kenya and South Africa and genetic distance was measured as the difference between variances (spread) from population centre) of populations expected to combine to form the hybrids for production at an advanced stage in this research.

The goal was to establish if potential of hybrids resulting from male-female population combinations could be predicted. The specific objectives were to:

1. Characterize and quantify yield potential of parents,
2. Determine relative genetic distances between hybridizing male and female parent populations,
3. Predict relative heterosis in the hybrids resulting from combining male and female populations, and
4. Rank parental populations according to genetic distance.

The hypotheses according to objectives were:

1. Yield potential and characteristics of the parents were the same, and
2. Genetic distance and relative heterosis between hybridizing male and female populations are not different.

3.2 **Materials and methods**

One hundred and twenty one sorghum parental lines consisting of sixty-eight R-lines and fifty-three A-lines were evaluated for agronomic traits at the University of Kwa Zulu, Natal, South Africa and Kiboko, Kenya. In South Africa, they were evaluated in a greenhouse and a growth tunnel from 29 August 2003 to February 2004. In Kenya, the lines were evaluated from June to October 2004. Male fertile (B) lines were used in lieu of counterpart A-lines in the tests as A-lines are self sterile. Details of origin, type and number of lines are given (Table 3.1).

Table 3.1: Source, type and numbers of sorghum lines used in the study

Place of acquisition	Type	
(Source)	Males (R-lines)	Females (A or B lines)
ICRISAT, Zimbabwe	24	2
KARI, Kenya	23	0
Purdue, USA	0	40
Kansas, USA	8	5
Texas, USA	13	4
Total	68	53

The parental lines were grouped into populations according to parental sources. Parental source populations were either female B lines or male R lines acquired from a specific source. Source combinations were males of one source population paired with females originating from another source population without actual hybridization. If females and males from a given source were each considered a population, then there was a total of four female and four male populations (Table 3.1). This is because of the absence of male lines from Purdue and female lines from Kenya. From the male and female parent source populations, seventeen female-male population source combinations were paired and their genetic distances were estimated.

In South Africa, parental lines were each planted in a seedling tray and transplanted to a greenhouse or a growth tunnel in spaced trials. Two seedlings were planted in a ten litre-flower pot in the greenhouse, and two seedlings per hill on growth tunnel beds in the tunnel. The two seedlings per parental line (genotype) constituted an experimental plot. Plots were arranged in an 11 x 11 randomised triple (three replications) square lattice design. Standard potting media was used in the pots and natural soil in the growth tunnel beds. Tunnel beds were limed at the rate used in the area (lime had been applied when field was acquired). Each experimental unit (plot) received two grams of NPK fertilizer at transplanting. Additional nitrogen was supplied with irrigation water from drip system (rate not recorded but assumed sufficient). Water was supplied through drip irrigation in the growth tunnel and through sprinkler irrigation in the greenhouse. The basic difference between the greenhouse and tunnel was using of pots the greenhouse and the natural soil in the pots. In both cases adequate water was supplied and there was no other different irrigation regimes taking place in the neighbourhood of any of the trials in South Africa. Each plant occupied 0.23 m^2 space (0.46 m^2) for the two seedlings. Each trial was considered a different environment. In each environment, guard plots separated trial plots from outside environment.

In Kenya, trials were planted exactly as in South Africa with the following exceptions: Trials were laid out in the field. Four environments were used; high density (9 plants m^{-2}) and low density (1 plant m^{-2}) plots were evaluated over two irrigation regimes (27mm of water weekly up to 60 and until up to 100 days after planting). The trials were irrigated through sprinklers and fertilized with NPK 17:17:0 and 18:46:0 in the high and low moisture irrigation regimes respectively. It was applied in split doses of 0.8 g m^{-2} (8 kg ha^{-1}) at planting and 9.6g m^{-2} (96 kg ha^{-1}) injected into the rhizosphere at 4-leaf stage. Nitrogen was applied at the rate of 9.6 g m^{-2} (96 kg ha^{-1}) as calcium ammonium nitrate ($CaNH_4NO_3$ = 26%N) injected with the last dose of NPK fertilizer. Plants received sufficient nutrients for proper growth and performance. To avoid treatment effects, for example irrigation regime, from one trial affecting the neighbouring trials, the trials were planted as separate independent units as in multiple location trials. A trial comprised of one plant density and one irrigation regime. The nearest trials were 12 m apart and each trial had three guard rows planted round the trial. Guard row plots layout was exactly as those of trial genotypes but had standard sorghum varieties grown in the region of the kiboko region. Genotypes in a trial were treated similarly so that performance differences in an environment were due to genotypic effects. Growth conditions over the six environments are summarized (Table 3.2).

Table 3.2: Summary of growth conditions (environments) in which genotypes were tested

Country	Density regimes	Moisture regimes	
		High Potential HP	Low Potential LP
Kenya	High Density HD	9 plants m^{-2} (90,000 plants ha^{-1}) + 27mm/ wk over 100 days (sprinkler irrigation) + 10.4 g m^{-2} NPK 17:17:0 + 9.6g m^{-2} CaNH4NO3 (26%N) + field condition	9 plants m^{-2}(90,000 plants ha^{-1}) + 27mm/ wk over 60 days (sprinkler irrigation) + 10.4 g m^{-2} NPK 18:46:0 + 9.6g m^{-2} CaNH4NO3 (26%N) + field condition
	Low Density LD	1 plant m^{-2} (10,000 plants ha^{-1}) + 27mm/wk over 100 days (sprinkler irrigation) + 10.4 g m^{-2} NPK 17:17:0 + 9.6g m^{-2} CaNH4NO3 (26%N) + field condition High potential	1 plant m^{-2} (10,000 plants ha^{-1}) + 27mm/ wk over 60 days (sprinkler irrigation) + 10.4 g m^{-2} NPK 18:46:0 + 9.6g m^{-2} CaNH4NO3 (26%N) + field condition Low potential
South Africa	Intermediate Density ID	4.2 plants m^{-2} (42,000 plants ha^{-1}) + Unlimited water supply (drip irrigation) + 2 g pot $^{-1}$ NPK 17:17:0 + N supplied through irrigation + Natural soil + Tunnel condition High potential	4.2 plants m^{-2}(42,000 plants ha^{-1}) + unlimited water supply (sprinkler irrigation) + 2 g pot $^{-1}$ NPK 17:17:0 + N supplied through irrigation + Std potting medium + Green house condition High potential

In each trial, genotypes were scored for seedling vigour at the fourth leaf stage on a 1 to 5 scale where 5, was most vigorous and 1 least vigorous. The basis of vigour score was visual plant size assessment. Days to 50% flowering was recorded as number of days from the first day of irrigation to the day 50% of plants in a plot had flowered, number of tillers were recorded as total number of stems in a plot minus stand after thinning (3 weeks after planting), plant height was recorded as (cm) as height from ground level to the tip of the first fully flowered stem and head exsertion (cm) was recorded as distance from flag leaf to the base of the panicle.

The following applied to Kenya only:

Stem weight (g m^{-2}) was recorded as weight in grams of stems harvested in a plot and dried at the point of harvest for three weeks at approximately 27^0C day temperature. Head weight (g m^{-2}) was recorded as weight in grams of heads harvested in a plot and dried in a freely ventilated shed at about 26^0C day temperature. Total dry weights (g m^{-2}) were derived by adding head weight and stem weight for each genotype. A statistical model for data analysis was identified according to expected sources of variation which are included in the model and defined below. Data was analyzed following Residual Maximum Likelihood (REML) procedure of Genstat 8 (Lawes Agricultural Trust, 2006). Combined analysis in estimation of male and female parents' performance followed the model (1) below:

$$y_{ijklmn} = \mu + \alpha(\beta)_{ij} + M_k + F_l + E_m + C_n + EM_{km} + EF_{lm} + CM_{kn} + CF_{ln} + ECM_{kmn} + ECF_{lmn} + e_{ijklmn}$$

Where y_{ijklmn} was the yield in i^{th} block within the j^{th} replication in the m^{th} trial corresponding to the k^{th} male or i^{th} female in the n^{th} country, μ was overall mean, *a was* the replication effect α $(\beta)_{ij}$ was the j^{th} block effect within the i^{th} replication, M_k was the k^{th} male effect, F_l was the l^{th} female effect, EF_{lm} was the lm^{th} interaction effect between the l^{th} female and E^{th} environment. E_m was the effect of the m^{th} environment; EM_{km} was the interaction effect between the m^{th} environment and k^{th} male, EF_{lm} was the interaction effect between the m^{th} environment and l^{th} female, EFC_{lmn} was the interaction effect among the i^{th} female, the m^{th} environment in the n^{th} country while e_{ijklmn} was the error term in estimating all the parameters. When male and female population performance was required the M and F terms were replaced by the respective populations. When male-female population combination was estimated, the relevant male and female populations (M and F) were pooled.

Population variances were used to compute other variances as follows:

Variances between groups (populations) (σ^2_B) were computed as variance between group means: Var. ($m_1 - m_2$) = var. (m_1) + var. (m_2) – 2 times covariance (m_1, m_2). Covariance (m_1, m_2) was considered equal to zero because parent source populations (groups) were considered uncorrelated. Total phenotypic variances (σ^2_T) of hybridizing groups were computed by analysis of variance on the relevant male and female pools together. Between group correlation t was computed following the relationships: $t=\sigma^2_B/\sigma^2_T$ therefore $\sigma^2_B=t\sigma^2_T$:

$\sigma^2_T=\sigma^2_B + \sigma^2_w$ $t=\sigma^2_B/ (\sigma^2_B + \sigma^2_w)$ and $\sigma^2_w = (1-t)\ \sigma^2_T$ (Falconer and Mackay, 1996). Where σ^2_B = between group (population) variance, σ^2_w = within group (population) variance

According to Falconer, and Mackay (1996), a big interclass correlation (t) value reflects a close relationship. It follows that a small t-value should reflect a distant relationship between populations. Thus interclass correlation (t) could express distance between hybridizing populations. Because big (t) value reflects a close relationship between populations and a small value a distant one, the inverse function (1/t) was used to express distance because it tallied with distance between populations.

A comparative heterosis factor was deduced as follows; if the interclass correlation (t) is the distance between hybridizing populations and genetic correlation (distance) between hybrids and parents, r, r value is given (Falconer, and Mackay, 1996), the ratio (r/t) fits the inter-parent distance onto the parent-hybrid distance. If inter-parent distance fits exactly onto the parent-hybrid distance, there is neither in nor out breeding that is no heterosis. If r, was greater than (t) then there was useful heterosis. The relationship between parents and hybrids in this research was quarter sib (0.25); t was computed from data of this research. Using computed t values, (r/t) values between combining populations (sources) were computed to indicate relative heterosis.

3.3 Results

Analysis of variance revealed significant differences between parents ($p<0.01$), test environments ($p<0.01$), parental populations (sources) ($p<0.01$) and between sexes ($p<0.01$) (Table 3.3). Parents did not interact with test country or test environments within countries (Table 3.3). There was significant country by sex ($p<0.001$), country by source ($p<0.001$), test environment by sex ($p<0.001$) and test environment by parental sources ($p<0.001$) interactions (Table 3.3).

Table 3.3: Analysis of variance in parental lines grown at Kiboko, Kenya, and University of Natal, South Africa

Source of Variance	Degrees of Freedom	Mean squares	Prob. Level
Parents	119	2.32	0.005
Environment	5	183.47	<0.001
Country	1	6.01	0.998
Parent x environment	362	0.91	0.894
Parent x country	117	1.37	0.005
Source of parent	4	13.97	<0.001
Country x source	4	3.27	0.011
Environment x source	20	1.89	<0.001
Sex	1	26.48	<0.001
Country x sex	1	21.93	<0.001
Environment x sex	5	1.55	<0.001

Males were more variable than females. They exhibited significant variation for all traits examined (Table 3.4). While males had significant variation in virtually all traits measured, females varied in days to half bloom, plant height and head exsertion only (Table 3.4).

Table 3.4: Trait variation in male and female parents over six environments (2 in South Africa) and (4 in Kenya)

	Males			Females		
Trait	Mean	SED	difference	Mean	SED	difference
Seedling vigour (score)	2.5	0.1	**	2.3	0.1	NS
Days to 50%_flowering	83.7	2.1	**	85.2	2.0	*
Number of tillers	2.3	0.1	**	2.2	0.1	NS
Number of productive tillers	3.6	0.2	**	3.2	0.1	NS
Plant height (cm)	137.0	2.7	**	118.0	1.8	**
Head exsertion (cm)	11.1	0.4	**	13.6	0.5	**
Stem weight (g m^{-2})	480.4	38.0	*	393.8	26.1	NS
Head weight (g m^{-2})	246.5	9.5	*	210.6	6.4	NS
Total Dry weight (g m^{-2})	754.7	49.0	*	635.5	30.6	NS

*, ** Significant respectively at 0.05 and 0.01 levels of probability

Male parents performed differently in selected traits (Table 3.5). ICSV111, a Kenyan line was the highest yielding check variety, but was significantly lower yielding than Kiboko Local, also a Kenyan line. SDSL89473, an introduction from ICRISAT, Zimbabwe had head weight similar to ICSV111 (Table 3.5). Male parents differed significantly ($p<0.05$) in plant vigour, number of tillers, plant height, head exsertion, stem weight, head weight and days to 50% flowering (Table 3.5).

Table 3.5: Agronomic traits performance in sorghum male parental lines over six environments (2 in South Africa) and (4 in Kenya)

	Male traits						
Parents Name (As introduced)	**Vigour (score)**	**Tillers (No.)**	**Ht (cm)**	**Head Exsertion (cm)**	**Stem wt(g)**	**Head wt (g)**	**DT50% F**
BJ28	2.2	2.2	113.1	17.0	338.8	165.1	65.0
E1291	2.8	1.2	174.4	4.4	637.5	302.1	68.6
E6518	2.6	1.2	287.6	-1.0	*	*	*
FPR(168xGS70)	2.7	1.3	159.9	8.9	653.8	267.7	70.0
GADAM-EL-HAMAM	2.5	3.4	125.7	12.6	326.9	233.5	68.2
ICSV111*	2.6	2.9	163.9	11.5	788.4	375.0	70.0
IESV91111DL	2.6	1.8	103.9	7.3	364.7	204.6	68.9
Ikinyaruka	3.0	2.0	152.5	4.8	547.7	321.6	68.7
IRAT-204	2.3	2.4	109.8	12.2	238.4	321.6	64.9
IS-76#23	2.9	2.2	134.2	8.0	427.6	228.1	66.9
Kaguru	2.7	4.7	189.6	25.3	470.1	224.1	60.2
KARI Mtama-1*	2.8	2.0	145.5	9.0	455.5	286.6	70.9
KAT-369xMakueni Local	2.5	3.0	196.7	14.0	766.7	332.5	69.5
KAT-412	2.8	1.1	118.7	6.4	282.4	194.2	70.7
KAT-487	2.7	2.2	156.3	13.0	371.4	237.2	65.0
Kiboko Local	3.3	3.8	163.6	6.5	1262.0	388.1	*
Lanet-1	2.2	2.4	165.6	14.4	595.0	277.1	79.5
Mexco-R-line15	2.8	1.9	151.4	11.6	638.8	297.0	68.4
Mexico-R-line19	2.7	2.2	162.4	6.4	645.9	286.5	68.2
Mexico-R-line-5	2.7	1.5	161.4	12.4	505.2	270.6	68.7
Muveta (Mugeta)	2.4	3.0	166.0	16.1	511.5	181.2	78.7
Mahube	2.3	2.4	123.0	22.8	400.4	195.1	68.8
Red Swazi	2.6	2.9	148.0	12.0	658.1	287.5	67.6
P890012x(148xE354)xCS-35	2.5	2.1	174.7	11.1	431.5	247.4	75.2
SEREDO*	3.0	2.8	127.6	7.2	716.1	328.2	67.7
SERENA*	2.6	4.6	130.2	7.8	641.4	351.1	71.1
TegemeoxIS-8193	2.8	2.9	160.9	11.4	451.0	247.5	67.4
AWN98	2.6	2.3	149.3	18.0	376.3	218.6	68.0
NL9623	2.2	1.3	125.2	13.0	325.4	211.7	78.4
CHOKWE	2.3	1.9	155.5	12.2	642.3	296.4	78.6
Dwarf Wonder	2.3	2.9	110.4	7.9	255.4	192.2	70.2
GV 3017	2.8	3.9	120.0	11.6	390.6	216.0	63.3
MRS94	2.4	2.4	169.1	15.3	691.8	326.4	69.9
ICSR92074	2.3	2.7	129.0	7.5	518.5	197.5	80.8
GV3020	2.2	2.1	147.0	13.7	536.5	275.1	74.8
SDS 3472	2.7	2.5	158.5	12.0	596.0	281.5	69.6
ICSR91005	2.2	2.6	109.0	9.4	321.9	197.2	78.1
ICSR91030	2.5	1.8	130.0	11.4	474.8	242.4	71.1
Marcia	2.5	1.2	139.8	11.1	438.6	238.9	63.5

			Male traits				
Parents Name (As introduced)	**Vigour (score)**	**Tillers (No.)**	**Ht (cm)**	**Head Exsertion (cm)**	**Stem wt(g)**	**Head wt (g)**	**DT50% F**
KUYUMA	2.0	2.2	27.7	5.6	501.1	285.2	74.3
SDSR 91014	2.2	1.4	117.8	13.3	270.2	206.1	83.4
PIRIRA 1	2.8	1.5	134.3	7.1	365.0	258.2	72.9
R8602	2.5	3.4	117.7	22.0	329.8	259.0	69.5
SDS3978	2.3	2.7	120.6	24.0	261.0	182.9	68.8
SDS5232	2.6	1.2	131.5	8.7	393.8	262.8	77.1
ICSR89060	2.3	1.7	123.7	7.3	564.5	301.4	82.0
SDSL89473	2.5	1.7	167.4	9.0	683.0	380.4	77.5
SDSL89572	2.5	1.4	171.3	8.2	787.5	308.8	80.8
01MN7951-70652-4-4/TX2737	2.2	3.3	121.7	11.5	506.4	242.5	71.9
01MN7995-GD82-S-7/91BE7414	2.3	2.6	140.5	11.6	491.7	239.1	80.9
02mn4034-(k70647-1-1/pl1	2.3	1.9	100.3	7.1	446.8	221.4	74.4
GD82-S-7/R9019(77CS4/TX430	1.8	2.6	114.8	22.0	518.1	181.8	70.0
KS115	2.0	3.3	114.8	10.8	352.6	168.2	75.4
N249/R9019(77CS4/TX430)	2.1	1.7	112.6	12.8	340.9	197.8	74.3
TX2737/91BE7414	2.2	2.6	113.5	10.8	524.1	247.2	76.9
02mn5099-(k70647p-1-1/pl3	2.5	2.2	137.1	8.3	599.8	245.1	80.2
02mn5453-(k70647p-1-1/pl4	2.7	3.0	123.5	7.3	600.7	267.8	73.6
01MN8079-GD82-S-7/91BE7414	1.9	1.9	109.4	8.9	270.7	161.4	82.6
01Aphid207	2.6	2.5	113.6	8.4	328.5	181.9	78.0
RTx436	2.1	1.8	117.9	11.3	404.8	214.6	86.3
01Aphid102	2.6	1.9	122.2	9.7	455.9	233.4	76.0
01Aphid136	2.5	2.7	148.0	12.9	387.3	256.7	77.0
01Aphid148	2.6	2.3	148.6	12.9	389.9	224.7	80.0
Tx2737	2.4	2.1	110.3	7.4	378.5	216.4	82.1
Tx2767	2.3	1.4	97.5	4.3	523.0	222.5	77.8
Tx2783	2.3	1.9	97.4	6.1	356.7	232.8	80.0
Tx2883	2.4	1.7	105.6	8.3	494.8	255.3	74.9
Tx7078	2.1	1.3	97.9	8.4	237.7	143.3	80.1
Mean	2.5	2.3	137.0	11.1	480.4	246.5	73.2
SED	0.1	0.1	2.7	0.4	38.0	9.5	5.82

* Indicates that the variety was a check

Performance of female parents in a few selected traits is shown in Table 3.6. The female parent population was not as variable as the male population (Table 3.4). Female parents differed significantly ($p<0.05$) in plant vigour, number of tillers, plant height, head exsertion, stem weight, head weight and days to 50% flowering. There was opportunity to select significantly different individual female parents (Table 3.6).

Table 3.6: Agronomic performance of sorghum female parental lines over six environments (2 in South Africa) and (4 in Kenya)

Female Parents Traits							
Parent	Vigour (score)	Tillers (No.)	Height (cm)	Head exsertion (cm)	Stem Dry wt (g)	Head Dry wt (g)	Days to 50% flower
CK60B	2.1	3.0	123.1	15.3	361.2	270.7	68.4
ICSB12	2.8	2.0	109.2	4.0	250.6	176.0	80.9
P9501B	2.3	1.6	120.9	21.4	382.2	281.9	68.8
P9502B	2.1	2.1	133.8	19.4	401.8	272.1	78.5
P9503B	2.1	1.9	124.7	19.5	380.6	231.4	75.8
P9504B	2.1	2.0	109.9	13.1	317.2	255.3	80.7
P9505B	2.5	3.0	125.0	18.5	405.7	308.8	70.0
P9506B	2.1	2.5	125.5	22.0	373.7	292.7	80.8
P9507B	2.4	1.9	120.9	12.6	355.7	278.6	79.0
P9508B	2.4	1.7	140.6	17.8	375.9	310.8	77.9
P9509B	2.4	2.2	117.1	9.8	55.2	319.9	80.6
P9510B	2.3	1.7	121.5	15.5	424.1	207.3	71.8
P9511B	2.2	2.8	125.0	16.6	398.1	269.9	69.3
P9512B	2.2	2.1	115.9	16.4	271.4	242.0	70.1
P9513B	2.6	1.5	121.2	14.0	353.3	211.2	75.7
P9514B	2.2	2.9	120.6	15.6	390.2	243.8	71.8
P9515B	2.5	3.5	108.4	12.9	338.1	233.7	71.6
P9516B	2.0	2.6	113.5	16.4	224.3	197.7	78.3
P9517B	2.2	2.3	109.4	13.5	300.0	199.8	82.1
P9518B	2.2	2.7	116.9	17.4	344.0	253.4	77.2
P9519B	2.0	2.0	102.5	8.2	394.8	240.8	78.4
P9520B	2.2	1.9	116.3	22.9	517.2	284.5	77.7
P9521B	2.0	2.2	121.8	20.6	322.7	219.2	79.7
P9522B	2.2	1.8	118.1	12.3	273.6	175.7	77.0
P9523B	2.3	2.3	126.4	17.2	328.5	271.5	71.7
P9524B	2.3	1.7	122.3	16.4	277.4	263.6	73.3
P9525B	2.4	2.2	116.2	14.4	299.2	265.6	76.5
P9526B	2.1	2.9	118.0	8.5	331.3	246.7	74.5
P9527B	2.1	2.3	109.1	10.8	333.9	287.9	75.7
P9528B	2.3	2.7	131.8	9.2	353.4	265.0	73.8
P9529B	2.6	2.4	114.2	14.2	371.4	308.0	73.0
P9530B	2.4	3.2	119.4	17.8	429.9	308.2	79.2
P9531B	2.3	2.2	127.5	11.3	359.4	258.0	79.1
P9532B	2.4	2.0	116.7	11.3	342.4	227.7	81.9
P9533B	2.3	1.6	125.4	11.1	281.0	250.5	64.5
P9534B	2.4	2.3	110.1	5.3	469.6	186.9	70.2
P9535B	2.4	2.4	113.6	6.3	326.6	263.8	81.0
P9536B	2.2	2.2	102.0	5.0	409.7	198.1	*
P9537B	2.4	2.6	114.8	6.4	314.5	353.4	73.8
P9538B	2.2	1.8	108.0	16.2	329.2	206.1	72.6
P9539B	2.7	2.3	112.5	16.9	540.7	305.9	69.4

P9540B	2.6	2.4	108.3	15.2	362.4	307.0	71.0
01MN1589-B (B Wheatland/P9 516)	2.5	2.5	96.5	10.5	237.4	179.0	69.7
BKS22/BON34	2.3	1.5	106.5	11.3	216.2	179.8	70.6
BKS24ms3/BON34	2.0	2.0	114.5	11.3	308.3	196.0	79.6
TXARG1/KS67 (B)	2.4	2.8	109.3	11.6	281.9	274.9	82.0
TXARG1/N133 (B)	2.4	1.8	109.5	14.3	248.5	233.1	77.2
BTx3197	2.7	1.7	135.2	13.0	329.8	208.0	74.5
BTx378	2.2	1.9	128.2	13.2	392.5	265.3	74.5
BTx399	2.4	1.7	109.1	12.6	254.9	250.1	69.4
BTx631	2.1	2.1	137.9	7.8	696.9	222.7	*
Mean	2.3	2.2	117.7	13.5	348.4	249.2	75.2
SED	0.3	0.7	8.5	3.6	146.2	68.6	5.0

NB: Kenya does not have male sterile varieties that could be used as check, CK 60B is an old male sterile variety from USA. It was used to compare male sterile lines (Table 3.7) above.

A comparison of male and female parent of similar and dissimilar sources was made (Table 3.7). In general, male parent populations had significantly higher yield potential than the female parents (Table 3.7). Texas male and female parents had similar yield potential (Table 3.7). Female parent populations had similar yield irrespective of source (Table 3.7)

Table 3.7: A comparison of the yield of maintainer (B-lines) and restorers (R-lines) from different sources in the study

	Source of parents						
Line class	Kansas	Kenya	Purdue	Texas	Zimbabwe	Mean	SED
B-Line	165.8	*	212.8	205.7	213.7	211.1	26.74
R-Line	226.8	264.3	*	212.1	256.7	246.5	26.74
Mean	196.3	264.3	212.8	208.9	235.2	229.7	19.04
SED	22.54	*	*	22.54	22.54	19.04	

Relative genetic differences were determined on the basis of head, stem and total dry weights and they were then ranked according to magnitude (Table 3.8). There was no way of testing the significance of the differences between different population combinations. Nevertheless, there was a clear trend in both distance $(1/t = 1/ (\sigma^2_B M+\sigma^2 F)/\sigma^2 T)\}$ and heterosis (r/t) (Table 3.8).

Table 3.8: Relative genetic distances between hybridizing male and female source population based on head, stem and total dry weight t expressed as inverse interclass correlation (1/t) units

Head weight							
Source Combination	σ^2_M	σ^2_F	σ^2_T	$\sigma^2{}_B M+F$	"Distance" $1/t=1/(\sigma^2{}_B M+\sigma^2 F/\sigma^2 T)$	Rel. Heterosis r/t	Samp size
All males x All females	154	170	3930	324	12.13	3.032	121
Zimbabwe males x Purdue females	203	178	3757	382	9.85	2.462	64
Kenya males x Purdue females	206	178	3772	385	9.80	2.451	63
Kansas males x Purdue females	276	178	3848	454	8.47	2.117	53
Texas males x Purdue females	312	178	3749	490	7.65	1.912	49
Zimbabwe males x Kansas females	203	436	3673	639	5.75	1.437	29
Kenya males x Kansas females	206	436	3667	642	5.71	1.428	28
Kansas males x Kansas females	276	436	3801	712	5.34	1.335	18
Kenya males x Zimbabwe females	206	541	3657	748	4.89	1.222	25
Zimbabwe males x Zimbabwe females	203	541	3612	745	4.85	1.212	26
Zimbabwe males x Texas females	203	589	3790	792	4.78	1.196	28
Kenya males x Texas females	206	589	3796	796	4.77	1.193	27
Kansas males x Zimbabwe females	276	541	3804	818	4.65	1.163	15
Kansas males x Texas females	276	589	4009	865	4.63	1.158	17
Texas males x Kansas females	312	436	3445	747	4.61	1.152	14
Texas males x Texas females	312	589	3685	901	4.09	1.023	13
Texas males x Zimbabwe females	312	541	3348	853	3.92	0.981	11

Stem Weight							
Source Combination	σ^2_M	σ^2_F	σ^2_T	$\sigma^2{}_B M+F$	$1/t=1/(\sigma^2{}_B M+\sigma^2 F)/\sigma^2 T)$	r/t	Sample size
All males x All females	368	431	13130	799	16.44	4.1	121
Zimbabwe males x Purdue females	537	459	12767	996	12.82	3.2	64
Kenya males x Purdue females	556	459	12813	1015	12.63	3.2	63
Kansas males x Purdue females	829	459	13505	1288	10.49	2.6	53
Texas males x Purdue females	931	459	13053	1390	9.39	2.3	49
Kenya males x Kansas females	556	1305	12349	1861	6.64	1.7	28
Zimbabwe males x Kansas females	537	1305	12161	1842	6.60	1.7	29
Kansas males x Kansas females	829	1305	13472	2134	6.31	1.6	18
Kenya males x Zimbabwe females	556	1618	12351	2174	5.68	1.4	25
Zimbabwe males x Zimbabwe females	537	1618	12014	2155	5.57	1.4	26
Kansas males x Zimbabwe females	829	1618	13640	2447	5.57	1.4	15
Texas males x Kansas females	931	1305	11823	2236	5.29	1.3	14
Kansas males x Texas females	829	1940	14373	2768	5.19	1.3	17
Kenya males x Texas females	556	1940	12869	2496	5.16	1.3	27

Zimbabwe males x Texas females	537	1940	12658	2476	5.11	1.3	28
Texas males x Zimbabwe females	931	1618	11596	2550	4.55	1.1	11
Texas males x Texas females	931	1940	1287	2871	4.49	1.1	13

Total Dry Weight

Source Combination	σ^2_M	σ^2_F	σ^2_T	σ^2_BM+	1/)=1/(σ^2_BM+σ^2)/σ^2T)	r/t	Sample size
All males x All females	1799	1997	30523	3795.8	8.04	2.01	121
Zimbabwe males x Purdue females	2238	2063	29899	4301.2	6.95	1.74	64
Kenya males x Purdue females	2256	2063	29808	4319.2	6.90	1.73	63
Kansas males x Purdue females	2863	2063	31074	4926.3	6.31	1.58	53
Texas males x Purdue females	3091	2063	30078	5154.3	5.84	1.46	49
Zimbabwe males x Kansas females	2238	4036	29000	6274.3	4.62	1.16	29
Kenya males x Kansas females	2256	4036	28678	6292.3	4.56	1.14	28
Kansas males x Kansas females	2863	4036	30464	6899.4	4.42	1.10	18
Zimbabwe males x Zimbabwe females	2238	4986	28665	7224.0	3.97	0.99	26
Kenya males x Zimbabwe females	2256	4986	28732	7242.0	3.97	0.99	25
Kansas males x Zimbabwe females	2863	4986	30784	7849.1	3.92	0.98	15
Zimbabwe males x Texas females	2238	5479	30162	7717.2	3.91	0.98	28
Kansas males x Texas females	2863	5479	32353	8342.3	3.88	0.97	17
Kenya males x Texas females	2256	5479	29795	7735.2	3.85	0.96	27
Texas males x Kansas females	3091	4036	26764	7127.4	3.76	0.94	14
Texas males x Texas females	3091	5479	28945	8570.3	8.04	2.01	13
Texas males x Zimbabwe females	3091	4986	26166	8077.1	6.95	1.74	11

NB Small (t) = large distance, large (t) = small distance, r = 0.25

Source of parent populations were analysed for head weight potential (Table 3.9), in Kenya (Ken) and South Africa (RSA). Female population sources did not exhibit differences in the two countries. Though the differences were not significant, males tended to yield higher in South Africa than in Kenya (Table 3.9).

Table 3.9: Yield (g m^{-2} head weight) of male (R-lines) and female (B-lines) parental lines from different sources over six environments in Kenya and South Africa

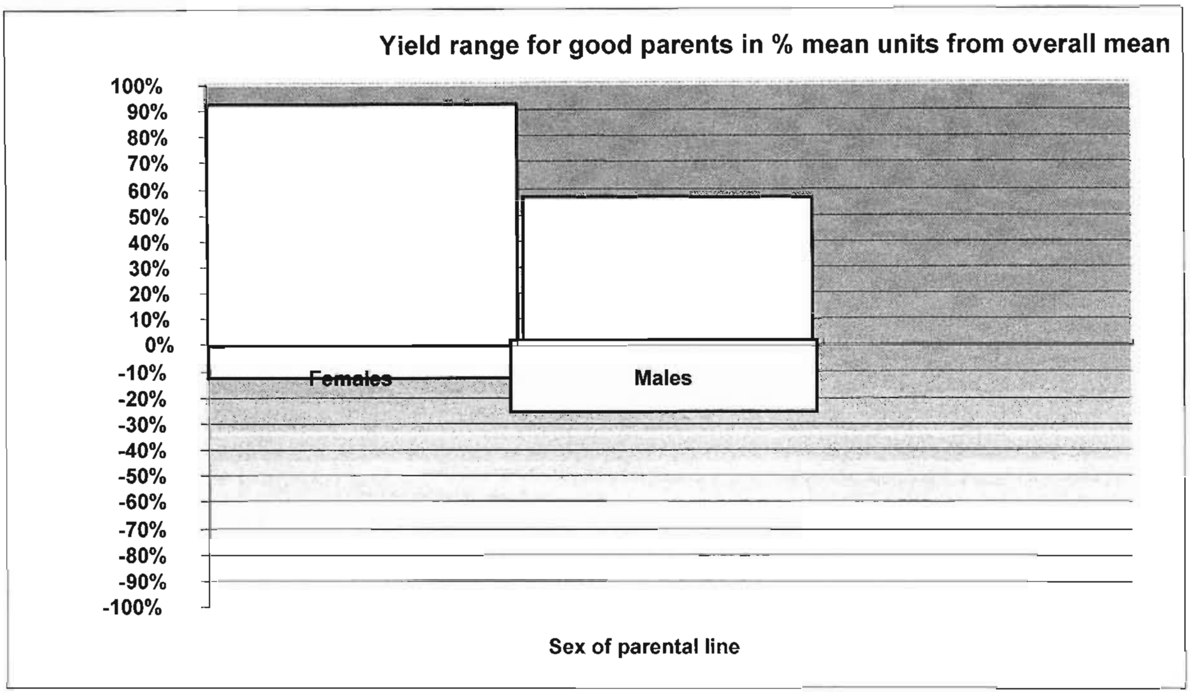
Source	Ken	RSA	Mean	Lsd (0.05)
		Females (B-lines)		
Kansas	240.0	160.6	200.3	84.6
Kenya	*	*	*	*
Purdue	209.6	204.9	207.3	53.7
Texas	193.6	209.1	201.3	68.3
Zimbabwe	208.1	219.9	214.0	337.7
		Males (R-lines)		
Kansas	193.6	264.2	228.9	57.9
Kenya	229.1	309.4	269.2	54.8
Purdue	*	*	*	*
Texas	198.4	222.7	210.6	59.2
Zimbabwe	247.5	260.6	254.0	55.6
Mean	230.9	238.1	228.4	23.8
Lsd (0.05)	26.8	26.8	24.1	

After the hybrids were produced and tested, hybrids that yielded highest in the high density, high moisture environment were partitioned according to male and female parent sources (Table 3.10). Zimbabwe parents had the highest yielding hybrid per a male parent while Purdue had the highest yielding hybrids per a female parent. Male and female parent from Zimbabwe had the highest number of hybrids in the top bracket followed by Kenya males. The Purdue female source contributed the highest number of high yielding hybrids. The proportion of high yielding hybrids from genetically distant populations tended to support the genetic distance concept (Table 3.8). Source combinations that were most distant genetically also produced the highest number of high yielding hybrids individually.

Table 3.10: Analysis of high yield performing (700-1000g m^{-2}) hybrids according to male and female parents' population source

Source	No parents	Hybrids per parent	% hybrids from source	Lowest Yield hybrid (gm^{-2})	Highest yield hybrid (gm^{-2})	mean yield (gm^{-2})
			Males			
Kansas	13	0	0.0	*	*	*
Kenya	23	0.74	39.5	707.7	851.20	752.7
Zimbabwe	24	0.88	48.8	704.6	935.40	758.3
Texas	9	0.56	11.6	707.8	798.1	741.6
			Females			
Kansas	5	0.6	7.3	707.7	714.0	709.8
Purdue	40	0.85	82.9	704.6	935.4	793.1
Zimbabwe	1	0	0.0	*	*	*
Texas	5	0.8	9.8	708.3	871.6	764.6

Using data from the high potential, high density environment, high yielding hybrids came from females in the yield range 12.5% below and 92% above mean female yield (figure 3.1). High yielding hybrids came from males in the yield range 25% below and 50% above mean male yield (figure 3.1). Parents that gave low yielding hybrids (< 700 g m^{-2}) and the highest yielding hybrids (700 to1000 g m^{-2}) among male and female parents in the high density, high potential environment were found in this range (Figure 3.1) supports earlier proposal that even low yielding parents can give high yielding hybrids.



NB: The mean was treated as zero

Figure 3.1: Yield range expressed in percentage mean units of good male and female parents

Figure 3.1 is a plot of parents' yield around parental mean expressed as a percentage of overall mean of the sex is provided (Figure 3.1). The fact that parents that gave low yielding hybrids (< 700 g m^{-2}) and the highest yielding hybrids (700 to1000 g m^{-2}) among male and female parents in the high density, high potential environment were found in Figure 3.1 supports earlier proposal that even low yielding parents can give high yielding hybrids. .

3.4 Discussion and conclusions

The significant differences ($p<0.05$) among males and among females (Tables 3.3, 3.5 and 3.6) were indicative of variation among parents. It was concluded that there was opportunity to select for yield and other desirable traits among the parents. Intermating populations of female and male parents were likely to generate equally variable hybrids thus providing an opportunity for selection among hybrids. Because heterosis is expected when male and female parents cross, hybrids from such variable parents are likely to be heterotic and higher yielding than the parents.

Lack of parent (genotype) by environment and parent interacted with country of testing (Table 3.3) implies that either of the environments or countries adequately ranked the parents according to grain yield potential (head weight). Therefore, a combined analysis was used to characterize and rank parents (Tables 3.5 and 3.6). Significant country by sex ($p<0.001$) and test environment by sex ($p<0.001$) interactions (Table 3.3), required males and females (sexes) to be separated in countries and environments of selection. The significant parents source by country ($p<0.001$) and parental source by test environment ($p<0.001$) interactions (Table 3.3) indicated that germplasm from different sources adapted differentially to test countries and test environments that were used in the study. This required parent sources to be matched with countries and environments they were most suited to.

Successful hybrid research programmes were compared for insight (Table 3.9). Kansas and Zimbabwe programs appeared to use distance between parents to choose parents. Texas appeared to select male and female parents that were equally high yielding as suggested (Collins and Pickett, 1972) (Table 3.7). Both systems worked as both the Kansas and Texas hybrid programmes have been successful. From this experience, there are several options to get good hybrids; adopt either the Kansas or the Texas approach, or both. The view of the study was that the two approaches can be combined. Possible approaches to selecting parents would be: (1) choose high yielding individual parents irrespective of source population, (2) choose high yielding complementary populations for parents, (3) choose complementary parental pairs by distance, (4) chose complementary parent populations by distance.

According to Kambal and Webster (1966), Niehaus and Pickett (1966; Malm (1968) and Majisu (1971) the most distant combining groups should have the best hybrids. The most distant populations were identified (Table 3.6). The Purdue female source was most distant to most male sources. It was most distant to Zimbabwean male source followed by Kenyan, Kansas and finally the Texas male source. According to Kambal and Webster (1966); Niehaus and Pickett (1966); Malm (1968) and Majisu (1971), it should have contained the most potent female parents for hybrids.

The Kansas female source was second most distant to male sources; it replicated the Purdue trend, breaking the continuum after Kansas males (Table 3.8). Using Purdue and Kansas female sources to discriminate male sources, the Zimbabwe male population (source) was most distant from the female sources. It was likely to contain the best hybrid male parents (Kambal and Webster, 1966; Niehaus and Pickett, 1966; Malm, 1968 and Majisu, 1971). The next in line was Kenya males (Table 3.8). There was no way of testing differences between the various populations; ranking was therefore used. Distance between male-female source combinations was clear from (1/t) values (Table 3.8). From results (Table 3.6); quality of hybrids could be ranked from distance between combining parents. Clearly, combinations from the whole females set and the whole male set carried the best hybrid was produced.

All males x all females, Zimbabwe males x Purdue females, Kenya males x Purdue females, Kansas males x Purdue females were most distantly related in that order. The population: Kenya males x Zimbabwe females, Zimbabwe males x Zimbabwe females had intermediate genetic distance and the populations: Texas males x Texas females, Texas males x Zimbabwe females had the least genetic distance of all population combinations in that order.

Genetic variation for yield has been demonstrated and a reason advanced as to why hybrids will exhibit commensurate variation and allow genetic gain and progress in yield Genetic distance has been quantified and shown to be a possible and viable method of short listing and prioritizing populations intended for selection of parents for hybridization. In summary, it was feasible to select good parents without reference to progeny population and it is believed that we have contributed significant information to breed better cultivars.

Analysis of the resultant top yielding hybrids (Table 3.10) clearly indicated distance between hybridizing parent populations was an accurate selector of prospective hybrid parent populations. The genetic distance between populations increased as number of traits considered increased (Table 3.8, head weight vs. total dry weight).

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CHAPTER FOUR

THE ROLE OF COMBINING ABILITY ESTIMATES IN THE CHOICE OF PARENTS FOR HYBRIDISATION IN SORGHUM BREEDING

4.0 Abstract

Combining ability estimates are required for efficient identification of good parents for the production of hybrid varieties. This is a common practice in breeding open pollinated crops like maize where hybrids are predominant. In sorghums, this practice may not apply. The objective of the study was therefore to determine the role of combining ability estimates in the choice of parents for hybrid production in sorghum. Seven hundred and twenty-two hybrids from 41 male and 51 male sterile exotic parents and 27 local pollen parents were tested for agronomic performance in four environments including low and high plant density, and low and high moisture regimes in a triple square lattice design. Hybrid performance was estimated from data on head weights. Deviations from the mean head weight of hybrids over the test environments were used to estimate female and male effects (GCA) in those environments. The mean head weight of the hybrid and the male and female GCAs were used to estimate specific combining ability (SCA) effects of the hybrids. Male and female parents' GCAs differed significantly. Hybrids differed significantly in SCA. Parents with high GCAs generally gave high yielding hybrids, parents with intermediate GCAs tended to give high though sometimes low yielding hybrids. Parents characterized by Low GCA gave low yielding hybrids. High SCA estimated generally resulted in high yield in hybrids but extremely high or extremely low SCA values did not result in very high yielding hybrids. General combining ability and SCA tended to be compensatory and suggested existence of an optimum balance between them. High yielding hybrids generally had high SCA.

4.1 Introduction

Many economic traits are fundamental to agriculture but have very low heritabilities. It has been very difficult to improve economic traits like yield. Varieties grown today have been selected for agronomic stability which has had serious consequences. The current sorghum varieties perform well in non-stressful environments but barely survive in extreme drought. Current sorghum varieties perform well in non-stress environments but barely survive in stressful environments (Ceccarell *et al.*, 1998). Whenever such varieties are used as parents, they have resulted in progenies that behaved similarly. Consequently, breeding for varieties that perform well over multiple environments has been even more difficult.

In crop breeding, breeding values of parents are quantified by heritability estimates and combining ability (Simmonds and Smartt, 1999; Falconer and Mackay, 1996). Heritability is the regression coefficient in parents-offspring regression (additive variance in a population) (Falconer and Mackay, 1996). General combining ability is the mean deviation of F_1's of a common parent from the mean of all crosses (Kambal and Webster, 1965; Falconer and Mackay, 1996). Heritability and combining ability estimates are required for efficient identification of good parents (Kambal and Webster, 1965; Falconer and Mackay, 1996).

Both general and specific combining ability have been studied in sorghum (Niehaus and Pickett, 1966; Kambal and Webster, 1965; Beil and Atkins, 1967). They are both important in the expression of sorghum grain yield in hybrids (Kambal and Webster, 1965). General combining ability (GCA) was more important in sorghum hybrid yield than SCA (Niehaus and Pickett, 1966; Kambal and Webster, 1965; Beil and Atkins, 1967). General combining ability and SCA increased with parental diversity (Niehaus and Pickett, 1966) and were stable over years and locations (Kambal and Webster, 1965; Beil and Atkins, 1967). Three to four testers were required to make preliminary estimates of both GCA and SCA (Andrews *et al.*, 1996). The true mean (X_m) of all crosses, any cross (X) between any two parents, expected cross (X) value, general combining ability of each of the parents and the specific combining ability (interaction between the two crossing parents) have a relationship. The relationship is avalable (Simmonds and Smartt, 1999; Falconer and Mackay, 1996). That relationship was used in the study to estimate GCA values of male and female parents and specific combining abilities in the hybrids. The relationship is reproduced for clarity:

$$X - X_m = GCA_m + GCA_f + SCA_{mf}$$

X_m is the mean of all the crosses being tested, GCA_m and GCA_f are the general combining abilities (GCA) due to male and female parents and SCA_{mf} is a residual component due to interaction of the mth male with the fth female (Simmonds and Smartt, 1999).

For a given set of parents, the summation of either GCA or SCA is zero (Griffing, 1956b, Falconer and Mackay, 1996). Consequently, GCA and SCA values are traditionally tested for difference from zero. Combining ability is used to quantify breeding values and to select parents. The aim of the study was to estimate genetic components of parents in the study to infer heritability estimates and heterosis for yield. Lines were treated as fixed factors whose effects were to be estimated. The goal was to select parents that would give rise to high yielding hybrids in multiple environments based on general combining ability and specific combining ability estimates. The specific objectives of the study were: (1) to identify good OPV parents based on general and specific combining ability for yield, (2) to identify high yielding and widely adapted hybrids for further testing, and (3) to compare parent germplasm source combinations in hybrid performance and identify good sources of hybrid parents.

The hypotheses are given according to objectives;

1. General combining ability for yield can be used to select parents for high yielding hybrids and SCA can be used to select high yielding hybrids,
2. Parents that have positive GCA in all environments and that combined to give high SCA in those environments would give high yielding hybrids in multiple environments, and
3. Parental sources vary in the yield potential of hybrids they produce.

4.2 **Materials and methods**

The KARI sorghum breeding programme has no male sterile sorghum lines on which to base hybrid production. Therefore, male sterile lines in the study were acquired from collaborators in the INTSORMIL group of universities in the USA (from Texas, Kansas, and Indiana) and ICRISAT Zimbabwe. The inclusion of Local germplasm was expected to enhance hybrid vigour and adaptation of the hybrids to local conditions. The introduced germplasm consisted of 94 parental lines: 41 pollen parents and 51 male sterile parents. They were screened together with 27 pollen parents from Kenya for co-adaptation at the University of Kwa-Zulu Natal, South Africa (29^0 40'S, 30^0 25'E), and together with their hybrid combinations at Kiboko, Kenya (2^0 12'S, 37^0 43'E, 915m altitude) on a luvisol soil. At the time of hybridization, flowering periods under Kenya conditions were unknown. Therefore, mating could not be planned between any mating parental pairs because of nicking problems. The South African study had established significant differences for yield potential among the male fertile and male sterile lines. Male fertile lines had higher yield potential and were also more variable in other traits than male sterile lines.

Sixty-eight pollen parents and 51 male sterile lines went successfully through the South Africa tests but two male sterile lines were unadapted and were dropped. The successful lines were used for the study. More details are provided (Table 4.1).

Table 4.1: Source, type and numbers of sorghum lines producing hybrids for the study

Place of acquisition (Source)	Type	
	Males (R-lines)	Females (A or B lines)
ICRISAT, Zimbabwe	24	2
Kenya	23	0
Purdue, USA	0	40
Kansas, USA	8	5
Texas, USA	13	4
Total	68	51

NB: all the lines were used in crosses but many crosses did not produce adequate seed

A factorial parental mating design (each male is mated with each female) involving 68 males and 51 females was used. Out of these, 867 hybrids were generated from which 722 hybrids were selected for evaluation. The 722 hybrids, plus 119 parents were evaluated in a 29 x 29 triple square lattice design with three replications in four factorial trials involving two levels of plant density and two levels of irrigation regimes at Kiboko, Kenya. Fertilization was by NPK 17:17:0 and 18:46:0 fertilizers applied in the high and low irrigation regimes respectively, applied at the rate of 0.8 g m^{-2} (8 kg ha^{-1}) at planting and 9.6 g m^{-2} (96 kg ha^{-1}) three weeks after planting. A single nitrogen dose was applied as calcium ammonium nitrate [$CaNH_4NO_3$ (26%N)] to all trials at the rate of 9.6 g m^{-2} (96 kg ha^{-1}) with the last dose of NPK. The first dose of NPK fertilizer was drilled in the soil immediately after planting and the second dose was drilled two weeks thereafter. The nitrogen fertilizer was drilled together with the second NPK fertilizer dose. This fertilization was adequate for proper growth. Different types of fertilizers were used only because of availability problems in the market supply. To stop treatment effects in one trial affecting the neighbouring trials, trials were planted as separate independent units as in multiple location trials. A trial comprised of one plant density and one irrigation regime.

The nearest trials were the high density, high irrigation and the low density high irrigation regime trials and they were 12 m apart. Each trial had three guard rows planted round the trial exactly as the trial genotypes but with standard sorghum varieties cultivated in the Kiboko region. Other management practices were in accordance with KARI standards (KARI, 1997). The treatments are summarized (Table 4.2).

Table 4.2: Summary of treatments applied on the hybrids and their parents at Kiboko research station

	Moisture regimes	
Density regimes	High Potential HP	Low Potential LP
High Density HD	9 plants m^{-2} (90,000 plant ha^{-1}) + 27mm/ wk over 100 days (sprinkler irrigation) + 10.4 g m^{-2} NPK 17:17:0 + 9.6g m^{-2} CaNH4NO3 (26%N) + field condition	9 plants m^{-2} (90,000 plant ha^{-1}) + 27mm/ wk over 60 days (sprinkler irrigation) + 10.4 g m^{-2} NPK 18:46:0 + 9.6g m^{-2} CaNH4NO3 (26%N) + field condition
Low Density (LD)	1 plant m^{-2} (10,000 plant ha^{-1}) + 27mm/wk over 100 days (sprinkler irrigation) + 10.4 g m^{-2} NPK 17:17:0 + 9.6g m^{-2} CaNH4NO3 (26%N) + field condition High potential	1 plant m^{-2} (10,000 plant ha^{-1}) + 27mm/ wk over 60 days (sprinkler irrigation) + 10.4 g m^{-2} NPK 18:46:0 + 9.6g m^{-2} CaNH4NO3 (26%N) + field condition Low potential

Dry panicle and stem weights were recorded. Seedling vigour, plant stand, days to 50% flowering, plant height, and stem weight were also recorded for additional description of the hybrids and parents. Measurements were taken as follows: seedling vigour was scored at the four-leaf stage on a 1 to 5 scale where 5 was the most vigorous, three was intermediate and one was least vigorous, plant stand was the count of seedlings after thinning and before tillering, days to 50% flowering as number of days from the first day from planting to the day 50% of plants in a plot were shedding pollen, head weight as weight (g $plot^{-1}$) of heads harvested in a plot and dried in a freely ventilated shed at about 26^{0}C day temperature for 3 weeks and stem weight (g plot^{-1}) as weight in grams of stems harvested in a plot and dried at the point of harvest for three weeks at approximately 27^{0}C day temperature. Data was analyzed following residual maximum likelihood (REML) procedure of Genstat 8 statistical computer programme (Lawes Agricultural Trust, 2006). An outline for the analysis of variance is shown (Table 4.3).

Table 4.3: An outlines for the analysis of traits measured in the study

Source of variance	df
Replications (r)	r-1
Block (replications) r(b)	r(b-1)
Environments (E)	E-1
Males (m)	m-1
Females (f)	f-1
Males x Females	(m-1)(f-1)
Environments x males	(E-1) (m-1)
Environments x Females	(E-1) (f-1)
Environments x males x Females	(E-1) (m-1) (f-1)
Error (e)	(e)
Total variance (T)	(T)

The statistical model for combined analysis of genetic effects integrating expected sources of variance as outlined in Table 4.3 follows:

$$y_{ijklm} = \mu + \beta_i + \alpha(\beta)_{ij} + M_k + F_l + MF_{kl} + E_m + EM_{km} + EF_{lm} + EFM_{klm} + e_{ijklm} \qquad (1)$$

Where y_{ijklm} is the effect in i^{th} block within the j^{th} replication in the m^{th} trial corresponding to the k^{th} male crossed with the l^{th} female, μ is overall mean, β_i is the i^{th} replication effect; α $(\beta)_{ij}$ is the j^{th} block effect within the i^{th} replication, M_k is the k^{th} male effect, F_l is the l^{th} female effect, MF_{kl} is the lk^{th} interaction effect between the l^{th} male and k^{th} female. E_m was the effect of the m^{th} environment; EM_{km} is the interaction effect between the m^{th} environment and k^{th} male, EF_{lm} is the interaction effect between the m^{th} environment and l^{th} female, EFM_{klm} was the interaction effect among the k^{th} male, the l^{th} female and the m^{th} environment, while e_{ijklm} was the error term in estimating all the parameters. When single trials (environment) were analyzed the model reduced to:

$$y_{ijkl} = \mu + \beta_i + \alpha(\beta)_{ij} + M_k + F_l + MF_{kl} + e_{ijkl} \qquad (2)$$

Terms are as earlier defined in model (1) above. The model for combined analysis for yield was derived from sources of variation in a similar way as the genetic model above. Sources of variation were blocks within replication, hybrid and parent genotypes, environment and an interaction, genotype x environment, usually referred to as G x E and an error term in the estimations. Thus the model became:

$$y_{ijkl} = \mu + \beta_i + \alpha(\beta)_{ij} + \text{genotype}_k + E_l + (E \times \text{genotype})_{lk} + e_{ijkl} \qquad (3)$$

When a single location (environment) was analyzed, the terms E_l + (E x genotype)$_{lk}$ were not applicable.

A regression model for estimating SCA to GCA regression coefficient was derived following standard regression procedure. The measured (observed) yield could be expressed as: $Y_i = \beta_o + \beta_1X_{1i} + \beta_2X_2i + \beta_3X_{1i}X_{2i} + E_{ij}$, where β_o represents effect of μ, β_1X_{1i} represented effect of male, β_2X_2i represents effect of female and $\beta_3X_{1i}X_{2i}$ represents the interactive effect of the male and female and E_{ij} represented the error effect on the observed yield. Similarly, the expected yield could be expressed. $E(Y) = \beta_o + \beta_1X_{1i} + \beta_2X_2i + E_{ij.}$ Let Y_i = observed yield $Y_{oi,}$ and expected yield $E(Y_i) = Y_{ei}$. Then regressing Y_{ei} on Y_{oi} provided:

$$Y_{oi} = \alpha + \alpha_1 Y_{ei} + e_i \qquad (4)$$

Where α was the intercept and α_1 was the slope and e_i was an error term of the regression. The above model was used to estimate the regression coefficient of SCA to GCA.

Statistical analysis was performed following model (3) above to estimate mean (estimator of μ) in performance of hybrids without parents in each of the four environments (trials). Panicle weight deviations from environmental (trial) means were computed for each hybrid in each replication in all the environments using Microsoft excel computer programme (Microsoft excel ® 2001). The deviations were then subjected to Analysis of variance to estimate the effects of males, females and environments following model (1) above.

Parental (male and female) effects were used to estimate expected yield of each hybrid as the quantity $\sum$ (Effects $_{\text{male}}$ + Effects $_{\text{female}}$ + μ $_{\text{hybrids}}$) and the SCA of each hybrid as the quantity [Observed yield – expected yield] (Falconer and Mackay, 1996). Effects $_{\text{male}}$ and Effects $_{\text{female}}$, respectively, are the male and female GCAs. The derived SCA data was subjected to analysis of variance following model (3) and substituted with hybrids instead of genotypes.

Relative importance of SCA to GCA was quantified by regressing observed yield on expected yield (Falconer and Mackay, 1996). Analytical model for the regression coefficient of expected yield to observed yield was model (4) above.

Hybrid source combinations were constructed by replacing parents in each of the hybrids with the sources of the parent followed by analysis of variance following model (3). Data was analyzed following Residual Maximum Likelihood (REML) procedure in Genstat 8 (Lawes agricultural trust, 2006). Parents were ranked according to size of GCA and parent combinations (hybrids) according to magnitude of SCA.

4.3 **Results**

General Combining Ability (GCA) of yield varied significantly ($p<0.01$) in female and in male parents (Table 4.4). There were significant female parent x environment and male parent x environment interactions ($p<0.01$) (Table 4.4). Significant ($p<0.01$) male parent x female parent interactions were also observed (Table 4.4). Significant parents (OPV lines) x environment interactions ($p<0.01$) was observed. Hybrids did not significantly interact with the environments (Table 4.4).

Table 4.4: Analysis sources of variance of parental head weight GCA, SCA, and yield in the study

Analysis of deviations from mean hybrid head weight			
Source	df	Mean squares	Prob. of diff
Environments	3	0.78	All ns
Female parents (GCA)	43	12.47	**
Male parents (GCA)	63	3.83	**
Male parents (GCA)* Female parents(GCA)	581	2.67	**
Female parents (GCA)* Environments	129	1.79	**
Male parents(GCA) * Environments	189	1.31	**
Male parents (GCA)* Female parents(GCA) * Environment	1442	1.03	ns
Analysis of SCA for head weight			
Hybrids	709	1.61	**
Environments	3	22.86	**
Hybrids * Environments	1448	0.97	(0.161) NS
Analysis of yield (head weight)			
Hybrids	709	3.09	**
Environments	3	644.99	**
Hybrids * Environments	1448	1.05	ns
Parents * Environments	315	9.19	**

Generally hybrids were higher yielding than parents. Hybrid yields increased significantly ($p<0.05$) from HDLP through HDHP environments (Table 4.5).

Table 4.5: Mean head weight (g m-^{2}) of hybrids and parents (OPV lines) in four test environments (HDHP, HDLP, LDHP and LDLP)

	Environments					
Groups	HDHP	HDLP	LDHP	LDLP	Mean	SED
Hybrids	363.7	253.9	181.5	156.6	238.9	8.3
Parents (OPV varieties)	299.2	214.0	140.9	142.1	199.1	8.3
SED	7.8	7.8	7.8	7.8	4.2	

Where, HDHP= high density high potential environment, LDHP= low density high potential environment HDLP= high density low potential environment and LDLP= low density low potential environment

General combining ability values for male parents were estimated (Table 4.6). Generally they were inconsistent over environments. A few parents had positive GCA in all four environments (Table 4.6). Generally negative GCA values increased as production potential of the environment decreased for male parents. On average, twenty male parents had positive GCA for yield (Table 4.6). Of the 25, male parents with average positive GCA for yield Lanet-1, Gadam el Hamam, SDS3472, ICSR92074, SDS5232, Chokwe ICSV111 and FPR (168XGS70) had the highest GCA for yield in that order and their GCA for yield was positive in all of the environments in the study.

Table 4.6: General combining ability values (head weight in g m^{-2}) of male parents in the four test environments of the study (data sorted by mean)

	Environments					
Males parents	HDHP	HDLP	LDHP	LDLP	Mean	SED
Lanet-1	94.2	73.3	38.2	51.2	64.2	47.6
Gadam el Hamam	27.6	44.9	54.4	85.7	59.3	47.6
SDS3472	67.2	93.1	7.9	36.1	51.1	47.6
ICSR92074	48.6	63.4	8.3	55.7	44.0	47.6
SDS5232	108.0	18.9	29.7	3.2	39.9	47.6
Chokwe	94.5	22.9	16.1	25.8	39.8	47.6
Seredo	53.4	59.1	-6.9	25.2	32.7	47.6
ICSV111	40.1	16.1	58.2	14.4	32.2	47.6
TX2737/91BE7414	11.7	86.5	26.4	-2.4	30.5	47.6
TegemeoxIS-8193	76.5	64.3	-19.6	-3.9	29.3	47.6
FPR (168XGS70)	7.6	66.3	11.6	10.4	24.0	47.6
Ikinyaruka	-2.4	28.3	50.5	14.0	22.6	47.6
01Aphid136	117.9	-30.4	-13.8	-12.3	15.4	47.6
Serena	47.6	-0.2	2.0	9.5	14.7	47.6
Tx2783	-60.2	91.8	31.8	-15.4	12.0	47.6
E1291	33.5	24.9	-8.6	-6.1	10.9	47.6
Kuyuma	35.4	22.9	-31.6	17.1	10.9	47.6
Kaguru	23.7	-30.9	53.2	-3.0	10.8	47.6
Mexico-R-line 19	25.6	-1.0	0.1	17.9	10.6	47.6
NL9623	12.2	14.3	-1.4	11.1	9.1	47.6
Mexico-R-line5	96.0	-24.9	-13.0	-24.6	8.4	47.6
Red Swazi	20.4	8.2	-22.6	23.3	7.3	47.6
KARI Mtama - I	12.8	-22.9	-14.4	4.9	4.9	47.6
PIRIRA1	-23.6	22.9	14.0	5.3	4.7	47.6
02mn5099-(k70647p-1-1/p13	40.5	-13.6	25.3	-35.5	4.2	47.6
RTx436	-56.4	32.1	20.9	15.6	3.0	47.6
IS76#23	-13.4	0.4	25.0	-2.2	2.5	47.6
KAT-487	46.8	-16.5	-15.2	-17.6	-0.6	47.6
01Aphid148	-11.5	18.5	-13.0	0.8	-1.3	47.6
Muveta	-11.3	-1.3	-6.0	12.1	-1.6	47.6
P890012x(148xE354)xCS-35	-16.6	-18.5	32.8	-7.9	-2.6	47.6
N249/R9019(77CS4/TX430)	-11.9	-23.6	26.8	-19.4	-7.0	47.6
Tx2767	-44.6	16.4	-9.5	7.8	-7.5	47.6
01Aphid207	-25.8	-54.3	54.7	-14.8	-10.0	47.6
GV3017	-78.3	3.0	14.7	17.4	-10.8	47.6
ICSR91030	18.9	-27.8	-16.7	-18.7	-11.1	47.6
KAT-412	85.5	-10.7	-28.7	0.1	-11.5	47.6
02mn4034- (k70647-1-1/pl1	6.8	-13.4	-12.1	-30.5	-12.3	47.6
01MN7995-GD82-S-7/91BE7414	-141.2	101.8	44.7	46.8	-13.0	47.6
Awn 98	-67.3	27.9	15.9	-33.2	-14.2	47.6
02mn5453 - (k70647p-1-1/p14)	31.5	-93.1	-30.8	33.7	-14.7	47.6
01Aphid102	-54.4	-48.0	55.6	-14.3	-15.3	47.6
KAT-36xMakueni Local	-12.2	-16.5	-3.0	-29.5	-15.3	47.6
IRAT-204	-52.9	-21.3	-1.1	5.2	-17.5	47.6
Mexico-R-line15	-40.0	2.6	-19.8	-14.7	-18.0	47.6

Males parents	Environments HDHP	 HDLP	 LDHP	 LDLP	 Mean	 SED
R 8,602	-49.4	-7.4	-14.1	-4.3	-18.8	47.6
SDSL89572	15.9	-41.5	-37.4	-15.2	-19.6	47.6
MRS94	-10.6	-72.3	-12.3	14.1	-20.3	47.6
BJ28	-70.3	-11.2	3.2	-6.0	-21.1	47.6
01MN8079-GD82-S-7/91BE7414	-126.2	12.9	39.4	-22.9	-24.2	47.6
IESV91111DL	-42.2	-29.4	-33.2	6.7	-24.5	47.6
Tx2883	-92.5	32.0	-29.6	-11.3	-25.4	47.6
ICSR91005	-66.5	-11.8	-21.1	-5.6	-26.3	47.6
Dwarf Wonder	-101.3	-38.8	66.4	-38.5	-28.1	47.6
SDSL89473	-69.3	-26.7	-19.3	1.8	-28.4	47.6
GV3020	-57.9	-28.1	-30.2	-6.9	-30.8	47.6
Macia	-28.9	-50.9	-29.1	-17.3	-31.5	47.6
Mahube	-74.7	-31.0	-20.0	-12.3	-34.5	47.6
ICSR89060	-26.5	-15.4	-15.4	-43.6	-39.4	47.6
KS115	-6.4	-88.3	2.7	-76.5	-42.1	47.6
SDSR91014	-93.8	-22.5	-37.2	-23.2	-44.2	47.6
Tx7078	-60.6	-79.8	-41.5	1.6	-45.1	47.6
Tx2737	-24.9	-80.6	-36.0	-59.0	-50.1	47.6
SDS3978	-42.2	-44.7	-64.3	-51.7	-50.7	47.6
Mean	-8	-1.4	2.1	-2.4	-2.432	6.268
SED	46.47	46.47	46.47	46.47	24.01	

General combining ability values for female parents were estimated (Table 4.7). Generally they were inconsistent over environments like the male parents' GCAs. On average, 23 female parents had positive GCAs (Table 4.7). Of the 23 parents that had positive average GCA's, P9540A, P9520A, P9519A, P9537A, P9535A, P9509A, P9507A, P9510A, P9518A, and ICSA12 had the highest GCA for yield in that order. Their GCA for yield was also positive in all environments (Table 4.7). Generally parents having negative GCA values in at least one environment (inconsistent parents) were more frequent than parent having positive GCA in all environments.

Head weight per hybrid was evaluated (g m^{-2}). The forty highest performing hybrids are shown (Table 4.8). Head weight generally increased from LDLP through to HDHP environments (Table 4.8).

Table 4.7: General combining ability values (head weight in g m^{-2}) in female parents in the four test environments in the study (data sorted by mean)

	Environments					
Females parents	HDHP	HDLP	LDHP	LDLP	Mean	SED
P9540A	120.4	36.7	40.2	61.9	64.8	43.8
P9520A	106.9	73.8	22.2	22.2	56.2	43.8
P9538A	23.9	166.6	26.3	-9.5	51.8	43.8
P9519A	83.1	58.0	27.6	28.2	49.2	43.8
P9513A	97.8	77.9	-27.0	-2.8	36.5	43.8
P9537A	24.5	28.1	38.1	28.7	29.8	43.8
P9535A	46.3	28.8	19.0	21.6	28.9	43.8
P9525A	83.3	-21.6	30.9	17.0	27.4	43.8
P9531A	67.4	44.8	6.4	-10.9	26.9	43.8
P9509A	53.1	38.2	1.8	12.3	26.3	43.8
P9507A	43.9	10.6	20.5	28.7	25.9	43.8
P9510A	32.1	44.6	21.8	1.9	25.1	43.8
P9518A	1.0	40.1	10.6	18.3	17.5	43.8
P9536A	32.1	45.8	0.8	-15.2	15.9	43.8
ICSA12	18.8	5.8	18.3	20.1	15.7	43.8
P9508A	58.4	6.5	-3.4	1.4	15.7	43.8
P9515A	120.3	-58.1	0.6	-2.2	15.1	43.8
P9534A	-41.0	31.3	13.0	40.4	10.9	43.8
P9539A	-35.1	42.4	36.0	-0.6	10.7	43.8
P9504A	16.4	53.7	-3.8	-25.6	10.2	43.8
TXARG1/N133(A)	-8.0	44.5	-5.3	8.5	9.9	43.8
CK60A	45.3	9.9	-1.6	-26.7	6.7	43.8
P9533A	14.5	10.2	-6.6	4.3	5.6	43.8
P9521A	7.2	1.6	-10.8	-4.0	-1.5	43.8
P9512A	-30.6	7.5	24.3	-8.5	-1.8	43.8
P9524A	2.1	-1.1	10.2	-21.4	-2.5	43.8
P9511A	-53.3	14.8	13.0	15.2	-2.6	43.8
P9532A	-29.6	3.5	2.6	-4.9	-7.1	43.8
01MN1589-B (A Wheatland/P9516)	-64.4	-10.9	-20.4	12.1	-20.9	43.8
TXARG1/KS67(A)	-45.8	-19.7	-20.8	0.0	-21.6	43.8
P9501A	-32.6	-42.4	5.1	-25.4	-23.8	43.8
P9502A	-58.1	-51.5	-3.8	10.9	-25.6	43.8
P9517A	-90.2	-36.3	-31.6	46.4	-27.9	43.8
P9530A	-32.7	-111.7	36.1	-16.7	-31.2	43.8
P9514A	-37.7	-41.8	-41.6	-26.1	-36.8	43.8
A-line BC3F1	-35.4	-49.2	-30.6	-49.7	-41.2	43.8
ATX 378	-109.8	-19.0	-4.7	-33.9	-41.8	43.8
ATx399	-102.1	-29.9	-34.3	-27.1	-48.4	43.8

P9505A	-77.7	-69.8	-52.9	-8.8	-52.3	43.8
P9528A	-116.6	-30.0	-34.0	-64.5	-61.3	43.8
P9522A	-133.8	-100.1	-59.3	-39.1	-83.1	43.8
ATx3197	-149.7	-90.7	-26.1	-66.9	-83.4	43.8
P9503A	-123.7	-111.4	-101.5	-41.0	-94.4	43.8
P9523A	-121.8	-150.5	-48.6	-64.4	-96.3	43.8
SED	42.2	42.2	42.2	42.2	22.2	

Table 4.8: Multiple environment head weight (g m^{-2}) of hybrids whose parents had consistently positive GCA in all environments of the study

Hybrid		Environments					
Female parent	male parent	HDHP	HDLP	LDHP	LDLP	Mean	SED
P9540A	SDS5232	746.7	447.2	387.8	575.8	539.4	130
P9509A	Lanet-1	514.5	489.2	270.1	408.2	420.5	130
P9520A	SDS5232	567.1	363.9	339.8	296.0	391.7	130
P9520A	FPR(168xGS70)	612.1	366.6	183.5	375.3	384.4	130
ICSA12	Ikinyaruka	548.6	410.3	258.1	291.1	377.0	130
P9540A	Chokwe	604.6	284.1	322.7	277.4	372.2	130
P9537A	FPR(168xGS70)	407.8	659.0	281.7	138.0	371.6	130
P9535A	Chokwe	545.0	353.2	247.5	332.5	369.6	130
P9510A	Lanet-1	544.6	578.9	186.4	161.0	367.7	130
P9519A	Ikinyaruka	397.6	380.1	431.3	219.3	357.1	130
ICSA12	FPR(168xGS70)	338.6	507.7	265.7	304.7	354.2	130
P9531A	ICSR92074	668.0	369.6	270.0	97.2	351.2	130
P9508A	ICSV111	540.4	173.1	364.0	309.4	346.7	130
P9533A	Chokwe	512.2	478.1	227.4	157.5	343.8	130
P9520A	ICSV111	483.5	400.3	310.3	179.5	343.4	130
P9520A	Chokwe	677.3	246.1	223.7	192.8	335.0	130
P9520A	TX2737/91BE7414	368.2	472.6	181.4	270.1	323.1	130
P9509A	ICSV111	490.5	282.4	256.7	257.9	321.9	130
P9520A	Lanet-1	540.5	294.2	197.3	244.6	319.2	130
P9540A	ICSV111	498.8	275.3	364.2	118.9	314.3	130
P9507A	SDS5232	554.6	198.7	270.6	200.5	306.1	130
P9535A	ICSR92074	443.9	384.2	68.0	326.6	305.6	130
ICSA12	ICSV111	396.6	317.9	304.8	200.5	305.0	130
P9509A	Seredo	398.8	290.4	199.7	327.7	304.1	130
P9537A	Chokwe	468.4	202.9	290.5	242.5	301.1	130
P9509A	SDS5232	457.6	276.3	209.0	220.1	290.8	130
P9510A	SDS5232	416.9	248.5	332.5	155.8	288.4	130
P9508A	SDS5232	495.8	240.5	231.9	163.2	282.9	130
P9537A	Mexico-R-line19	336.3	309.3	281.8	198.8	281.6	130
ICSA12	Gadam el Hamam	432.4	286.0	188.5	198.2	276.3	130
P9537A	Gadam el Hamam	368.6	321.8	226.8	184.2	275.4	130
P9507A	Chokwe	372.3	312.6	245.3	129.4	264.9	130
P9531A	Chokwe	425.4	232.6	238.5	153.0	262.4	130
P9535A	Red Swazi	372.1	238.7	149.2	277.6	259.4	130
P9519A	SDS5232	409.5	383.9	107.7	126.7	256.9	130

Hybrid		Environments					
Female parent	male parent	HDHP	HDLP	LDHP	LDLP	Mean	SED
P9538A	FPR(168xGS70)	404.9	428.7	145.6	34.8	253.5	130
P9520A	Mexico-R-line19	423.8	337.7	98.9	113.2	243.4	130
P9508A	Serena	320.5	212.7	240.4	168.4	235.5	130
P9519A	FPR(168xGS70)	311.6	222.5	203.5	161.8	224.8	130
P9508A	Chokwe	346.3	234.8	75.9	183.4	210.1	130
SED		129.9	129.9	129.9	129.9	66.2	

Female parents with consistently positive GCA across environments were identified (Table 4.9). A follow up on head weight using parental codes indicated they were generally high yielding hybrids. These parents also ranked high in GCA (yield) among parents.

Table 4.9: General combining ability for head weight of female parents based on hybrids that had consistently high yield over all environments in the study (parents are sorted according to magnitude of GCA)

	Environment					
Females	HDHP	HDLP	LDHP	LDLP	Mean	SED
P9540A	272.7	108.4	156.1	122.7	164.9	83.9
P9533A	147.0	216.7	48.3	1.1	103.3	83.9
P9520A	161.1	90.3	39.9	96.4	96.9	83.9
ICSA12	69.4	133.3	71.4	92.5	91.7	83.9
P9510A	111.9	201.7	41.1	6.7	90.4	83.9
P9509A	96.4	87.5	47.7	119.8	87.9	83.9
P9535A	94.9	70.9	0.6	132.5	74.7	83.9
P9537A	47.6	96.3	81.1	28.6	63.4	83.9
P9531A	188.5	53.9	66.0	-68.4	60.0	83.9
P9507A	116.7	9.9	79.1	-2.9	50.7	83.9
P9519A	17.0	89.7	75.9	17.0	49.9	83.9
P9508A	70.7	-34.3	31.1	55.7	30.8	83.9
P9538A	31.6	160.9	-34.1	-140.3	4.5	83.9
Mean	109.7	98.9	54.2	35.5	74.5	24.2
SED	82.2	82.2	82.2	82.2	42.5	

Male parents with consistently positive GCA across environments were identified (Table 4.10). Their hybrids were generally among the high yield fraction of hybrids (table 4.8).

Table 4.10: General combining ability for head weight of male parents based on hybrids that had consistently high yield over all environments in the study (parents are sorted according to magnitude of GCA)

	Environment					
Males	HDHP	HDLP	LDHP	LDLP	Mean	SED
Ikinyaruka	115.3	146.0	173.9	97.6	133.2	92.4
Lanet-1	155.5	201.7	37.2	73.2	116.9	92.4
SDS5232	204.4	61.5	86.9	86.8	109.9	92.4
SDS3472	142.8	123.7	102.9	40.2	102.4	92.4
ICSR92074	200.2	128.3	23.8	-19.4	83.2	92.4
ICSV111	113.4	34.6	131.5	53.3	83.2	92.4
TX2737/91BE7414	11.8	217.0	-1.3	98.6	81.5	92.4
FPR(168xGS70)	45.6	186.9	20.7	51.3	76.1	92.4
Chokwe	142.8	34.0	47.7	48.4	68.2	92.4
Seredo	21.5	40.0	9.8	167.1	59.6	92.4
Gadam el Hamam	34.7	55.4	32.5	32.7	38.8	92.4
Mexico-R-line19	29.5	69.4	5.4	14.3	29.6	92.4
Red Swazi	8.5	-16.8	-38.4	121.1	18.6	92.4
Serena	-34.1	-47.3	61.7	10.9	-2.2	92.4
Mean	85.1	88.2	49.6	62.6	71.4	26.3
SED	95.0	95.0	95.0	95.0	48.2	

Parents (males and females) with consistently positive GCAs in all environments were identified (Table 4.11). Regression of their GCA on mean environmental head weights identified three GCA stability patterns; (1) large positive regression coefficient $0.23 \leq b \leq 0.5$) (consistent over environments) (2) intermediate regression coefficient $- 0.23 \leq b \leq 0.23$ (non-consistent) and (3) anti-consistent i.e. high negative GCA regression coefficient $b \leq -0.23$ (Table 4.11). In non consistent pattern the coefficient of regression is positive while in anti-consistent patterns, the coefficient was negative.

Table 4.11: Male and female parents having positive GCA in all study environments and characterization of important GCA stability parameters

	Males parents Environmental GCA					Regression	
Males parents	HDHP	HDLP	LDHP	LDLP	Mean	b-value	Mean GCA× b-value
SDS5232	108.0	18.9	29.7	3.2	39.9	0.5	18.2
Lanet-1	94.2	73.3	38.2	51.2	64.2	0.2	16.0
Chokwe	94.5	22.9	16.1	25.8	39.8	0.4	14.0
SDS3472	67.2	93.1	7.9	36.1	51.1	0.2	12.5
ICSR92074	48.6	63.4	8.3	55.7	44.0	0.1	3.3
ICSV111	40.1	16.1	58.2	14.4	32.2	0.0	0.9
FPR (168XGS70)	7.6	66.3	11.6	10.4	24.0	0.0	0.3
Gadam el Hamam	27.6	44.9	54.4	85.7	59.3	-0.2	-13.9
	Females parents GCA						
P9520A	106.9	73.8	22.2	22.2	56.2	0.4	24.7
P9540A	120.4	36.7	40.2	61.9	64.8	0.3	20.5
P9519A	83.1	58.0	27.6	28.2	49.2	0.3	13.9
P9509A	53.1	38.2	1.8	12.3	26.3	0.2	6.2
P9535A	46.3	28.8	19.0	21.6	28.9	0.1	3.7
P9510A	32.1	44.6	21.8	1.9	25.1	0.1	3.2
P9507A	43.9	10.6	20.5	28.7	25.9	0.1	2.1
ICSA12	18.8	5.8	18.3	20.1	15.7	0.0	-0.2
P9518A	1.0	40.1	10.6	18.3	17.5	-0.1	-0.9
P9537A	24.5	28.1	38.1	28.7	29.8	0.0	-1.2

Hybrids containing positive GCAs in all environments were characterised according to regression of GCA in the environments (Table 4.12). Three GCA pattern types as identified by environmental GCAs/yield regression coefficients, combined to form the hybrids of the following types; non-consistent x non-consistent, consistent x non-consistent, non-consistent x consistent and anti-consistent x non-consistent. Parental GCAs over environments of the study were regressed on the hybrids group environmental means to identify parental GCA stability patterns. The results are presented in Table 4.11 (column 7). The analysis supported the initial hypothesis that the highest GCA-environmental yield regression coefficient, b, cannot exceed 0.5 (Table 4.11). The three GCA stability patterns were: (1) consistent over environments GCA's had large positive regression coefficient $0.23 \leq b \leq 0.5$; (2) non-consistent GCA pattern parents had intermediate regression coefficient $-0.23 \leq b \leq 0.23$ and (3) anti-consistent GCA pattern parents had high negative GCA regression coefficient $b \leq -0.23$. Hybrids of parents combining those patterns are shown (Table 4.12).

Table 4.12: Environmental head weights (gm^{-2}) of hybrids combining parents in different GCA pattern categories among parents that had consistently positive, all environments GCA in the study

Hybrid Male x Female	Description Parents pattern	Environments HDHP	HDLP	LDHP	LDLP	Mean	SED
ICSR92074 x P9535A	Non-con x non-con	443.9	384.2	68.0	326.6	305.6	130.0
ICSV111 x ICSA12	Non-con x non-con	396.6	317.9	304.8	200.5	305.0	130.0
FPR(168xGS70) x ICSA12	Non-con x non-con	338.6	507.7	265.7	304.7	354.2	130.0
FPR(168xGS70) x P9537A	Non-con x non-con	407.8	659.0	281.7	138.0	371.6	130.0
Sub-mean		396.7	467.2	230.1	242.5	**334.1**	130.0
ICSV111 x P9509A	Non-con x con	490.5	282.4	256.7	257.9	321.9	130.0
ICSV111 x P9520A	Non-con x con	483.5	400.3	310.3	179.5	343.4	130.0
ICSV111 x P9540A	Non-con x con	498.8	275.3	364.2	118.9	314.3	130.0
FPR(168xGS70) x P9519A	Non-con x con	311.6	222.5	203.5	161.8	224.8	130.0
FPR(168xGS70) x P9520A	Non-con x con	612.1	366.6	183.5	375.3	384.4	130.0
Sub-mean		479.3	309.4	263.6	218.7	**317.8**	130.0
Chokwe x P9507A	Con x non-con	372.3	312.6	245.3	129.4	264.9	130.0
Chokwe x P9535A	Con x non-con	545.0	353.2	247.5	332.5	369.6	130.0
Chokwe x P9537A	Con x non-con	468.4	202.9	290.5	242.5	301.1	130.0
SDS5232 x P9507A	Con x non-con	554.6	198.7	270.6	200.5	306.1	130.0
Lanet-1 x P9510A	Con x non-con	544.6	578.9	186.4	161.0	367.7	130.0
SDS5232 x P9510A	Con x non-con	416.9	248.5	332.5	155.8	288.4	130.0
Sub-mean		483.6	315.8	262.1	203.6	**316.3**	130.0
Chokwe x P9520A	Con x con	677.3	246.1	223.7	192.8	335.0	130.0
Chokwe x P9540A	Con x con	604.6	284.1	322.7	277.4	372.2	130.0
Lanet-1 x P9509A	Con x con	514.5	489.2	270.1	408.2	420.5	130.0
Lanet-1 x P9520A	Con x con	540.5	294.2	197.3	244.6	319.2	130.0
SDS5232 x P9509A	Con x con	457.6	276.3	209.0	220.1	290.8	130.0
SDS5232 x P9519A	Con x con	409.5	383.9	107.7	126.7	256.9	130.0
SDS5232 x P9520A	Con x con	567.1	363.9	339.8	296.0	391.7	130.0
SDS5232 x P9540A	Con x con	746.7	447.2	387.8	575.8	539.4	130.0
Sub-mean		564.7	348.1	257.3	292.7	**365.7**	130.0
Gadam el Hamam x ICSA12	ant x non-con	432.4	286.0	188.5	198.2	276.3	130.0
Gadam el Hamam x P9537A	ant x non-con	368.6	321.8	226.8	184.2	275.4	130.0
Sub-mean		400.5	303.9	207.7	191.2	**275.9**	130.0
Overall trial mean		471.2	337.1	239.5	221.5	317.3	21.0
Overall trial SED		129.9	129.9	129.9	129.9	66.2	

Hybrids were characterized by head weight, female parent GCA, male parent GCA, total GCA, SCA and SCA: GCA regression coefficient (Table 4.13). Results of the best performing hybrids that out yielded the best KARI varieties are listed (Table 4.13). Generally, but not exclusively, parents (both males and females) that had positive GCA's in all environments were the most frequent parents among the best performing or highest yielding hybrids hybrids (Table 4.13).

Table 4.13: Mean over environments head weights (gm^{-2}) of the highest yielding hybrids, their male, female and total parental GCA's and SCA of the male by female combination and SCA regressed on parents GCA

Hybrid		Trait					
Female	Male	Head wt (g m^{-2})	♀ GCA (g m^{-2})	♂ GCA (g m^{-2})	Total GCA (g m^{-2})	SCA (g m^{-2})	SCA:GCA
P9539A	01Aphid207	367.7	10.7	-10	0.7	133.3	190.4
P9521A	Serena	348.4	-1.5	14.7	13.2	110.4	8.4
P9538A	PIRIRA 1	452.3	51.8	4.7	56.5	227.8	4.0
ICSA12	Mexico-R-line19	422.5	15.7	10.6	26.3	104.0	4.0
P9535A	PIRIRA 1	426.2	28.9	4.7	33.6	116.6	3.5
P9504A	SDS3472	449.3	10.2	51.1	61.3	190.2	3.1
P9509A	E1291	394.1	26.3	10.9	37.2	107.6	2.9
ICSA12	Ikinyaruka	379.8	15.7	22.6	38.3	108.5	2.8
P9508A	ICSV111	358.5	15.7	32.2	47.9	98.8	2.1
P9531A	ICSV 111	394.9	26.9	32.2	59.1	121.6	2.1
ICSA12	FPR(168xGS70)	353.2	15.7	24	39.7	81.5	2.1
TXARG1/N13 3(A)	Seredo	373.8	9.9	32.7	42.6	82.5	1.9
CK60A	ICSV111	355.0	6.7	32.2	38.9	74.6	1.9
ICSA12	Red Swazi	340.6	15.7	7.3	23	40.9	1.8
P9519A	Gadam el Hamam	341.2	49.2	10.9	60.1	104.8	1.7
P9540A	SDS5232	481.9	64.8	39.8	104.6	166.3	1.6
P9537A	FPR(168xGS70)	349.2	29.8	24	53.8	73.0	1.4
P9504A	Lanet-1	442.9	10.2	64.2	74.4	99.4	1.3
P9520A	Mexco-R-line5	374.5	56.2	8.4	64.6	79.6	1.2
P9520A	Kuyuma	402.9	56.2	10.9	67.1	72.3	1.1
P9520A	KAT-487	422.6	56.2	-0.6	55.6	53.4	1.0
P9520A	P890012x(148xE354)xC S-35	421.4	56.2	-2.6	53.6	49.1	0.9
P9535A	Chokwe	360.3	28.9	39.8	68.7	59.6	0.9
P9519A	Ikinyaruka	365.4	49.2	22.6	71.8	60.6	0.8
P9520A	FPR(168xGS70)	379.6	56.2	24	80.2	67.5	0.8
P9508A	NL9623	411.3	15.7	9.1	24.8	19.0	0.8
P9509A	Lanet-1	400.4	26.3	64.2	90.5	67.6	0.7
P9520A	Serena	393.9	56.2	14.7	70.9	46.8	0.7
P9510A	Lanet-1	373.6	25.1	64.2	89.3	50.5	0.6
P9508A	Lanet-1	369.3	15.7	64.2	79.9	43.1	0.5
P9520A	SDS3472	414.0	56.2	51.1	107.3	55.1	0.5
P9540A	Chokwe	353.4	64.8	39.8	104.6	42.9	0.4
P9520A	Chokwe	380.9	56.2	39.8	96	38.7	0.4

Hybrid		Trait					
Female	Male	Head wt (g m^{-2})	♀ GCA (g m^{-2})	♂ GCA (g m^{-2})	Total GCA (g m^{-2})	SCA (g m^{-2})	SCA:GCA
P9520A	ICSV111	366.4	56.2	32.2	88.4	28.8	0.3
P9518A	Lanet-1	343.2	17.5	64.2	81.7	9.9	0.1
P9519A	SDS3472	414.0	49.2	51.1	100.3	-11.3	-0.1
P9532A	IRAT-204	370.0	-7.1	-17.5	-24.6	119.1	-4.8
CK60A	ICSR91005	353.5	6.7	-26.3	-19.6	100.2	-5.1
CK60A	ICSR91030	342.2	6.7	-11.1	-4.4	54.1	-12.3
P9533A	KAT-369xMakueni Local	347.9	5.6	-15.31	-9.71	132.4	-13.6
Mean		210.4				1.7	
SED		10.7				70.9	

The relationship between harvested head weight (g m^{-2}) and expected yield was investigated using regression procedures (Table 4.14). There was a significant linear relationship ($p<0.01$) (Table 4.14). The regression (R-value) accounted for 53.9% of the relationship.

Table 4.14: Regression analysis of harvested yield (head weight) on expected yield (g m^{-2})

Summary of the regression analysis					
Source of variation	D.F.	S.S.	M.S.	V.R. F	PR.
Regression	1	50502321	50502321	5015	<.001
Residual	4282	43120800	10070		
Total	4283	93623121	21859		

The rate of change of specific combining ability with changes in general combining ability was estimated using the hybrids in the study. The regression coefficient of specific combining ability to the general combining ability (measure of the rate) was estimated by regression of observed head weight on expected head weight. The regressions are provided (Table 4.14) and estimated of the regression coefficient (b-value) (Table 4.15). The constant is the estimate of the mean yield and the b-value is an estimate of the regression coefficient of SCA to GCA (Table 4.15). Both estimates were significant ($p<0.05$) in the linear relationship between observed and expected yield representing SCA and GCA respectively in the regression (Table 4.15)

Table 4.15: Estimate of the yield intercept and the regression coefficient of SCA to GCA (rate of change) among the hybrids

Parameter	Estimates	S.E.	t(4282)	t-probability
Constant	231.56	1.54	150.85	<0.001
b-value	1.0107	0.0143	70.82	<0.001

The R^2 value for the regression was 53.9%

4.4 Discussion and conclusions

Mean male and female GCA's for yield over test environments were not zero. However, when weighed with LSD's (Table 4.3 and 4.5), they were not significantly different from zero. The results are therefore consistent with the literature (Griffing, 1956b; Falconer and Mackay, 1996; Simmonds and Smartt, 1999) and competent to compare parents according to breeding values using the combining ability method.

By standards of least significant difference (LSD 0.05) based on mean GCA yield, parents appeared not to have significant GCA effects, at least in some environments (Table 4.4 and 4.5). However, the significant ($p<0.01$) GCA variation among female and male parents (Table 4.3) is evidence that the parents differed in GCA for yield. Therefore, selecting individual parents was both worthwhile and fruitful.

Combinations of high GCA males (Table 4.6) and female (Table 4.7) resulted in high yielding hybrids (Table 4.8). Combinations of low GCA males (Table 4.6) and low GCA female (Table 4.7) resulted in low yielding hybrids (Table 4.8). The trend was not so clear when intermediate GCA males (Table 4.6) and intermediate GCA female (Table 4.7) were combined (Table 4.8). Some hybrids from these combinations were high yielding while others were low yielding. From an average approach hybrids between intermediate GCA males and female produced intermediate yield hybrids.

Variances of GCA and SCA were consistent over environments as reported by Rojas and Sprague (1952) in maize and Kambal and Webster in sorghum (1965), Beil and Atkins (1967). Our results agreed with their findings when parents are considered as a groups as done by those authors showing insignificant environmental effect on GCA (male and female GCA's together) and insignificant male GCA by female GCA (SCA) by environment interaction (Table 4.3). This supports their findings. Insignificant interaction between hybrids SCA with environment (Table 4.3) is further evidence of agreement with Lin and Binns (1994) who have pointed out stability tendency in groups. They attributed the stability to high performers compensating for low performers; this could have been the case in the study.

General (random effect) approaches to breeding values are not conducive to genetic gain and progress. Quantifying breeding values by heritability methods was rejected herein for this reason; it is not specific to individual parents. Our research focused on individual parents' (fixed effects) breeding values. From this perspective, individual parents' GCA's were generally inconsistent over environments with significant male GCA's by environment and female GCA's by environment interactions ($p<0.01$) (Table 4.3 and 4.4). We believe this is the natural trend on individual parent's GCA over environments. It is in agreement with general literature on plant breeding.

Researchers are unanimous that it is impossible to breed for different environments from a single, satellite breeding centre. Inconsistent parental breeding values over test environment are transmitted to progenies. The consequent inconsistent progeny performance in different environments is the root cause of yield instability problems that have bedevilled plant breeders in the last four to five decades. For example, Rosielle and Hamblin (1981) Lambert (1984), Simmonds (1991) and Ceccarelli *et al.* (1998) unanimously agreed that crop varieties must be selected in conditions representative of target production environments. Simmonds (1991) Witcombe *et al.* (1996) and Ceccarelli *et al.* (1998) were critical about selection in non-limiting research station, conditions. The general view is that it is not possible to breed crop varieties for multiple environments from one central environment (satellite breeding).

In comparison of parents and hybrid yields over environments (Table 4.3), parents were inconsistent while hybrids were highly significant (consistent) (Table 4.3, yield) (p-value for parent x environment was highly significant for hybrids x environment interaction was not significant, p-value was 0.161). The consistent hybrid performance over environments is disadvantageous because yield was proportional to potential of environments. Hybrid yield declined consistently with declining potential of environments (Table 4.4) (an inconsistent pattern where law of diminishing returns is obeyed would have been advantageous). Hybrids would yield well in high potential environments and poorly in low potential environments. For parents it was possible to select some that would yield relatively well in low potential environments because parents were inconsistent over environments (Table 4.4). Breeders have failed to develop hybrids that integrate the parents' type of reaction (homeostatic stability) in low potential environments and hybrid type of reaction to high potential environment (agronomic stability). Doing so could generate suitable germplasm for multiple environments. That is hybrids that yield as high as the potential of an environment in high potential environments but follow diminishing returns in low potential environments.

Parental GCA's over environments of the study were regressed on the hybrids group environmental means to identify parental GCA stability patterns. The results are presented in Table 4.11 (column 7). The analysis supported the initial hypothesis that the highest GCA-environmental yield regression coefficient, b, cannot exceed 0.5 (Table 4.11). The results (Table 4.11), identified three GCA stability patterns; (1) large positive regression coefficient $0.23 \leq b \leq 0.5$) (consistent over environments) (2) intermediate regression coefficient $-0.23 \leq b \leq 0.23$ (non-consistent) and(3) anti-consistent, that is high negative GCA regression coefficient $b \leq -0.23$.

Good parents can only be identified using good testers. Progenies between the parents and testers must be superior in the trait to be selected, for example, heterosis. They should equal or be superior in supporting traits, for example, grain quality, disease resistance, drought resistance (Yan and Wallace, 1995). Our concern was stability over environments. Using the parents identified herein as 'good' allowed us to stretch the net for good parents to include some distinct GCA patterns with inconsistencies in low density environments. Seredo, Mexico-R-line19, Serena, Ikinyaruka, TX2737/91BE7414, and Red Swazi were included in the male list and P9508A, P9538A, P9533A and P9531A in the female list (Table 4.5 and 4.6).

Hybrid combinations were analyzed to verify the approach. Hybrids that were not present in all environments were excluded since their stability pattern could not be established. The results are given (Tables 4.7). Analysis of variance (ANOVA) for yield of the parental combinations (Tables 4.7) revealed much higher consistency. They were worse off over environments compared to the original whole set of hybrids (p-value for interaction with environment was 0.361). Environmental GCA's based on the new combinations are presented (Tables 4.8 and 4.9), From the GCA's based on the combinations (Table 4.8 and 4.9), female parents P9531A, P9533A, P9508A and P9538A and males Ikinyaruka, Mexico-R-line19, Seredo, TX2737/91BE7414, Red Swazi and Serena were eliminated. They had very low or negative GCA in one or more environments. General combining ability of the remaining parents is shown (Table 4.10) and that of their hybrids (Table 4.11). The elimination tremendously increased consistency (decreased capacity to cope with multiple environments) in the remaining hybrids (Table 4.11). Over the environments p-value for hybrid by environment interaction increased to 0.845. This improvement in hybrids consistency over environments demonstrated two things; (1) hybrids sensitivity to environments can be manipulated through selection (2) by manipulating sensitivity, hybrids that were high yielding irrespective of environmental potential may be bred

A search for empirical methods for picking the best parents among the consistently positive GCA parents revealed that the product (coefficient of regression b * mean GCA over environments) was most effective (Table 4.10). The higher the product, the better the parent was in hybrids. There were exceptions; FPR (168XGS70) and ICSA12 (category 2) parents classification above) were not identifiable by the product despite the hybrid FPR (168XGS70) X ICSA12) being productive in all environments. From a different perspective, category 2 reflected homeostatic stability. This class, judging by mean GCA of the two parents over environments, had little additive genetic variance to contribute (they ranked lowest in mean GCA in their respective parental classes (Table 4.10). Their hybrids must have derived vigour (55.6%) largely from non-additive genetic interaction. Thus homeostatic stability could be founded on non-additive genetic variance and this may explain why breeders have not been able to exploit homeostatic stability.

Parents selected are presented (Table 4.10) and their hybrid combinations (Table 4.11). Four GCA pattern types combined to form the hybrids; non-consistent x non-consistent, consistent x non-consistent and non-consistent x consistent and anti-consistent x non-consistent. Examination over environments yield patterns of the hybrids (Table 4.11) in the light of parental GCA patterns revealed the following; non-consistent x non-consistent generally resulted in non-consistent hybrids that had homeostatic stability. Consistent x consistent pattern hybrids were relatively high yielding in both high potential and low potential environments (Table 4.11). They exhibited an open "L" response reflective of agronomic stability in high potential environments and homeostatic stability in low potential environments. Consistent x non-consistent and non-consistent x consistent and anti-consistent x non-consistent hybrid patterns gave steadily increasing/decreasing yields with potential reflective of agronomic stability (straight slanted line). However some hybrids of relatively high yield in high potential and low potential environments could be identified among their hybrids. Probably they were recombinants (although parents could predominantly be classifies in a pattern, they had some genes of the other patterns). The probability of hybridizing pattern (1) males with pattern (1) females was (4/44 x 4/64) or 0.0057 with a hybrid yield of 4 out of the 722 in the whole trial (probability of combining both pattern one male and female). By standards of LSD (0.05) in each environment, (Table 4.11), hybrid combinations SDS5232 x P9540A, Chokwe x P9540A, SDS5232 x P9520A, Lanet-1 x P9509A and FPR (168xGS70) x ICSA12 were high yielding in all environments. Examination (Table 4.10) revealed the parents generally fell in GCA pattern (1). The parents would be suitable for a satellite breeding programme. The discrepancy in realized and expected hybrids is caused by the hybrid FPR (168xGS70) x ICSA12 whose parents were not detectable by the empirical method.

The fact that this method was able to identify the overall best hybrid is testimony that this method is extremely sensitive. Hybrids identified by this method have excelled in selection by ANOVA (mean), density sensitivity, single plant potential and by high heterosis. However, in each case the rank order varied. This method is the only method so far that can identify parents and hybrids for satellite breeding.

An SCA to GCA regression coefficient of 1.0107 (one) in hybrids was evidence that SCA effects were as important as GCA effects in hybrid vigour in sorghum. The finding was at variance with other findings in sorghum. General combining ability (GCA) was more important than SCA in hybrid sorghum yield in previous studies (Niehaus and Pickett, 1966; Kambal and Webster, 1965; Beil and Atkins, 1967). Several reasons may explain the contrast. The 700 hybrids in this work may have given a more accurate estimate of the actual ratio than 40 hybrids or so used in previous studies. Previous authors may have used GCA pre-selected germplasm (higher GCA than SCA) germplasm. Concerted search for crop stability over environments has prevailed in past works in the area; for example, Finlay and Wilkinson (1963) in barley and Johnson *et al.* (1968), Reich and Atkins (1970) and Majisu and Doggett (1972) in sorghum. The role of SCA in homeostatic stability and consistent performance over environments has already been demonstrated (Kambal and Webster, 1966). The search for stability may have increased SCA in our germplasm or our germplasm may have been pre-selected for high SCA, especially the A-B heterotic group.

Because of better stability, high SCA hybrids should occur among the top category of performers. Chapter four (this publication) identified the top forty high yielding hybrids. High SCA hybrids were included in that list. Superimposition of the list on high SCA hybrids list showed striking agreement with the highest three SCA values occuring in the top three hybrids (Table 4.12). The list was modified to include female and male parent GCA's and hybrid SCA's (Table 4.12). From the foregoing, good parents must have high GCA and sufficient SCA in combinations for high hybrid vigour. Generally, hybrids that had higher positive SCA than GCA (SCA to GCA regression coefficient) Table 4.13 like *P9540A x SDS5232,* P9538A x PIRIRA 1, P9504A x SDS3472, P9504A x Lanet-1, P9535A x PIRIRA 1, P9520A x KAT-487 and ICSA12 x Mexico-R-line19, had the highest head weight. Those with a negative regression coefficient generally had low head weights. Extremely high or low SCA hybrids like 01Aphid207, P9521A x Serena, P9533A x KAT-369xMakueni Local and CK60A x ICSR91030 had lower yields (Table 4.23). It was concluded that a certain balance between SCA and GCA was necessary for high yield in hybrids. Whereas high SCA was required, too low GCA eroded the beneficial effects of the high SCA. Therefore good hybrids should have a certain regression coefficient of SCA to GCA. The optimum regression coefficient of SCA on GCA could not be established from literature but was estimated in the study.

There is a compromise balance somewhere. Mean regression coefficient for yield on environments (Finlay and Wilkinson, 1963) was 1.135. The value is not very different from SCA: GCA regression coefficient defined by hybrids in the study. This value has been defined by a large group of hybrids and should encompass stability according Lin and Binns (1994). Therefore hybrids that integrate agronomic and homeostatic stabilities should ideally have an SCA: GCA regression coefficient of one. In the study, significantly high yielding hybrids in all environments; SDS5232 x P9540A, Chokwe x P9540A, SDS5232 x P9520A, Lanet-1 x P9509A and FPR (168xGS70) x ICSA12 had SCA: GCA regression coefficients in the range 0.4 to 2.1 (Table 4.11). It should be remembered that all these hybrids are combinations of parents that had positive GCA in all or nearly all positive in all environments. It seems that SCA: GCA regression coefficient must be in this range for a good balance of homeostatic and agronomic stability for good performance in multiple environments.

In summary, GCA and SCA have been integrated in hybrids. In the process, agronomic and homeostatic stability has been integrated in high yielding hybrids. Breeders have been empowered with control of hybrid response to environments and therefore to breed for multiple environments from a satellite centre. Both good parents and hybrids for multiple environments have been selected on the integrated GCA and SCA regression coefficient. Initially, comparison of parental germplasm sources was an objective. Experience gained here is that such a task is not of any tangible value. Every germplasm accession should be selected on its own merit. A fixed effects model was more productive than the random effects model. However, comparing the parental selection list (Table 4.12), ICRISAT, Zimbabwe and Kenya sorghum programmes had exceptional males and the Purdue program had outstanding females. Effectively, we believe that we have made satellite breeding a more predictive process in Kenya.

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CHAPTER FIVE

POPULATION DENSITY AND WATER STRESS TOLERANCE IN SORGHUM HYBRIDS AND OPEN POLLINATED PARENTAL LINES

5.0 Abstract

Plant density stress in combination with moisture stress can be a powerful and complex stress that can be used to select crop hybrids and OPV lines for tolerance to abiotic and biotic stresses. To identify stress tolerant genotypes from 722 hybrids and 119 of their parental lines, four stress levels were simulated by two moisture levels and two plant density levels in a factorial arrangement superimposed in a triple square lattice design in Kiboko, Kenya. The treatments were the 841 genotypes and the four stress levels. Head weight was used to evaluate genotypes for sensitivity to density stress and single plants yield potential following regression procedures. The estimates were used in conjunction with the parabolic plant density/crop yield relationship to estimate crop yield parameters that could compare genotypic yield potential at optimum plant density. There were significant differences in sensitivity to stress and single plants yield potential among the genotypes. Hybrids showed significantly less sensitivity to stress and significantly higher single plant yield potential than OPV lines. Single plant yield potential and yield in low density had a significant positive correlation with the highest yield, total and average yield over a range of densities used and yield in the lowest and highest density under crop conditions. Hybrids were more likely than OPV lines to provide the high yielding genotypes the study aimed to select.

5.1 Introduction

Crop varieties in semi-arid areas of Kenya perform erratically. When the season is too dry or too wet, they fail. Whenever it is humid, they succumb to foliar diseases and perform dismally. Farmers do not operate at optimum plant density; therefore they are never able to exploit the full potential of the crops even when the growing environments are ideal. Crop varieties of semi-arid parts of Kenya have been selected under hot dry conditions at suboptimal crop densities. There is need to select crop varieties under multiple environments. There is also need to select for resistance to multiple forms of stress that the crop is likely to encounter in its production. Such selection should be conducted under optimum crop density.

Density stress provides both abiotic and biotic stress by promoting genotypic competition for resources and proliferating disease epidemics by bringing plants into closer contact (Harper, 1977). Plant density can simulate and quantify stress. Plants in dense stands assume a hierarchy whereby a few strong vigorous plants take up most resources and kill the weakest ones (Harper, 1977; Fasoula and Fasoula, 1997). Only hardy genotypes can survive dense, moist stands. Plant genotypes that are sensitive to high plant densities are likely to adjust according to prevailing density and result in yield closer to yield at optimal plant densities. Single common density yield trials do not accurately reflect genotypic yield potential (Warren, 1963); genotype by density interaction is an indication that genotypes have an optimum plant density. Further, genotypes require optimum planting densities for maximum expression of yield potential (Warren, 1963: Henderson *et al.*, 2000).

A genotype's yield response over a range of densities is unique. Over the range, yield is dependent on the most limiting resource (Donald, 1951). Yield becomes density independent when the limiting resource is provided (Donald, 1951). Therefore density tolerant genotypes are resource efficient and advantageous in agriculture. They should be selected for elevated agricultural resource productivity.

The relationship between yield and planting density is parabolic (Warren, 1963) and encompasses plant potential and rate of potential decline (Warren, 1963). If the rate of decline and potential (intercept) were known, optimal plant density and yield at the optimal planting density are estimable by feeding the two parameters into the quantitative parabolic and derivative relationships (Duncan, 1958; Warren, 1963). Yield potential and maximum tolerable densities are difficult to estimate since the regression of yield on density has no X and Y intercepts (Harper, 1977). There is no yield at zero density and yield is never zero at high planting densities. According to Harper (1962, 1977) and Yoda *et al.* (1963), genotypes are self-thinning at high densities and will always leave survivors to give some yield. In their view, the single plant/plant density yield relationship is unsuitable to compare genotypes and environments. However, the problem is minimized if the relationship is used cautiously. Yield at very high density tends to zero and density of one plant m^{-2} tends to zero density. Under the circumstances extrapolation of the regression line will estimate the intercepts with minimal error. Furthermore, the estimates are unbiased because genotypes are treated similarly. We regressed single plant yields on plant densities to estimate genotypic potential and rate of potential decline (densities used in the trials were low (1 plant m^{-2}) and high (9 plant m^{-2}). The estimates enabled use of the parabolic yield/density relationship (Duncan, 1958; Warren, 1963; Yan and Wallace, 1995) with which the highest density for highest yield (optimal density), total and average yield over a range of densities (two plants below and two above optimal density m^{-2} equivalent to a range of twenty thousand plants below and above optimal plant density ha^{-1}). Genotypes that yield well over this range are not likely to be affected by fluctuations about the optimum plant density. The estimates were used to compare genotypes.

Dry matter yield is dependent on density, species, and species combinations (intercrops) and available resources (Harper, 1961). As density increases, resources per plant decrease and a yield limit is set. Density increases beyond the limit are absorbed in plant plastic responses. Therefore genotypic adaptation to density depends on morphological plasticity of plant traits (Harper, 1977). Genotypes exhibit variation in constant yield limits and lowest density for maximum yield (Harper, 1977). According to Donald, (1951), constant yield depends on the most limiting resource, not plant density, because increases in the limiting resource increase yield.

Plasticity of traits has been explored in sorghum (Gerik and Neely, 1987; Krishnareddy and Stewart, 2004), in wheat (Clement, 1929; Puckridge and Donald, 1967), in gamagrass (Springer *et al.*, 2003), sunflower (Clement, 1929), field bean (*Vicia faba*) (Hodgson and Blackman (1957a and b), corncockle (*Agrostemma githago*) (Harper, 1977), nine broad leaf species (Palmblad, 1968). Numbers of tillers, leaves, flowers and ears had a plastic response (Harper, 1977; Puckridge and Donald, 1967). Seed size and number of seeds per capsule were adaptive (Harper, 1977). Rice cultivars (Gravois and Helm, 1996) and barley hybrids and OPV varieties (Severson and Rasmusson, 1968) exhibited variation in response to plant density. Seeds per main culm, tiller heads and tiller contribution to grain yield were most adaptive in sorghum (Gerik and Neely, 1987). Sorghum genotypes exhibited differential reaction to plant density. According to Springer *et al.* (2003), higher plant densities produced greater dry matter yields in the highest sustained forage yields obtained at a density of 4.8 plants m^{-2}. In high plant density a larger number of tillers fail to produce heads (Krishnareddy and Stewart, 2004). Growing plants in clumps (low density) under low moisture decreased tillering and promoted grain filling and higher yield (Krishnareddy and

Stewart, 2004). According to Henderson *et al.* (2000) and Springer *et al.* (2003), there is an optimum plant density for maximum productivity. Findings of Krishnareddy and Stewart (2004), suggested that the optimum plant density is dependent on availability of growth moisture.

Scientists have established yield/plant density relationships. Constant maximum yield and density relationship (Harper, 1977), logarithmic single plant grain yield and plant density relationship (Duncan, 1958) and reciprocal single plant grain yield/plant density relationships (Harper, 1977; Duncan, 1958) are linear. The reciprocal yield and plant density function called "reciprocal yield law" is also linear (Harper, 1977 Shinozaki and Kira, 1961). The law does not hold at high densities (Harper, 1977; Hirano and Kira, 1965). The logarithmic single plant grain yield/plant density function is linear with two sections; a flat linear and inclined linear section. Setting of density stress initiates the inclination (Harper, 1977). It has prospects for quantifying threshold density stress (Harper, 1977). Other relationships have been derived: the self-thinning relationship called the 2/3 power relationship (Yoda, 1963), the optimal densities for producing specialised parts relationship (Shinozaki and Kira, 1961; Bleasdale and Nelder, 1966, 1967) and the linear logarithmic total yield per plant/ plant part relationship (Harper, 1977).

The relationship between total yield and plant density is parabolic (Pickett, 1944: Duncan, 1958; Warren, 1963: Harper, 1977) and does not have X and Y intercepts (Harper, 1977). The relationship between single plant yield and plant density is linear (Duncan, 1958; Warren, 1963; Fasoulas, 1990; Yan and Wallace, 1995). These relationships were used in the study. Each relationship looks at different aspect of plant density, for example, at what plant density does stress set in? Which genotypes thin faster? The logarithmic single plant grain yield/plant density relationship (Harper, 1977) is based on transformed data which makes it difficult to interpret results. Many of the relationships reviewed could not be used in the study; the specialized plant parts relationship could not be used because heads comprised of grain (specialized) and refuse (unspecialized). The parabolic whole plant/plant density relationship worked well with numbers and fresh weights of sweet corn cobs (Warren, (1963); it could work with number and head weights of sorghum without genotypic parts' details. The 2/3 power thinning relationship could not be used because quantity of seed required is large and quantity of seed for trials in the study was a constraint to the extent some genotypes could not be tested; the density stress threshold relationship was equally unusable; two densities were used because of the many number of genotype used so that trial size could be controlled. A compound trait like head weight was used to round up plant parts relationships and minimise the difficulties. Crop potential, total yield and average yield over a range of densities were estimated using linear relationships and the parabolic derivative functions (Duncan, 1958; Warren, 1963). From the review, plant parts/plant density relationships are complex, erratic and difficult to summarise. The problems notwithstanding, there were good prospects for selection of density adaptive sorghum genotypes. Head weight yield was used to round up parts in the head relationships and minimise the difficulties.

The objectives were to:

1. Estimate single plant yield potential and sensitivity to plant density,
2. Estimate optimum plant density, crop yield potential and mean yield over a range of densities,
3. Investigate if genotypic sensitivity to plant density is adaptive to stress,
4. Compare hybrids and OPV lines in sensitivity to plant density, and
5. Select density tolerant adapted genotypes (hybrids and OPV lines).

The hypotheses tested were:

1. Single plant yield potential and sensitivity to plant density can be used to identify optimum plant density, crop yield potential and mean yield over a range of densities,
2. Optimum plant density, crop yield potential and mean yield over a range of densities can identify stress tolerant genotypes,
3. Density insensitive genotypes are stress tolerant,
4. Hybrids and OPV lines respond similarly to density stress.

5.2 Materials and methods

Sixty-eight pollen parents and 51 male sterile lines from a screening study in South Africa and Kenya were used in the study. Details about source, number and sex are provided (Table 5.1).

Table 5.1: Source, type and numbers of sorghum lines producing hybrids for the study.

Place of acquisition (Source)	Type	
	Males (R-lines)	Females (A lines)
ICRISAT, Zimbabwe	24	2
Kenya	23	0
Purdue, USA	0	40
Kansas, USA	8	5
Texas, USA	13	4
Total	68	51

The 68 males and 51 females were hybridized in a 68 x 51 factorial parental mating design during the January to July 2003 period at Kiboko research station in Kenya. The hybridization generated 867 hybrids. Out of these 722 hybrids and119 of their parents making a total of 841 genotypes were evaluated for performance of agronomic traits under factorial treatments. The treatment factors involved two population density levels x two irrigation levels. The densities were 1 and 9 plants m^{-2} and the irrigation levels were 27 mm weekly for 60 days and 27 mm weekly for 100 days. The factorial treatments were superimposed in a 29 x 29 triple square lattice design with three replications, such that each lattice design accommodated one density and one irrigation regime. Like the hybridization, hybrid evaluation also took place at Kiboko, Kenya. Fertilization was by NPK 17:17:0 and 18:46:0 fertilizers applied in the high and low irrigation regimes, respectively. The fertilizers were applied by drilling at the rate of 0.8 g m^{-2} (8 kg ha^{-1}) at planting and 9.6 g m^{-2} (96 kg ha^{-1}) three weeks thereafter. A single nitrogen dose was applied as $CaNH_4NO_3$ = 26%N to all trials at the rate of 9.6 g m^{-2} (96 kg ha^{-1}) with the last dose of NPK. The first dose of NPK fertilizer was drilled in the soil immediately after planting and the second dose was drilled two weeks thereafter. The nitrogen fertilizer was drilled together with the second NPK fertilizer dose. Fertilization was adequate for proper growth: different types were used only because of problems with supply in the market. Trials were planted as separate independent units as in multiple location trials; a trial comprised of one plant density and one irrigation regime. The nearest trials were the high density, high irrigation and the low density high irrigation regime trials and which were separated by a 12 m empty space to stop treatments effects like irrigation in one trial from affecting the neighbouring trials. Each of the trials had three guard rows planted round exactly as the trial genotypes but with standard sorghum varieties cultivated in the Kiboko region. Management of the trials was in accordance with KARI standards (KARI, 1997). The treatments are summarized in Table 5.2.

Table 5.2: Summary of treatments applied on the hybrids and their parents at Kiboko research station

	Moisture regimes	
Density regimes	**High Potential HP**	**Low Potential (LP)**
High Density (HD)	9 plants m^{-2} (90,000 plant ha^{-1}) + 27mm/ wk over 100 days (sprinkler irrigation) + 10.4 g m^{-2} NPK 17:17:0 + 9.6g m^{-2} CaNH4NO3 (26%N) + field condition	9 plants m^{-2} (90,000 plant ha^{-1}) + 27mm/ wk over 60 days (sprinkler irrigation) + 10.4 g m^{-2} NPK 18:46:0 + 9.6g m^{-2} CaNH4NO3 (26%N) + field condition
Low Density LD	1 plant m^{-2} (10,000 plant ha^{-1}) + 27mm/wk over 100 days (sprinkler irrigation) + 10.4 g m^{-2} NPK 17:17:0 + 9.6g m^{-2} CaNH4NO3 (26%N) + field condition	1 plant m^{-2} (10,000 plant ha^{-1}) + 27mm/ wk over 60 days (sprinkler irrigation) + 10.4 g m^{-2} NPK 18:46:0 + 9.6g m^{-2} CaNH4NO3 (26%N) + field condition
	High potential	Low potential

Seedling vigour, plant stand, days to 50% flowering, plant height, dry head weight and stem weights were recorded. Head weight per plot (1 m^{2}) was used to evaluate genotypic performance and the other traits for additional description of the hybrid and parent genotypes. Measurements were taken as follows: seedling vigour was scored at four leaf stage on a 1 to 5 scale where 5 was the most vigorous, three was intermediate and one was least vigorous; plant stand was the count of seedlings after thinning and before tillering; days to 50% flowering as number of days from the first day of irrigation to the day 50% of plants in a plot were shedding pollen, head weight (g plot^{-1}) as weight in grams of heads harvested in a plot and dried in a freely well ventilated shed at about 26^{0}C day temperature for 3 weeks and stem weight (g plot^{-1}) as weight in grams of stems harvested in a plot and dried at the point of harvest for three weeks at approximately 27^{0}C day temperature. Grain yield was derived as 70% head weight in grams plot^{-1} (Majisu and Doggett, 1972) divided by the plant stand in the plot, number of tillers as total number of stems minus plant stand and number of panicles as count of panicles in a plot. Single plant head weights were derived as head weight plot^{-1} divided by plant density (plant stand) using Microsoft excels software (Microsoft Corporation, 2000). Single plant head weight was derived as the plot yield divided by the number of plants (plant stand) in that plot. Single plant head weight potential and sensitivity to plant density stress were quantified by regression analysis following regression procedures in Genstat 8 statistical computer software (Lawes Agricultural Trust, 2006). The following regression model was used to analyze for the single plant head weight potential and sensitivity to plant density:

$$Y_i = G + D.Gi + E_{ij}$$

Where Y_i represented the i^{th} genotypic single plant head weight and G represented the genotypic mean (single plant head weight for a genotype), while G_i represented the I^{th} density genotypic single plant head weight and E_i represented the error term in estimation of the genotypic effects and D.Gi was the sensitivity to plant density. Maximum tolerable plant density D_{max} was estimated by applying genotypic head weight as the regressor in the genotypic head weight/plant density regression model (1).

The estimates of genotypic single plant head weight potential and genotypic sensitivity to plant density stress were used in the single plant yield/plant density linear relationship (Duncan, 1958; Warren, 1963; Fasoulas, 1990; Yan and Wallace, 1995) and the derivative parabolic high density/crop yield relationships (Duncan, 1958; Warren, 1963) to estimate additional variables to compare genotypes. The relationships used to compute those variables follow:

$$(1) \qquad Y = a + bp$$

Y is yield per plant, p is plant population (density), "a" is the Y intercept and b is the slope in a linear regression (Warren, 1963). Multiplying the single plant yield/plant density relationship by the number of plants m^{-2} gives yield $m\text{-}^{2}$ in a quadratic (curvilinear) relationship (Pickett, 1944: Duncan, 1958; Warren, 1963: Harper, 1977) below. Relationship (1) was used to estimate single plant head weight potential and sensitivity to plant density, and is given by:

$$(2) \qquad Y = ap + bp^2$$

The notation is as previously used, but in this case Y represents yield $(plot^{-1})$ $m\text{-}^{2}$. Relationship (2) was an expression of plot head weight (crop yield potential) using the approach of relationship (1). The highest densities (optimum plant density) Pm producing highest yield m-^{2} follows:

$$(4)\ Pm = -\ a/2b$$

It was used to estimate optimum plant density in the study. Similarly the highest yield Ym produced m^{-2} (maxima for yield) is presented (4) below: It was used to estimate crop yield potential.

$$(4) \qquad Ym = -\ a^2/4b$$

Total yield Y_T over a range of densities is represented by the area under the curve subscribed by yield between densities of interest. It is an integral of function (2) between the lower p_1 and the higher p_2 densities of investigation. Two plants below and two above the genotypic optimum plant density were used as the limits in the study:

$$(5) \qquad Y_T = [a/2\ (p_2^2 - p_1^2) + b/3(p_2^3 - p_1^3)]$$

Average yields Y_A over a range of densities are obtained by dividing function (5) by the range of density $(p_2 - p_1)$:

1. $Y_A = [a/2\ (p_2^2 - p_1^2) + b/3(p_2^3 - p_1^3)]/\ (p_2 - p_1)$

From the functions, two plant densities could adequately estimate optimal plant density, crop yield potential, and total yield over a range of densities, yield over a range of plant densities around optimum plant density, average yield over a range of densities around optimum plant density. Crop grain yield potential was estimated by multiplying plot yield by 70% (Majisu and Doggett, 1972).

5.3 **Results**

Regressions of single plant head weights on plant densities and densities on single plant head weights revealed significant differences in hybrids and parental responses to density (Table 5.3). Also, densities had significant ($p<0.05$) effects on single plant head weights (Table 5.3) in both hybrids and OPV lines (parents). Regression values for both yield on density and density on yield (Table 5.3) were intermediate (60–70%).

Table 5.3: Regressions of single plant head weight (gm^{-2}) on plant densities (plant m-^{2}) and plant densities on single plant head weights

Group	Regression	d.f.	V:R	F pr.	% R-value	SED
Hybrids and parent	Single plant head wt on density	1431	7.75	**	61.8	56.9
Hybrids and parent	Plant density on Single plant head wt	1625	8.04	**	65.7	2.34

Estimates of single plant yield potential (Table 5.4) revealed significant differences ($p< 0.05$) in single plant potential among hybrids and parents. Hybrids had significantly ($p<0.05$) higher single plant yield potential than OPV lines (parents). Single plant yield potential and sensitivity to plant density estimates (Table 5.4) revealed significant differences among hybrids and parents (Table 5.4). Based on standard errors, hybrids were significantly ($p<0.05$) more sensitive to plant density than OPV lines (parents) (Table 5.4).

Table 5.4: Single plant potential (maximum head weight) (g plant^{-1} m^{-2}) and sensitivity to plant density (g plant^{-1} m^{-2}) in hybrids and parents as one group and hybrids and parents as separate groups

	Intercept	Estimate	S.E.	t probability
Hybrids and parent	Single plant potential (g plant-1)	183.2	1.30	**
Hybrids	Single plant potential (g plant-1)	187.7	1.45	**
Parents	Single plant potential (g plant-1)	153.9	2.59	**
	Sensitivity to density			
Hybrids and parents	Single plant sensitivity (g plant-1 m-2)	-16.72	0.21	**
Hybrids	Single plant sensitivity (g plant-1 m-2)	-17.09	0.23	**
Parents	Single plant sensitivity (g plant-1 m-2)	-13.92	0.37	**

Optimum plant density, yield potential in high density situation, total yield over the density range of the trials (1-9 plants m^{-2}), average yield two plants above and two below optimum plant density range m^{-2}, grain yield potential (70% head weight potential under cropped situation m^{-2}) and maximum tolerable plant density m^{-2} were estimated following relationships outlined (Duncan, 1958; Warren, 1963). The results are provided in Table 5.5. Generally, as sensitivity to plant density increased, crop yield potential, total yield two plants below and two plants above optimum density m^{-2}, average yield two plants below and two plants above optimum density m^{-2} and grain yield potential m^{-2} decreased (Table 5.5). Although not so obvious, as single plant yield potential increased, sensitivity to plant density decreased. Generally, as sensitivity to plant density increased, optimum plant density requirement for genotypes increased (Table 5.5). The relationship between maximum tolerable plant density m^{-2} and genotypic sensitivity to plant density was not clear.

Table 5.5: Estimates of plant density adaptive traits in individual genotypes among hybrids and parents in the density response study

	Hyb/OPV	G. code	Max D	Opti D	SP	DS	CYP	TY	AY	GY	PS
1	ICSA12 x Mexico-R-line19	292	10	4.9	535.5	-54.5	1316.4	4975.1	1243.8	921.5	top 40
2	P9540A x SDS5232	247	10	5.3	434.9	-41	1154.7	4400.4	1100.1	808.3	GCA
3	ICSR91030 (OPV line)	452	9	4.8	424.0	-44.1	1020.3	3846.2	961.6	714.2	Sensitivity
4	P9504A x Lanet-1	220	10	5.3	371.1	-34.8	989.6	3772.9	943.2	692.7	top 40
5	P9520A x SDS3472	215	10	5.2	375.0	-35.8	983.4	3742.9	935.7	688.4	GCA
6	P9508A x ICSV111	80	9	5.2	359.6	-34.8	930	3534.8	883.7	651	top 40
7	P9540A x Chokwe	10	10	5.3	343.8	-32.5	909.5	3464.7	866.2	636.6	GCA
8	P9501A x 01Aphid207	604	7	4.7	391.9	-41.9	917.3	3445.8	861.4	642.1	Sensitivity
9	P9534A x FPR (168xGS70)	585	9	4.8	381.3	-39.8	912.3	3436.9	859.2	638.6	Sensitivity
10	P9508A x NL9623	350	10	5.2	342.8	-32.8	894.6	3403.2	850.8	626.2	top 40
11	P9512A x 01Aphid102	202	9	4.9	368.6	-37.9	895.5	3379.7	844.9	626.9	Sensitivity
12	P9519A x Ikinyaruka	343	9	5.1	346.6	-33.8	889.6	3378.3	844.6	622.7	top 40
13	P9520A x ICSV111	288	9	5.3	327.4	-30.9	868.4	3308.9	827.2	607.9	top 40
14	P9511A x ICSV111	271	10	4.8	356.9	-36.9	863.7	3258.1	814.5	604.6	Sensitivity
15	ICSA12 x Ikinyaruka	144	10	5.4	312.8	-28.8	849.6	3245	811.2	594.7	top 40
16	P9509A x Lanet-1	72	8	5.5	310.7	-28.5	847.4	3237.7	809.4	593.2	GCA
17	TXARG1/KS67A x Dwarf Wonder	297	10	4.9	344.6	-35.1	846.5	3199	799.8	592.6	Sensitivity
18	P9535A x Chokwe	7	9	5.4	312.6	-29.2	837.8	3195.6	798.9	586.4	top 40
19	ICSA12 x FPR (168xGS70)	183	10	5.3	312.7	-29.7	822.5	3131.6	782.9	575.8	GCA
20	P9502A x ICSR92074	139	10	5	328.1	-32.6	825	3126.1	781.5	577.5	Sensitivity
21	P9520A x 02mn5099-(k70647p-1-1/pl3	322	10	5.1	320.3	-31.3	819.7	3111.9	778	573.8	Sensitivity
22	ICSA12 x BJ28	512	9	5	327.1	-32.8	815	3085	771.2	570.5	Sensitivity
23	P9532A x IRAT-204	57	10	5.3	302.7	-28.4	806	3072.5	768.1	564.2	top 40
24	P9520A x FPR (168xGS70)	342	8	5.5	289.4	-26.2	798.9	3055.6	763.9	559.2	top 40
25	P9532A x 8602	154	9	5	320.1	-32.1	798	3020.8	755.2	558.6	Sensitivity
26	NL9623 (OPV line)	468	10	4.9	325.2	-33.2	796.6	3009.3	752.3	557.6	Sensitivity

	Hyb/OPV	G. code	Max D	Opti D	SP	DS	CYP	TY	AY	GY	PS
27	CK60A x ICSV111	101	10	5.3	297.2	-28.2	784.2	2986.5	746.6	548.9	top 40
28	P9522A x IS76#23	115	8	6.4	240.3	-18.8	769.9	2979.7	744.9	538.9	Sensitivity
29	P9520A x Macia	239	8	5.4	290.6	-27.1	780.2	2976.5	744.1	546.1	Sensitivity
30	P9520A x P890012x(148xE354)xCS-35	408	12	6.2	246.7	-19.9	763.4	2947.4	736.9	534.4	top 40
31	P9520A x Kuyuma	14	11	5.7	268.5	-23.5	766	2938.4	734.6	536.2	top 40
32	Mexico-R-line19 (best OPV male)	436	9	5	308.7	-30.7	775.5	2938.2	734.6	542.9	Sensitivity
33	P9521A x Serena	70	10	5.5	277.1	-25.3	758.1	2897.5	724.4	530.7	top 40
34	P9511A x IS76#23	347	10	5.1	295.0	-28.7	759.4	2884.7	721.2	531.6	Sensitivity
35	P9509A xICSV111	203	9	5.3	282.0	-26.4	754.2	2876.3	719.1	527.9	Sensitivity
36	Seredo (Check)	369	9	5.3	218.7	-20.7	577.9	2201.4	550.3	404.6	Check
37	Serena (Check)	368	11	5.4	197.8	-18.3	534.8	2041.6	510.4	374.3	Check
38	Gadam el Hamam (Check)	461	9	5.4	172.7	-15.9	470.4	1797.2	449.3	329.3	Check
39	ICSV111 (Check)	451	10	6.9	112.4	-8.2	387.1	1504.7	376.2	270.9	Check
40	KARI Mtama-1 (Check)	445	10	7.8	93.3	-6	363.3	1421.3	355.3	254.3	Check
41	IS76#23 (Check)	447	11	6	116.7	-9.7	349.9	1347.8	336.9	244.9	Check
	Mean		8.12	5.4	183.2	-16.72	501.9	1917.3	479.3	351.3	
	SE		2.34	0.05	1.3	0.21	2.1	1.4	0.3	0	

Abbreviations for column headings (Table 5.5)

Hyb/OPV =Hybrid or open pollinated line
SP = Single plant yield potential (g plant^{-1})
AY =Average yield (gm^{-2}) ±2 plants around optimum density
TY =Total yield (gm^{-2}) at ±2 plants around optimum density
G code =genotype (code)
DS =Density sensitivity (g plant^{-1}M^{-2})

Opti D = Optimum density (plants m^{-2})
CYP = Crop yield potential (g m^{-2})
GY = Grain yield potential (gm^{-2})
PS = Previous selection in other tests
Max D = Max density (plants m$_{-2}$)

Performance of the thirty highest yielding hybrids and the best performing two males and two female provided in Table 5.6. The additional variable for description should help select more balanced hybrids. Correlation between hybrids' realized head weights and sensitivity to plant density (Table 5.6 vs. Table 5.5), realized head weight increased as sensitivity to plant density decreased. Sensitivity to plant density and stem weight, plant height, days to 50 % flowering, number of tillers, and number of panicles were not strongly correlated with density insensitivity. Genotypes that differ in stem weight, plant height, days to 50 % flowering, number of tillers, and number of panicles could be selected.

Optimal plant density, yield potential under high density situation, total yield over the density range of the trials (1 to 9 plants m^{-2}), average yield around optimal plant density m^{-2} and grain yield potential (70% yield potential under cropped situation m^{-2}) and maximum tolerable plant density m^{-2}) were estimated (Table 5.6).

Table 5.6: Additional characteristics of 35 genotypes (hybrids and OPV parents) most adapted to plant density and 5 checks (OPV) identified in the study (sorted according to realized head weight)

	Hybrid/OPV	Head wt (gm^{-2})	Stem wt (gm^{-2})	Plant ht (cm)	Days half bloom	No tillers	No. Panicle
1	ICSA12 x Mexico-R-line19	441.7	456.5	179.2	73.1	2.6	5.5
2	P9540A x SDS5232	511.4	666.2	151.6	82.7	2.8	4.8
3	ICSR91030 (OPV line)	304.7	405.7	139.5	71.1	1.8	6.2
4	P9504A x Lanet-1	421.9	615.2	181.3	74.8	4.5	8.1
5	P9520A x SDS3472	408.1	519.0	181.8	71.7	3.5	5.7
6	P9508A x ICSV111	365.3	439.3	182.8	69.1	2.5	4.7
7	P9540A x Chokwe	366.1	532.1	155.2	75.8	2.0	4.4
8	P9501A x 01Aphid207	257.8	519.1	111.8	--	2.6	3.2
9	P9534A x FPR (168xGS70)	264.7	338.7	163.0	–	3.5	2.6
10	P9508A x NL9623	367.7	490.7	156.0	68.9	1.4	7.6
11	P9512A x 01Aphid102	289.5	421.5	148.1	70.0	1.9	4.5
12	P9519A x Ikinyaruka	346.4	924.1	179.0	79.2	1.4	5.2
13	P9520A x ICSV111	360.4	503.9	184.5	71.6	2.3	4.4
14	ICSA12 x Ikinyaruka	382.3	779.0	184.2	75.5	2.7	6.0
14	P9511A x ICSV111	264.0	411.8	190.1	71.0	1.4	3.4
16	P9509A x Lanet-1	385.8	584.4	181.9	69.4	4.0	4.9
17	TXARG1/KS67A x Dwarf Wonder	290.5	390.4	137.2	62.4	2.7	5.6
18	P9535A x Chokwe	361.5	504.2	141.9	74.3	2.5	4.5
19	ICSA12 x FPR (168xGS70)	349.8	511.0	163.0	68.8	2.6	4.9
20	P9502A x ICSR92074	313.9	492.8	186.7	76.3	1.8	4.0
21	P9520A x 02mn5099-(k70647p-1-1/pl3	315.8	582.4	177.1	70.7	2.8	6.8
22	ICSA12 x BJ28	298.5	402.3	126.0		4.1	6.1
23	P9532A x IRAT-204	347.2	452.9	168.9	64.7	2.9	5.4
24	P9520A x FPR (168xGS70)	371.8	528.8	185.9	70.2	2.8	4.9
25	P9532A x 8602	281.3	356.3	140.1	73.3	2.2	4.5
26	NL9623 (OPV line)	276.6	310.1	123.5	78.4	1.7	4.5
27	CK60A x ICSV111	32.6	3547.7	160.9	68.2	3.3	5.3
28	P9522A x IS76#23	179.7	287.7	117.5	80.9	2.1	3.2
29	P9520A x Macia	340.1	523.7	147.3	76.6	2.1	4.8
30	P9520A x P890012x(148xE354)xCS-35	414.9	520.3	180.4	68.8	2.4	4.4
31	P9520A x Kuyuma	375.3	489.3	179.8	69.0	2.8	5.8
32	Mexico-R-line19	275.9	490.7	151.2	68.3	2.1	4.3
33	P9521A x Serena	348.6	519.5	173.2	71.2	3.8	4.9
34	P9511A x IS76#23	301.3	399.1	163.3	73.7	2.9	3.5

	Hybrid/OPV	Head wt (gm^{-2})	Stem wt (gm^{-2})	Plant ht (cm)	Days half bloom	No tillers	No. Panicle
35	P9509A xICSV111	331.7	529.4	198.4	68.3	2.1	4.9
36	Seredo (Check)	242.3	315.5	120.7	67.7	2.3	4.3
37	Serena (Check)	235.0	373.4	118.7	71.1	3.5	5.6
38	Gadam el Hamam (Check)	216.0	271.3	112.6	68.2	3.2	5.3
39	ICSV111 (Check)	228.7	428.6	145.8	70.0	2.6	3.7
40	KARI Mtama-1 (Check)	218.9	298.1	135.9	70.9	1.7	4.0
41	IS76#23 (Check)	193.1	334.3	126.5	66.9	2.8	4.5
	Mean	209	354.5	140.2	72.43	2.24	3.8
	SE	78.1	114.2	14.44	4.94	0.98	1.83

Correlation analysis (Table 5.7) revealed significant associations among traits. The intercept (single plant yield potential) was positively correlated with highest yield, total yield and average yield over a range of densities and yield in the lowest and at highest density of the study (Table 5.7). Sensitivity to density was positively correlated with lowest density required to give maximum yield (optimum density) (Table 5.7). Highest possible yield (yield potential) had a strong correlation with total yield, average yield and yield in low density conditions. Low density yield was positively correlated with yield under high plant density (Table 5.7). From the higher number of traits significantly correlated with single plant potential and sensitivity to plant density, optimum plant density and total and average yield over a range of plant densities (Table 5.7), single plant potential and density sensitivity are suitable traits for indirect selection of cultivars that are high yielding under stress (tolerant to stress). They were highly correlated with all traits that were strongly correlation with yield (Table 5.7).

Table 5.7: Correlations between estimated head weight and plant density parameters in hybrid and OPV density trials

Trait	Single PP	Highest D	Density S.	Optimum D.	Yield opt D	YT	YA	Grain Y	Yield LD	Yield HD	Observed Y	stem wt	Plant ht	Days 50'
Single PP	1.00													
Highest D	-0.17	1.00												
Density S.	-0.99**	0.17	1.00											
Optimum D.	-0.74**	0.11	0.79**	1.00										
Yield opt D	0.98**	-0.17	-0.94**	-0.63**	1.00									
YT	0.96**	-0.16	-0.92**	-0.61**	1.00**	1.00								
YA	0.96**	-0.16	-0.92**	-0.61**	1.00**	1.00**	1.00							
Grain Y (Single pp)	0.98**	-0.10	-0.97**	-0.74**	0.96**	0.95**	0.95**	1.00						
Yield LD	0.98**	-0.10	-0.97**	-0.74**	0.96**	0.95**	0.95**	0.96**	1.00					
Yield HD	0.21	0.25	-0.10	0.13	0.33	0.39**	0.39**	0.33	0.3	1.00				
Observed Y	0.68**	0.12	-0.60**	-0.32*	0.76	0.79**	0.79**	0.76**	0.73	0.85**	1.00			
Stem wt	0.40**	0.05	-0.34**	-0.21*	0.45	0.48**	0.48**	0.45**	0.43	0.62**	0.67**	1.00		
Plant ht	0.43**	0.08	-0.39**	-0.21*	0.48	0.50**	0.50**	0.48	0.44	0.58*	0.65**	0.63**	1.00	
Days 50% F	0.28	-0.21	-0.23	-0.02	0.34*	0.36*	0.36*	0.34**	0.27	0.10	0.22	0.33	-0.03	1.00
No. tillers	-0.06	0.13	0.10	0.02	-0.01	0.02	0.02	-0.01	-0.03	0.40	0.26	0.10	0.12	-0.19

* *significant at 0.01 levels of probability, * significant at 0.05 levels of probability, Correlation values not marked with asterisks were not significant

Abbreviations of the table column headings

Single pp = Single plant potential (g plants^{-1} m^{-2})
Density sensitivity = (plantsm^{-2})
Density S. = Density sensitivity (plants m^{-2})
Yield opt D = Head wt yield at optimum density (g m^{-2})

Highest tolerable density = Density Intercept (plantsm^{-2})
Highest D = Highest density m^{-2})
Optimum D. = Optimum density (plants m^{-2})
YT = total yield over the density range 2plant below and

2 above optimum plant densities

YA = average yield over the density range 2plant below and 2 above optimum plant densities

Yield LD = Yield in low density trial (g m^{-2})

Observed Y = Mean head yield all four trials in the study (g m^{-2})

Plant ht = Mean plant height in all four trial (cm)

Grain Y = Grain Yield at optimum density (g m^{-2})

Yield HD = Yield in the high density trial (g m^{-2})

Mean stem wt = Mean stover yield (all density trials) g m-2)

Days 50% F = Days to 50 % flowering

5.4 Discussion and conclusions

The regressions of single plant head weights (single plant potential) on plant densities and densities on single plant potential among hybrids and OPV lines (parents) were significant ($p<0.05$) (Table 5.3). There was significant variation in single plant potential response to plant density among sorghum hybrids and OPV lines. Also, plant density had significant differential effect on hybrids and OPV lines' single plant potential. This implied that there were opportunities to select more or less density sensitive hybrids or OPV parents. The intermediate (60–70%) regression values (Table 5.3) indicated that regression did not account for all variation in single plant potentials and plant densities among the hybrids and OPV parents. Despite the shortfall, the regression values were high enough to reflect a linear relationship between single plant potential and plant density. Single plant potentials were more variable than plant densities (regression standard errors suggested). This was expected as only a few plant densities were used in the study.

The significant differences ($p<0.05$) in single plant potential among hybrids and parents (Table 5.4) indicate that there was variation in single plant potential. The implication is that it is possible to select for single plant potential in both hybrids and OPV parents. From the estimated values and their standard errors, it was quite evident that hybrids had significantly higher single plant yield potential ($p<0.05$) than OPV lines (parents). Thus hybrids were more likely to provide the high yield plant potential genotypes to select as compared to OPV lines. From a random model approach, it can be inferred that sorghum hybrids have higher single plant yield potential than OPV sorghum varieties.

From the estimates of single plant potential sensitivity to plant density, hybrids were significantly less sensitive to plant density ($p<0.05$) than OPV lines (parents) (Table 5.4). Thus hybrid single plant head weights were more adaptive to plant density than OPV lines. Furthermore, it can be inferred that single plant head weight of hybrids would not reduce as much as single plant head weight of sorghum OPV lines as plant density increased. Consequently, hybrids would give higher yield at higher plant densities than OPV lines.

Individual hybrids and OPV line single plant potential and sensitivities were estimated (Table 5.5). Using the estimates and the yield/plant density parabolic relationship (Duncan, 1958; Warren, 1963; Yan and Wallace, 1995), multiple plant parameters; optimal plant density, yield potential in crop condition, total yield over the density ranges (two plants above and below optimum plant density m^{-2}), average yield (over the same density range m^{-2}), grain yield potential (70% yield potential under cropped situation m^{-2}) and maximum tolerable plant density m^{-2}) were estimated (Table 5.5). Considering the highest recorded head weights in any of the replications in the trials (1875, 1186, 1136 and 1131 g m^{-2}) and the averaging effect across replications and trials, our opinion is that the estimates were fairly accurate. This is deduced from comparing the field figures with the highest yield potential in Table 5.5). We concluded that the estimates were reliable and dependable. Hybrids and OPV parents selected herein are therefore most likely to adapt to variable plant densities found in field situations. Rana, *et al.* (1996) have identified 175-180 cm as the range in height for ideal sorghum hybrids. Karari *et al.* (2005) widened the window to cover the range 150-180 cm. High yielding hybrids in the study fell in the height range 112-199 cm (Table 5.6), a much wider height range. This finding is at variance with our previous finding and that of Rana, *et al.* (1996). It is believed that this is a more accurate picture because sorghum hybrids cultivated in agriculturally advanced world countries are both productive and short (combine harvest height).

Correlations among traits were high (Table 5.7). Single plant potential was positively correlated with crop yield potential under crop environment, total crop yield and average crop yield over the range of densities used (Table 5.7). Thus selecting single high potential plants will result in high crop yield potential under different crop environments. Crop yield potential was correlated with total, average and low density crop yield. Low density and high density crop yield (Table 5.7) were positively correlated. Therefore selection for high crop yield potential can be done in either low density or high density environments.

Sensitivity to density was negatively correlated with optimum density required for maximum yield (Table 5.7). Therefore, as sensitivity to plant density reduces the yield potential of genotypes increased. Consequently, stress tolerant genotypes are more productive than stress sensitive genotypes. Thus hybrids are more likely to be more productive in sparse stands than OPV lines. Lack of significant difference ($p<0.05$) based on standard errors (Table 5.5) between hybrids and OPV lines to maximum tolerable density (Table 5.5), is testimony that less density sensitive genotypes were as good as more sensitive genotypes in dense stands. Thus in dense stands, less sensitive genotypes are able to adjust perhaps by plant plastic response or by self thinning (Harper, 1977). We concluded, therefore, that density sensitivity is a sensor of the prevailing plant density and perhaps other environmental factors that trigger response for adjustment. Therefore, low sensitivity to density is beneficial in adaptation to plant density. The biggest benefits are most likely to accrue in sparser than denser stands. Furthermore, low sensitivity must be selected for in combination with high single plant head weight potential. Therefore, less sensitive, high single plant yield potential genotypes should be selected. We used average yield for obvious reasons. Farmers are rarely accurate on plant density. Even when intended, optimum plant density is elusive because crop environment is erratically variable. Our opinion is that genotypes having high average potential over a range of densities about the optimum plant density are likely to have more stable yield around optimum plant density and would assure farmers of high yield amidst erratic crop stands.

From a comparative stand point, using average yield, hybrids were more tolerant of plant density than OPV lines. Only the OPV line ICSR91030 ranked among the top ten density-tolerant genotypes (Table 5.5) and only two ICSR91030 and NL9623 ranked in the top thirty genotypes.

Single plant potential and sensitivity to plant density stress are very important selection criteria (Table 5.8). They correlated to virtually all traits that have influence on yield. Variables resulting from them such as optimum plant density, total and average yield over a range of plant densities (Table 5.6) were almost equally correlated to traits that contribute to yield. These two variables are therefore most suited for indirect selection for yield. Low sensitivity to plant density stress is required for high performance in head weight under stress conditions (Table 5.6). Days to 50% flowering and number of tillers are unsuitable for indirect selection for yield (Table 5.7). In the field tests (Table 5.7), the hybrid with the highest head weight was P9540A x SDS5232, which was 151.6 cm tall. High yielding cultivars need not be extremely tall as reported in literature (Niehaus and Pickett, 1966). Like all OPV parents, KARI varieties (checks) were highly sensitive to plant density and relatively lower yielding (Tables 5.5 and 5.6).

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CHAPTER SIX

IS THERE A PLACE FOR SORGHUM HYBRIDS IN KENYA?

6.0 Abstract

Breeders in Kenya have started to find alternative methods to increase sorghum yield to break an apparent yield barrier in OPV sorghum varieties. Seven hundred and twenty-two sorghum hybrids and 119 parents were tested in a triple square lattice design for agronomic performance in two densities x two moisture regime levels. Hybrids and OPV parents were compared for yield. Hybrids were compared for heterosis and economic feasibility of the hybrid technology assessed. Hybrids and OPV parents differed significantly in head weight potential, head weight heterosis and all agronomic traits except the percentage of root lodging and number of leaves per plant. There was significant parental head weight x environment interaction. The highest yielding hybrid was 53% better than the best Kenyan OPV parent. It was concluded that hybrids were superior to Kenya OPV varieties and superiority was sufficient to cover hybrid cost. The best hybrid had 210% yield superiority over the best Kenyan OPV variety in the low density low potential environments contrary to belief that hybrids are only superior to OPV lines in high potential environments. There is a place for sorghum hybrids in Kenya if a base for hybrid sorghum is established.

6.1 Introduction

Past sorghum improvement in Kenya has been directed towards raising grain yield in OPV varieties on which production is based. Progress to date has been limited and current varieties yield about the same as old varieties. A yield barrier is apparent at 3 t ha^{-1}. Research experience to date has demonstrated that the apparent yield barrier cannot be broken by improving OPV varieties. Breeders are frustrated by the apparent yield barrier to increase yield. Sorghum is Kenya's number three cereal crop and is very important in semi-arid areas which justifies need to raise its yield. Breeders have started to find alternative methods to increase sorghum yield, and hybrids have been suggested as a suitable alternative to OPV lines.

In past research, sorghum hybrids have outyielded OPV varieties and hybrid-OPV variety mixtures. Up to 54% yield advantage has been reported. Hybrids have not been developed because sorghum farmers were viewed as too poor to afford hybrid seed. Hybrid seed affordability should not stand between farmers and the demonstrable economic benefits of sorghum hybrids. General observations and social economic studies have tended to support this view. The KARI seed unit is currently selling sorghum seed. The Kenya Seed Company has sold Seredo seed (sorghum variety) since 1972. The expected benefits from hybrids justify further research to gain a deeper understanding of what is at stake for Kenyan farmers.

Hybrid vigour is based on complementary heterotic groups (Pollack *et al.*, 1991; Andrews *et al.*, 1996). Crossing OPVs from different heterotic groups increase performance of hybrids due to a phenomenon called heterosis. Andrews *et al.* (1996), have recommend that genetic variability be manipulated within heterotic groups for conservation of heterosis. There are two heterotic groups in sorghum comprising of the A-B and the restorer R pools that have been identified so far.

Commercial sorghum hybrids are based on the A1 male sterile cytoplasm (Kafir and milo cytoplasm) (Stephens and Holland, 1954; Andrews *et al.*, 1996). Newer A2, A3, A4 (Andrews *et al.*, 1996) and 9E cytoplasms (Elkonin *et al.*, 1996) are available but undeveloped for hybrid production. They offer opportunities to widening the horizon of heterotic groups in sorghum (Andrews *et al.*, 1996; Gilbert, 1994) and to avert genetic vulnerability predisposed by the single A1 cytoplasm.

Single cross (F_1) sorghum hybrids are superior to OPV lines (Niehaus and Pickett, 1966; Kambal and Webster, 1966; Kirby and Atkins, 1968; Reich and Atkins, 1970; Jowett, 1972; Collins and Pickett, 1972; Rana *et al.*, 1996; Haussmann *et al.*, 1998, 2000). They have higher yield than the better of their parents (Collins and Pickett, 1972). They yielded higher than OPV lines and hybrid-OPV line mixtures (Ross, 1966; Reich and Atkins, 1970; Haussmann *et al.*, 2000). Single cross F_1 hybrids had better drought tolerance than OPV lines (O'Neill *et al.*, 1983; Haussmann *et al.*, 1998; Reich and Atkins, 1970).

Three-way and single cross F_1 hybrids are similar in yield; both express about 50% yield advantage over the mid-parent value (Jowett, 1972). Three-way and single cross F_1 hybrids were not different in both yield and tolerance to drought (Jowett, 1972; Ross and Kofoid, 1978; O'Neill *et al.*, 1983; Haussmann *et al.*, 2000). However, hybrids based on more than two parents are inferior to F_1 hybrids. In tests outside Kenya, three-way hybrids were heterogeneous and unacceptable to farmers (Andrews, 1987).

Heterosis in sorghum has been explored (Niehaus and Pickett, 1966; Kambal and Webster, 1966; Kirby and Atkins, 1968; Haussmann *et al.*, 1998). Heterosis varied with germplasm (Niehaus and Pickett, 1966; Kirby and Atkins, 1968), with parental performance (Kirby and Atkins, 1968; Miller and Lee, 1964), and with traits under investigation (Niehaus and Pickett, 1966; Kambal and Webster, 1966; Kirby and Atkins, 1968; Haussmann *et al.*, 1998). It is not quite clear whether test environment has any effect on heterosis (Haussmann *et al.*, 1998 vs. Kirby and Atkins, 1968). More work is needed to clear the uncertainty.

Heterosis varied with traits such as number of seeds per head, grain yield, height and days to 50% flowering showed the most heterosis (Niehaus and Pickett, 1966; Kambal and Webster, 1966; Kirby and Atkins, 1968; Haussmann *et al.*, 1998). Virtually all traits exhibited some heterosis (Kirby and Atkins, 1968; Haussmann *et al.*, 1998; Kambal and Webster, 1966).

It is possible to select directly or indirectly for heterosis in sorghum because sometimes heterosis in different traits is associated. Heterosis in yield and plant height, stem height and internode length, peduncle and head lengths are associated (Kambal and Webster, 1966). Heterosis in number of seed per head and grain yield are associated (Niehaus and Pickett, 1966; and Kirby and Atkins, 1968; Kambal and Webster, 1966). Heterosis in height and in grain yield or in seeds per head (Niehaus and Pickett, 1966) is also associated. Heterosis in other traits was not associated. For example, heterosis in seed size and number of seeds per head, in peduncle and stem height had no association. Head lengths and stem height had no heterotic association in hybrid sorghum (Ayyangar, 1939; Niehaus and Pickett, 1966; Kambal and Webster, 1966).

Rana *et al.* (1996) have described some productive hybrids. Productive hybrids generally have wider adaptation and higher yield and homeostatic stability than OPV varieties in multiple environments. They were 175-180 cm tall and flowered in about 70 days. They had few leaves, high harvest indices and large seeds and were resistant to abiotic and biotic stresses. They yielded at least 10% higher than good OPV varieties. Hybrids exhibited significant positive correlations among yield, height and maturity period (Niehaus and Pickett, 1966; Majisu, 1971). Height would not be a constraint in Africa as sorghum is harvested by hand and can be harvested easily. However, late maturity would be a problem because sorghum is grown in semi-arid areas that have short rainfall durations. Consequently, late maturity is disadvantageous in semi-arid parts of Kenya. Because late maturing and tall height are positively associated, therefore tall, late maturity hybrids would be unsuitable for Africa except perhaps under irrigated conditions. The goal of the study was to identify if hybrids would break the current OPV yield plateau in Kenya.

The objectives were to:

1. Find out if hybrids have a higher yield potential than OPV varieties and identify hybrids for further testing,
2. Investigate the economic advantages of hybrids over OPV varieties, and
3. Compare parental sources in hybrid yield potential.

The hypotheses according to objective were:

1. The yield performance of hybrid and OPV varieties are the same,
2. Hybrids have no economic advantage over OPV varieties, and
3. Parental sources have no influence on the performance of their hybrids.

6.2 **Materials and methods**

The KARI sorghum breeding program has no male sterile sorghum lines on which to base hybrid production. Therefore, male sterile lines for the study were acquired from collaborators in the INTSORMIL group of universities in USA (from Texas, Kansas, and Indiana), and

ICRISAT Zimbabwe. Local germplasm, expected to enhance hybrid vigour and adaptation of the hybrids was included. The introduced germplasm consisted of 94 parental lines: 41 pollen parents and 51 male sterile parents. They were screened together with 27 pollen parents from Kenya for co-adaptation at the University of Kwa-Zulu Natal, South Africa (29^0 40'S, 30^0 25'E), and together with their hybrid combinations at Kiboko, Kenya (2^0 12'S, 37^0 43'E, 915m altitude) on a luvisol soil. At the time of hybridization, flowering periods under Kenyan conditions were unknown; therefore mating could not be planned between any mating parental pairs because of nicking problems. The South African study had established significant differences among the male fertile and male sterile lines. Male fertile lines had higher yield potential and were also more variable in other traits than male sterile lines. Parental details are provided (Table 6.1).

Table 6.1: Source, type and numbers of sorghum lines producing hybrids for the study

	Type of Parent	
Source parent	**Males (R-lines)**	**Females (A-lines)**
ICRISAT, Zimbabwe	24	2
Kenya	23	0
Purdue, USA	0	40
Kansas, USA	8	5
Texas, USA	13	4
Total	68	51

NB: all the lines were used in crosses but many crosses did not produce adequate seed

A parental mating design involving 68 males and 51 females was used (Table 6.1). Out of the parents, 867 hybrids were generated from which 722 hybrids were selected for evaluation. The 722 hybrids plus 119 parents were evaluated in 29 x 29 triple square lattice designs with three replications in four factorial trials involving two levels of plant density and two levels of irrigation regimes at Kiboko, Kenya. Fertilization was by NPK 17:17:0 and 18:46:0 fertilizers applied in the high and low irrigation regimes respectively, applied at the rate of 0.8 g m^{-2} (8 kg ha^{-1}) at planting and 9.6 g m^{-2} (96 kg ha^{-1}) three weeks after. A single nitrogen dose was applied as $CaNH_4NO_3$ (26%N) to all trials at the rate of 9.6 g m^{-2} (96 kg ha^{-1}) with the last dose of NPK. The first dose of NPK fertilizer was drilled in the soil immediately after planting and the second dose was drilled two weeks thereafter. The nitrogen fertilizer was drilled together with the second NPK fertilizer dose. Fertilization was adequate for proper growth. Different types of fertilizers were used only because of availability problems in the market. To stop treatment effects in one trial affecting the neighbouring trials, trials were planted as separate independent units as in multiple location trials. A trial comprised of one plant density and one irrigation regime. The nearest trials were the high density, high irrigation and the low density high irrigation regime trials and they were 12 m apart. Each of the trial had three guard rows planted around, exactly as the trial genotypes but with standard sorghum varieties cultivated in the Kiboko region. Other management practices were in accordance with KARI standards (KARI, 1997). The treatments are summarized (Table 6.2).

Table 6.2: Summary of treatments applied on the hybrids and their parents at Kiboko research station

	Moisture regimes	
Density regimes	High Potential (HP)	Low Potential (LP)
High Density (HD)	9 plants m^{-2} (90,000 plants ha^{-1}) + 27mm/ wk over 100 days (sprinkler irrigation) + 10.4 g m^{-2} NPK 17:17:0 + 9.6g m^{-2} CaNH4NO3 (26%N) + field condition	9 plants m^{-2} (90,000 plants ha^{-1}) + 27mm/ wk over 60 days (sprinkler irrigation) + 10.4 g m^{-2} NPK 18:46:0 + 9.6g m^{-2} CaNH4NO3 (26%N) + field condition
Low Density (LD)	1 plant m^{-2} 10,000 plants ha^{-1}) + 27mm/wk over 100 days (sprinkler irrigation) + 10.4 g m^{-2} NPK 17:17:0 + 9.6g m^{-2} CaNH4NO3 (26%N) + field condition	1 plant m^{-2} (10,000 plants ha^{-1}) + 27mm/ wk over 60 days (sprinkler irrigation) + 10.4 g m^{-2} NPK 18:46:0 + 9.6g m^{-2} CaNH4NO3 (26%N) + field condition
	High potential	Low potential

Dry panicle and stem weights were recorded. Seedling vigour, plant stand, days to half to 50% flowering, plant height, and stem weight were also recorded for additional description of the hybrids and parents. Measurements were taken as follows: seedling vigour was scored at four leaf stage on a 1 to 5 scale where 5 was the most vigorous, three was intermediate and one was least vigorous, plant stand was the count of seedlings after thinning and before tillering, days to 50% flowering was recorded as number of days from the first day of irrigation to the day 50% of plants in a plot were shedding pollen, head weight (g $plot^{-1}$) as weight of heads harvested in a plot and dried in a freely ventilated shed at about 26^{0}C day temperature for 3 weeks and stem weight (g plot^{-1}) as weight in grams of stems harvested in a plot and dried at the point of harvest for three weeks at approximately 27^{0}C day temperature. Effective tillering was derived as total number of stems minus plant density. Grain colour was scored on a 1 to 6 scale (IBPGR, 1987), where 1 represents the lightest colour, white, and 6 the darkest colour, black. Data was analyzed following residual maximum likelihood (REML) procedure of Genstat 8 statistical computer programme (Lawes Agricultural Trust, 2006). An outline for the analysis of variance is shown (Table 6.3).

Table 6.3: An outlines for the analysis of the traits measured in the study

Source of variance	df
Replications (r)	r-1
Block (replications) r(b)	r(b-1)
Environments (E)	E-1
Males (m)	m-1
Females (f)	f-1
Males x Females	(m-1)(f-1)
Environments x males	(E-1) (m-1)
Environments x Females	(E-1) (f-1)
Environments x males x Females	(E-1) (m-1) (f-1)
Hybrids (H)	H-1
Hybrids X Environments	(H-1)(E-1)
Hybrids and parents (group)	group-1
Hybrids and parents x Environments	(group-1)(E-1)
Error (e)	(e)
Total variance (T)	(T)

Combined analysis for different effects was performed on the following model

$$Y_{ijkl} = \mu + \beta_i + \alpha\ (\beta)_{ij} + g_k + E_l + gE_{kl} + e_{ijkl} \qquad (1)$$

Where ß stood for blocks, α stood for replication, "g" for genotypes which were hybrids or parents, E stood for environment and e stood for error. Y_{ijklm} was the yield in ith block within the jth replication in the lth trial, μ was the overall mean, β_i was the ith replication effect $\alpha\ (\beta)_{ij}$ was the jth block effect within the ith replication, g_k was the kth genotype (hybrid or parent) effect gE_{kl} was the interaction effect between the kth genotype and lth environment while e_{ijkl} was the error term in estimating all the parameters. When single trials (environment) were analyzed the model reduced to:

$$Y_{ijkl} = \mu + \beta_i + \alpha(\beta)_{ij} + g_k + e_{ijk} \quad (2)$$

Using the market price for maize hybrid seed on weight basis and sorghum seed rate, the difference in yield between the highest yielding hybrid and inbred variety was converted to money and then discounted for the cost of hybrid seed to deduce the cost of hybrid technology. The cost of the inbred variety grain used as seed was considered to cover cost of transportation which does not occur when inbred varieties are grown.

6.3 **Results**

Significant head weight variation among hybrids and parents ($p<0.01$) over the test environments was observed. There was significant parents' head weight x environment and parents and hybrids (group) head weight x environment interaction (Table 6.3). Hybrid head weights (yield) x environment interactions were not significant. Hybrids differed significantly from OPV parental lines ($p<0.01$) in all the traits examined except the percentage of root lodging and number of leaves (Table 6.8). Hybrids differed significantly from OPV parental lines ($p<0.01$) in seedling vigour, head weight, stem weight, number of panicles, plant height, tiller height, plant stand, plant vigour, head exsertion, panicle length, number of tillers, grain colour, effective tillering and number of nodal tillers. Hybrids differed significantly from OPV parental lines ($p<0.01$) in percentage of stem lodging. Hybrids and OPV parental lines were similar in percentage root lodging and number of leaves per plant (Table 6.8).

Table 6.3: Analysis of variance of dry head weight of sorghum hybrids and parents as a group, and separately over the four environments used in the study

Source of variation	Df	Wald/d.f.	Prob. of diff.
	Head weight		
Parents and hybrids	1	63.55	<0.001
Environments	3	212.22	<0.001
parents and hybrids * Environments	3	2.42	0.064
Hybrids	709	3.09	<0.001
Environments	3	644.99	<0.001
Hybrids * Environments	1448	1.05	0.111
Parents	117	1.89	<0.001
Environments	3	153.93	<0.001
Parents * Environments	318	1.19	0.010
	Percent hybrid heterosis over mid parent		
Hybrids	688	2.00	<0.001
Environments	3	0.31	0.822
Hybrids *Environments	1355	0.91	0.991

Environments were analysed for head weight performance of hybrids and parents in the study. Environments differed significantly ($p<0.05$) in hybrid head weights. The highest hybrid head weight was produced in the high density, high potential (HDHP) environment followed by high density, low potential (HDLP) followed by low density high potential (LDHP) and the least was in low density low potential (LDLP) environment. Environmental head weights differed significantly ($p<0.05$) in between the HDHP and HDLP environments. There was no difference in parental head weights between the LDLP and the LDHP environments (Table 6.4). While hybrid head weight was consistent with potential of environment, parental head weight was not (Table 6.4).

Table 6.4: Head weight yield (g m^{-2}) in hybrids and parents (OPV lines) in four test environments

	Environments					
Groups	HDHP	HDLP	LDHP	LDLP	Mean	SED
Hybrids	363.7	253.9	181.5	156.6	238.9	8.3

Parents (OPV varieties)	299.2	214.0	140.9	142.1	199.1	8.3
SED	7.8	7.8	7.8	7.8	4.2	

HDHP = High density high potential environment, HDLP = High density low potential environment, LDHP = Low density high potential environment and LDLP =Low density low potential environment

The highest yielding (head weight) hybrid and the highest yielding OPV Kenyan variety, were analyzed for head weight performance over the four environments in the study. The highest yielding hybrid and the highest yielding OPV Kenyan variety head weights differed significantly ($p<0.05$) in the HDHP and LDLP environments (Table 6.5). Head weights of the highest yielding hybrid in the HDHP environment differed significantly ($p<0.05$) from head weight in the other environments. The highest yielding (best) hybrid head weights in the HDLP, LDHP and in the LDLP environments were not significantly different ($p<0.05$) (Table 6.5). As for the highest yielding Kenyan OPV variety, the head weights in LDHP and LDLP environments were not significantly ($p<0.05$) different. Its head weight in the HDLP environment differed significantly from its head weights in the LDHP and LDLP environments (Table 6.5). The best Kenyan variety head weights in HDHP environment differed significantly from its head weight in either LDHP or LDLP environments but not from its head weight in HDLP (Table 6.5).

Table 6.5: Head weight (g m-^{2}) of the highest yielding hybrid and Kenya parental line (OPV line) in four test environments

	Environments					
Groups	HDHP	HDLP	LDHP	LDLP	Mean	SED
Best hybrid	745.0	450.7	300.0	488.0	495.9	105.8
Best Kenya OPV variety	510.0	442.0	185.0	158.7	323.9	105.8
SED	105.1	105.1	105.1	105.1	53.38	

Hybrids and parents were compared (Table 6.6) in head weight superiority based on hybrids head weight over the four environments in the study. On average, hybrids were 16% superior to parents. Hybrids were significantly ($p<0.05$) superior to parents in head weight in all the four environments in the study (Table 6.6). They were most superior in the LDHP environments.

Table 6.6: Percent yield superiority (head weight) of hybrids over parents (OPV lines) in four test environments based on mean of all hybrids

	Environments					
Groups	HDHP	HDLP	LDHP	LDLP	Mean	SED
Hybrids	0	0	0	0	0	3.519
Parents (OPV varieties)	-15.64	-15.873	-22.877	-10.081	-16.118	3.519
SED	3.298	3.298	3.298	3.298	1.774	

A comparison of the best hybrid and best Kenyan OPV variety with the mean hybrid head weight (Table 6.7) over the environment revealed that on average, the best hybrids head weight was 115.4 % higher than the mean hybrid head weight (Table 6.7). By subtracting the best Kenyan variety superiority based on mean of hybrid from the best hybrid (Table 6.7), the best hybrids was roughly 212% more superior in the LDLP environment over the best Kenyan variety (Table 6.7). The highest yielding hybrid mean head weight was on average 29.7% higher than mean head weight of highest yielding OPV (checks) grown in Kenyan (Table 6.7).

Table 6.7: Percent yield superiority (based on mean of all hybrids) of the highest yielding hybrid and Kenya parent (OPV line) in four test environments

	Environments					
Groups	HDHP	HDLP	LDHP	LDLP	Mean	SED
Best hybrid	105.9	77.8	65.6	212.4	115.4	46.7
best Kenyan OPV variety	40.9	74.4	2.1	1.6	29.7	46.7
SED	46.4	46.4	46.4	46.4	23.6	

A comparison of hybrids and parents in performance in agronomic traits (Table 6.8), revealed significant ($p<0.05$) difference between hybrids and parents in all traits tested in the study (Table 6.8) except in number of leaves per plant, and percentage root lodging. In general hybrids were superior (+) except in number of leaves per plant, number of nodal tillers, percentage stem lodging, plant height, tiller height, percentage root lodging and grain colour (Table 6.8). In number of nodal tillers, percentage stem lodging and grain colour hybrids were worse off compared to parents (Table 6.8).

Table 6.8: Mean performance of Hybrids and parents (OPV lines) for eighteen agronomic traits in four environments

Trait	Hybrids	OPV parents	Diff	Adv/disadvantage
Head weight (g)	238.2	198.2	**	+
Stem weight (g)	398.6	318.7	**	+
% Hybrid/OPV vigour	0	-16.118	**	+
Plant ht (cm)	147.3	121.1	**	±
Tiller ht (cm)	130.8	110.6	**	±
Stand m^{-2}	4.784	4.618	**	+
Seedling Vigour (score)	2.587	2.414	**	+
Head exert (cm)	16.62	11.70	**	+
Panicle length (cm)	21.35	18.80	**	+
No. of tillers	2.262	2.063	**	+
Grain colour (score)	2.848	2.121	**	-
Effective tillering	0.4389	-0.0009	**	+
No. of leaves	7.775	7.8965	NS	±
No. of Panicles	4.3	4.0	**	+
No. of nodal tillers	2.124	1.453	**	-
% Stem lodging	0.092	0.0655	*	-
% Root lodging	0.01132	0.01139	NS	0

+ indicates hybrids are advantageous, - means hybrids were disadvantaged, ± means trait in hybrids could be an advantage or disadvantage depending on use, and 0 means hybrids and parents were the same

Detailed performance of the highest thirty head weight hybrids and the best two male and two female head weight parents are provided for comparison of individual hybrids with the best parents (Table 6.9). Hybrids and inbred lines varied significantly in most of the trait in favour of hybrids (Table 6.8).. The best head weight parent was a male and ranked seventeenth in head weight. The best 16 genotypes were hybrids (Table 6.9).

Table 6.9: Performance of highest forty head weight hybrids in seven agronomic traits associated with grain yield

Female	Male	Genotype code	No of panicles	No of leaves	Head wt (g)	No of tillers	Effective tillering	Head exsertion (cm)	Grain
P9540A	SDS5232	247	5.0	9.3	481.9	2.8	-0.2	17.6	6.0
P9538A	PIRIRA 1	725	3.1	6.6	452.3	2.1	-0.1	10.3	---
P9504A	SDS3472	600	2.1	7.7	449.3	4.0	1.4	21.0	6.0
P9504A	Lanet-1	220	8.1	8.3	442.9	4.5	2.4	15.8	4.0
P9535A	PIRIRA 1	250	5.1	8.4	426.2	1.9	1.1	9.9	1.1
P9520A	KAT-487	333	6.2	8.4	422.6	2.3	-0.6	17.1	6.0
ICSA12	Mexico-R-line19	292	5.6	9.3	422.5	2.6	-1.0	13.5	1.0
P9520A	P890012x(148xE354)xCS-35	408	4.4	7.6	421.4	2.4	0.3	24.3	6.0
P9519A	SDS3472	217	6.1	9.1	414.0	1.6	-0.5	9.6	5.3
P9520A	SDS3472	215	5.9	7.8	414.0	3.5	3.8	23.6	4.0
P9508A	NL9623	350	7.5	9.6	411.3	1.4	0.2	12.9	1.1
P9520A	Kuyuma	14	5.8	7.6	402.9	2.8	1.8	24.8	5.0
P9509A	Lanet-1	72	5.1	7.1	400.4	4.0	2.3	13.8	4.0
P9531A	ICSV 111	560	3.7	7.2	394.9	3.0	2.0	21.0	1.0
P9509A	E1291	225	5.8	8.7	394.1	1.3	0.2	11.8	4.0
P9520A	Serena	291	5.5	7.6	393.9	1.7	0.2	17.9	3.0
Kiboko Local	(Best males)*		3.3	3.8	388.1	---	---	6.5	---
P9520A	Chokwe	214	5.4	9.6	380.9	2.4	0.9	18.1	5.9
SDSL89473	(Best males)*		2.5	1.7	380.4	---	---	9.0	---
ICSA12	Ikinyaruka	144	6.0	9.1	379.8	2.7	2.0	10.1	4.0
P9520A	FPR(168xGS70)	342	4.9	7.7	379.6	2.8	1.4	22.8	5.3
P9520A	Mexco-R-line5	407	4.6	8.1	374.5	1.5	0.8	23.8	5.9
TXARG1/N133(A)	Seredo	150	5.0	7.3	373.8	2.9	2.9	16.6	3.9
P9510A	Lanet-1	34	5.4	7.3	373.6	3.5	3.9	17.1	4.0
P9532A	IRAT-204	57	5.4	7.8	370.0	2.9	1.6	26.4	1.1
P9508A	Lanet-1	265	5.0	8.6	369.3	2.5	1.2	16.7	4.0
P9539A	01Aphid207	335	6.4	8.3	367.7	2.6	0.6	17.7	6.0
P9520A	ICSV111	288	4.5	8.4	366.4	2.3	0.7	20.9	2.1
P9519A	Ikinyaruka	343	5.1	9.6	365.4	1.4	0.6	6.2	4.0
P9535A	Chokwe	7	4.5	8.8	360.3	2.5	0.9	9.5	---
P9508A	ICSV111	80	4.8	8.3	358.5	2.5	2.1	18.6	3.3
CK60A	ICSV111	106	5.1	7.2	355.0	1.7	0.5	22.6	5.9
CK60A	ICSR91005	45	7.2	10.3	353.5	1.9	-0.5	16.2	1.0
P9540A	Chokwe	10	4.3	8.6	353.4	2.1	1.6	18.3	6.0

Female	Male	Genotype code	No of panicles	No of leaves	Head wt (g)	No of tillers	Effective tillering	Head exsertion (cm)	Grain
ICSA12	FPR(168xGS70)	183	5.0	8.8	353.2	2.6	0.8	15.3	1.0
P9537A	FPR(168xGS70)	282	3.9	6.7	349.2	1.9	0.3	13.0	*
P9521A	Serena	70	5.0	8.0	348.4	3.8	3.0	17.6	4.0
P9533A	KAT-369xMakueni Local	313	5.7	7.5	347.9	3.1	1.6	24.5	1.1
P9518A	Lanet-1	101	5.3	7.4	343.2	3.3	2.5	13.9	4.0
CK60A	ICSR91030	86	5.0	8.0	342.2	2.1	1.1	18.2	1.0
P9519A	Gadam el Hamam	673	3.1	7.2	341.2	4.0	7.4	11.2	*
ICSA12	Red Swazi	316	5.9	7.5	340.6	3.1	0.6	16.1	4.0
P9509B	(Best females)*	---	2.4	2.2	319.9	---	---	9.8	---
P9508B	(Best females)*	---	2.4	1.7	310.8	---	---	17.8	---
Mean (all hybrids)			3.8	7.5	210.4	2.3	1.1	15.9	2.8
SED			1.9	1.3	10.7	1.0	1.6	5.2	1.1

* Indicates best ranking males and female inbred lines in head weight, and --- indicates trait was not recorded

Source combinations of hybrids were evaluated for performance in the four environments of the study (Table 6.10). Zimbabwe x Kansas were the highest head weight source combinations but were not significantly different from the Kansas x Kenya, Zimbabwe x Zimbabwe, Zimbabwe x Kenya, Purdue x Kenya, Purdue x Kansas, Purdue x Texas, Purdue x Zimbabwe combination of sources. The source combinations: Kansas x Zimbabwe, Zimbabwe x Texas and Kansas x Kansas were similar but differed significantly ($p<0.0.05$) from the preceding group of combinations (Table 6.10). The combination of sources: Texas x Zimbabwe, Texas x Kenya and Kansas x Texas formed the third group of combination and had significantly ($p<0.05$) lower head weight potential in hybrids than the second (intermediate) group. Thus source combinations could be put in three groups according to their hybrid mean head weight potential (Table 6.10). A column of genetic distance from Table 3.8 head weight in Chapter Three was superimposed on the parental source combinations (6.10).

Table 6.10: Mean head weight yield (g m^{-2}) in hybrids composed of parents from different sources combined in hybrids (sorted according to mean)

Source combinations	GD	HDHP	HDLP	LDHP	LDLP	Mean	SED
Zimbabwe x Kansas	5.8	557.9	359.7	201.2	196.3	328.8	53.2
Kansas x Kenya	5.7	508.5	365.2	200.7	211.6	321.5	53.2
Zimbabwe x Zimbabwe	4.9	532.9	350.1	203.8	163.5	312.6	53.2
Zimbabwe x Kenya	4.9	511.0	325.3	213.4	198.8	312.1	53.2
Purdue x Kenya	9.8	516.3	307.1	214.5	190.7	307.2	53.2
Purdue x Kansas	8.5	514.9	280.6	226.6	203.7	306.4	53.2
Purdue x Texas	7.7	482.5	327.0	201.2	183.5	298.6	53.2
Purdue x Zimbabwe	9.9	490.3	302.3	198.3	194.8	296.4	53.2
Kansas x Zimbabwe	4.7	460.3	321.6	183.6	174.9	285.1	53.2
Zimbabwe x Texas	4.8	416.4	286.6	242.3	178.8	281.0	53.2
Kansas x Kansas	5.3	481.5	270.2	205.0	148.7	276.3	53.2
Texas x Zimbabwe	3.9	375.7	234.7	222.0	114.8	236.8	53.2
Texas x Kenya	4.8	312.2	245.0	180.0	192.3	232.4	53.2
Kansas x Texas	4.6	146.0	206.8	159.5	80.2	148.2	53.2
Texas x Texas	4.1	xx	290.5	99.8	147.0	xx	53.2
Texas x Kansas	4.6	xx	236.3	256.3	234.6	xx	53.2
		xx	294.3	200.5	175.9	282.1	15.8
SED		46.1	46.1	46.1	46.1	21.5	

GD= Genetic distance

XX=No data

A two sided correlations among population combinations head weights in HDHP, HDLP, LDHP, LDLP environments and overall mean head weight and genetic distance (GD) based on head weight were estimated. The correlation was different from zero which indicated presence of correlation. A one sided correlation (Y>0) showed a significant correlation between genetic distance and head weight in the low density, low potential environment. The correlation between GD and LDLP environment head weights was significantly greater than zero (Genstat 9 statistical computer software programme (Lawes Agricultural Trust, 2009) (Table 6.11)

Table 6.11: Correlation matrix among head weight realized in HDHP, HDLP, and LDHP, LDLP environments and overall mean head weight and genetic distances between population combinations (Table 6.10 column 1)

GD	1.000					
HDHP	0.406	1.000				
HDLP	0.202	0.833**	1.000			
LDHP	0.175	0.542*	0.211	1.000		
LDLP	**0.458***	0.741**	0.702**	0.360	1.000	
Mean	0.390	0.981* *	0.884**	0.540*	0.831**	1.000
	GD	**HDHP**	**HDLP**	**LDHP**	**LDLP**	**Mean**

GD =genetic distance HDHP= high density high potential environment, HDLP= high density low potential environment, LDHP= low density high potential environment and LDLP= low density low potential environment

Genetic distance between combining population from which combining hybrid parents were found was superimposed on hybrids (Table 6.9) to produce (Table 6.12). To fit the table in a page, columns were deleted leaving genotype code and head weight (g) and source combinations. Genetic distances of the source populations from Chapter Three, Table 3.8 were superimposed. The relationship is indicated in Table 6.12. The correlation between hybrid head weights and genetic distances was significant ($p<0.05$). The high genetic distance parental population combinations also had high GCA and SCA values (Table 6.12).

Table 6.12: **Highest yielding 46 genotypes, their yield and GCA and SCA component in hybrid genotypes and genetic distance between populations from which hybrid parents were drawn**

	Hybrid		Population combinations							
	Female	Male	Male source population	Female source population	Genotype code	Head wt (g)	Genetic Distance	Relative. Heterosis	Total GCA	Total SCA
1	P9540A	SDS5232	Purdue	Zimbabwe	247	481.9	9.85	2.462	104.6	166.3
2	P9538A	PIRIRA 1	Purdue	Zimbabwe	725	452.3	9.85	2.462	56.5	227.8
3	P9504A	SDS3472	Purdue	Zimbabwe	600	449.3	9.85	2.462	61.3	190.2
4	P9504A	Lanet-1	Purdue	Kenya	220	442.9	9.8	2.451	74.4	99.4
5	P9535A	PIRIRA 1	Purdue	Zimbabwe	250	426.2	9.85	2.462	33.6	116.6
6	P9520A	KAT-487	Purdue	Kenya	333	422.6	9.8	2.451	55.6	53.4
7	ICSA12	Mexico-R-line19	Zimbabwe	Kenya	292	422.5	4.89	1.222	26.3	104
8	P9520A	P890012x(148xE35 4)xCS-35	Purdue	Kenya	408	421.4	9.8	2.451	53.6	49.1
9	P9519A	SDS3472	Purdue	Zimbabwe	217	414	9.85	2.462	107.3	55.1
10	P9520A	SDS3472	Purdue	Zimbabwe	215	414	9.85	2.462	100.3	-11.3
11	P9508A	NL9623	Purdue	Zimbabwe	350	411.3	9.85	2.462	24.8	19
12	P9520A	Kuyuma	Purdue	Zimbabwe	14	402.9	9.85	2.462	67.1	72.3
13	P9509A	Lanet-1	Purdue	Kenya	72	400.4	9.8	2.451	90.5	67.6
14	P9531A	ICSV 111	Purdue	Kenya	560	394.9	9.8	2.451	59.1	121.6
15	P9509A	E1291	Purdue	Kenya	225	394.1	9.8	2.451	37.2	107.6
16	P9520A	Serena	Purdue	Kenya	291	393.9	9.8	2.451	70.9	46.8
17	Kiboko Local	(Best males)*	Kiboko Local	(Best males)*		388.1				
20	P9520A	Chokwe	Purdue	Zimbabwe	214	380.9	9.85	2.462		
22	ICSA12	Ikinyaruka	Zimbabwe	Kenya	144	379.8	4.89	1.222	38.3	108.5
23	P9520A	FPR(168xGS70)	Purdue	Kenya	342	379.6	9.8	2.451	80.2	67.5
24	P9520A	Mexco-R-line5	Purdue	Kenya	407	374.5	9.8	2.451	64.6	79.6
25	TXARG1/N1 33(A)	Seredo	Kansas	Kenya	150	373.8	5.71	1.428	42.6	82.5
26	P9510A	Lanet-1	Purdue	Kenya	34	373.6	9.8	2.451	89.3	50.5
27	P9532A	IRAT-204	Purdue	Kenya	57	370	9.8	2.451	-24.6	119.1
28	P9508A	Lanet-1	Purdue	Kenya	265	369.3	9.8	2.451	79.9	43.1
29	P9539A	Kansas	Purdue	Kansas	335	367.7	8.47	2.117	0.7	133.3
30	P9520A	ICSV111	Purdue	Kenya	288	366.4	9.8	2.451	88.4	28.8
31	P9519A	Ikinyaruka	Purdue	Kenya	343	365.4	9.8	2.451	71.8	60.6

	Hybrid		Population combinations							
	Female	Male	Male source population	Female source population	Genotype code	Head wt (g)	Genetic Distance	Relative. Heterosis	Total GCA	Total SCA
32	P9535A	Chokwe	Purdue	Zimbabwe	7	360.3	9.85	2.462	68.7	59.6
33	P9508A	ICSV111	Purdue	Kenya	80	358.5	9.8	2.451	47.9	98.8
34	CK60A	ICSV111	Zimbabwe	Kenya	106	355	4.89	1.222	38.9	74.6
35	CK60A	ICSR91005	Zimbabwe	Zimbabwe	45	353.5	4.85	1.212	-19.6	100.2
36	P9540A	Chokwe	Purdue	Zimbabwe	10	353.4	9.85	2.462	104.6	42.9
37	P9537B	(Best females)*	P9537B	(Best females)*		353.4				
38	ICSA12	FPR(168xGS70)	Zimbabwe	Kenya	183	353.2	4.89	1.222	39.7	81.5
39	P9537A	FPR(168xGS70)	Purdue	Kenya	282	349.2	9.8	2.451	53.8	73
40	P9521A	Serena	Purdue	Kenya	70	348.4	9.8	2.451	13.2	110.4
41	P9533A	KAT-369xMakueni Local	Purdue	Kenya	313	347.9	9.8	2.451	-9.71	132.4
42	P9518A	Lanet-1	Purdue	Kenya	101	343.2	9.8	2.451	81.7	9.9
43	CK60A	ICSR91030	Zimbabwe	Zimbabwe	86	342.2	4.85	1.212	-4.4	54.1
44	P9519A	Gadam el Hamam	Purdue	Kenya	673	341.2	9.8	2.451	60.1	104.8
45	ICSA12	Red Swazi	Zimbabwe	Zimbabwe	316	340.6	4.85	1.212	23	40.9
46	P9509B	(Best females)*	P9509B	(Best females)*	---	319.9				
Mean (all hybrids)					3.8	2.3				
SED					1.9	1				

Table 6.13: Correlation matrices for genetic distance and head weight from (Table 6.11) and probabilities of correlation value being greater than zero

Table 6.13 (1)

Correlation Matrix		
Head weight	1.000	
Genetic distance	0.298*	1.000
	Head weight	Genetic distance

Table 6.13 (2)

Probabilities (y>0)		
Head weight	1.00000	
Genetic distance	**0.03090**	1.000
	Head weight	Genetic distance

Refer to Table 6.13 above. Hybrid head weight had significant correlation with genetic distances between population combinations from which parents originated (Table 6.12). When a hybrid by distance frequency table was prepared, the outcome is shown (Table 6.14).

When a hybrid by distance frequency table was prepared, the result is shown (Table 6.14). All the forty high yielding hybrids, without exceptions, fell in the genetic distance range 4.85 to 9.85 units and in the upper side of the range. Thus genetic distance can discriminate population for high yielding hybrids (Table 6.14). The population combinations: Texas males x Zimbabwe females, Texas males x Texas females, Texas males x Kansas females, Kansas males x Texas females, Kansas males x Zimbabwe females, Kenya males x Texas females, Zimbabwe males x Texas females (Table 6.10) or 7 out of the population combinations used would have been eliminated without loosing any of the top 40 highest yielding hybrids. Generally, source combinations that were most distant genetically also produced the highest number of high yielding hybrids individually. These results agree with those in chapter three.

Table 6.14: Frequency distribution of hybrids according to genetic distances

Genetic Distance	Number of hybrids
4.85	3
4.89	4
5.71	1
8.47	1
9.80	20
9.85	11
Total	40

The range of genetic distances was 3.92 to 9.85 units (Table 6.10).

When correlations were estimated among genetic distance, relative heterosis, total GCA and total SCA components in the 40 highest head weight hybrids, tests of the correlations indicated that the correlation between genetic distance between the combining populations from which the parents were drawn and the hybrid GCA components were highly significantly ($p<0.01$) correlated with genetic distance (Table 6.15). Head weight was significantly correlated with both the GCA and the SCA component in the hybrids as expected.

Table 6.15: Correlation matrix of correlations among genetic distance, relative heterosis, total GCA and total SCA components in the hybrid and correlation matrix for tests of probabilities of the correlation values being greater than zero (Table 6.11)

Correlation Matrix					
GD	1.000				
Head wt	0.301	1.000			
Rel. Hete	1.000	0.301	1.000		
Total GCA	0.477	0.336	0.477	1.000	
Total SCA	0.009	0.386	0.009	-0.299	1.000
	GD	Head wt	Rel. Hete	Total GCA	Total SCA

Probability (Y>0)					
GD	< 0.001				
Head wt	0.0312	< 0.001			
Rel. Hete	< 0.001	0.0315	< 0.001		
Total GCA	0.0011	0.0181	0.0011	< 0.001	
Total SCA	0.4782	0.0077	0.4788	0.9678	< 0.001
	GD	Head wt	Rel_Hete	Total GCA	Total SCA

GD = genetic distance

Head wt = head weight

Rel. Hete = Relative heterosis

Total GCA = total general combining ability

Total SCA = total specific combining ability

The difference between the best hybrid and best inbred variety grain yield was converted to money using prevailing prices (Kes 120.00/ kg hybrid seed and Kes 10 per kg of sorghum or maize grain). Discounting the cost of hybrids seed which was assumed equal to cost of hybrid maize indicated there is likely to be a big benefit in growing sorghum hybrids.

6.4 Discussion and conclusions

Significant ($p<0.01$) variation in head weights of hybrids, parents and hybrids and environments was found. Genetic advance in yield (head weight) could be made by selecting among both parent and hybrids for high yield. The significant parents x environments and parents and hybrids (group) x environment interactions (Table 6.3) were a sign that parents could not be selected independently of environments. The non-significant hybrids x environment interaction (Table 6.3) indicated that any environment adequately ranked the hybrids by head weights. Hybrids were therefore ranked through combined analysis (Table 6.8). Parental effects were better considered in a separate chapter, chapter four which was created to ease discussion.

The significant heterotic differences ($p<0.01$) among hybrids (Table 6.3) indicated that hybrids could be ranked by heterosis. Therefore, heterosis was an additional hybrid comparative factor to the head weight yield factor. Lack of heterosis by environments interaction indicated that hybrids maintained the same heterotic order in all environments and heterosis was uniformly affected by environments. Therefore any one environment could have ranked the hybrids by heterosis. These results agreed with those of other hybrid researchers in Kenya and elsewhere (Niehaus and Pickett, 1966; Kambal and Webster, 1965; Kirby and Atkins, 1968; Reich and Atkins, 1970; Jowett, 1972; Collins and Pickett, 1972; Rana *et al.*, 1996; Haussmann *et al.*, 1998, 2000). It was concluded that hybrids were as heterotic in Kenya as any where else. Normally, heterosis must be applied based on a check cultivar like Kiboko Local in the case of this research for standardization.

Hybrids were ranked by head weight instead of heterosis. Heterosis is based on mid parent value which differs from hybrid to hybrid (non-uniform base). The differences between mid-parents and hybrid yield may be important but the bottom line is absolute grain (head weight) productivity. For that trait, head mass was considered superior to heterosis. Therefore head weight was adopted as the comparative parameter in the study. Kambal and Webster, (1966) have also noted deficiency of heterosis as a comparative parameter. It tends to be higher between low yielding parents than between higher yielding parents.

The significantly heavier ($p<0.01$) mean head weight in hybrids than parental (Tables 6.4 and 5.8) head weight meant that, in general, hybrids had higher head weight yield potential than OPV parental lines and that significant heterosis resulted when parents were combined to form hybrids. This confirms the general view that hybrids are higher yielding than OPV parental lines e.g. (Niehaus and Pickett, 1966; Kambal and Webster, 1966, 1965; Kirby and Atkins, 1968; Reich and Atkins, 1970; Jowett, 1972; Collins and Pickett, 1972; Majisu, 1971; Rana *et al.*, 1996; Haussmann *et al.*, 1998, 2000). Therefore, the high head weight genotypes identified in the study, are hybrids and not OPV parental lines in agreement with Majisu (1971), that hybrids have a higher yield potential than OPV lines. It is concluded that hybrids in the study are well above the yield barrier experienced in OPV lines.

Hybrids were combined with parental lines in mean head mass computation. There could have been very high yielding parental lines whose yield potential was masked by analyzing parents' and hybrids' head masses together. Computed mean head weights revealed that this was not the case. The best OPV parental head mass ranked seventeenth and was significantly lower ($p<0.05$) than the top eleven hybrids (Table 6.9). It was concluded that hybrids were higher yielding than OPV varieties (checks) and hybrids in the study are well above the yield barrier experienced in OPV lines in Kenya.

Yield alone was not sufficient to reflect agronomic superiority of hybrids over OPV parental lines. It was therefore imperative to compare hybrids and OPV parental lines in other agronomic traits (Table 6.8). Because sometimes a trait is advantageous when large and sometimes when small, the symbols (+ plus) were used when hybrids were advantageous, (- minus) when disadvantageous and (0 zero) when neither the hybrids nor the OPV parental lines were advantageous (Table 6.8). Hybrids had more pluses than OPV parental lines (Table 6.8). It was concluded that hybrids were not only superior to OPV parental lines in head weight yield but also in other agronomic traits. Having broken the yield plateau in OPV varieties and being superior to the OPV varieties in agronomic traits, it can be concluded that hybrids have potential to replace OPV varieties.

Yield superiority of hybrids was not enough of a reason to grow hybrids. Production is about economics. Was the yield difference big enough to cover the cost of hybrid seed and induce farmers to change from OPV lines in which they grow their own seed to hybrids where they would buy fresh seed every season? To answer those questions, we analyzed hybrid superiority over OPV varieties. The results of such analysis are presented (Table 6.6). On average, hybrids were superior to OPV parents by 16.12 % across all environments of the study (Table 6.6). The best hybrid was 29.7 % superior to the best OPV Kenya variety in head weight across all environments and in stressful (LDLP) environments hybrids were 212% superior to the best Kenya OPV variety (Table 6.7). Because the average OPV yield across all environments was 198.2 g m^{-2} (1.982 ton ha^{-1}), (Table 6.4 and Table 6.8, head weight), the advantage translated to 0.32 ton or 320kg ha^{-1}. Considering grain price at the Kenya National cereals and produce board price (Kes 10 kg^{-1}) and the price of hybrid maize seed (kes 120 kg^{-1}) and the sorghum seed rate (6-8 kg ha^{-1}) and a conversion factor (head wt to grain wt) of 70%, the yield superiority could adequately cover the cost of hybrid technology. Considering best hybrid's yield (4959 kg ha^{-1}) over the best Kenya OPV variety's yield (3239 kg ha^{-1}), (Table 6.5) and the conversion factor, the hybrid could produce an additional 1.2 tons ha^{-1} of grain sorghum. It was concluded that there was both a case and a place for sorghum hybrids in Kenya. At a preliminary standpoint, it appears to be economically feasible to grow hybrid sorghum in Kenya. However, farmer preferences must be addressed as was found out in Chapter Two, PRA to promote adoption hybrids.

The population combinations: Texas males x Zimbabwe females, Texas males x Texas females, Texas males x Kansas females, Kansas males x Texas females, Kansas males x Zimbabwe females, Kenya males x Texas females, Zimbabwe males x Texas females (Table 6.10) or 7 out of the population combinations used would have been eliminated without loosing any of the top 40 highest yielding hybrids

Correlations estimates among genetic distance, relative heterosis, total GCA and total SCA components in 40 hybrids with the highest head weight, tests of the correlation indicated that the correlation between genetic distance of the combining populations from which the parents were drawn and the hybrid GCA component was highly significantly ($p<0.01$) (Table 6.15). Genetic distance was uncorrelated with the total SCA component in the hybrids (Table 6.15). It was concluded that genetic distance between combining male and female populations indicated relative amounts of GCA combining male and female populations would impart in hybrids. It was concluded that selecting for greater genetic distance would select high GCA effects in parents and subsequently in the hybrids. The SCA and GCA component in the hybrids were significantly ($p<0.05$) correlated with head weight as expected. It was concluded that genetic distance selects for additive genetic variance (GCA).

In summary, this research demonstrated that heterotic response of sorghum hybrids in Kenya is as good as elsewhere. The study left no doubts that sorghum hybrids were superior to pure line varieties in yield and other agronomic traits over multiple environments. Contrary to the common belief that hybrids are superior to OPV varieties only in high potential environment, the best hybrid was 210% superior to the best of Kenya varieties in the low density low potential environment. Selecting for greater genetic distance between combining parent populations selected for high additive genetic variance (GCA) in the high yielding fraction of hybrids.

Semi-arid parts of Kenya is low potential and sorghum is grown in low density (30 000 to 35 000 plant ha^{-1}) (Chapter Two on PRA). Hybrids have therefore great potential to raise sorghum production in semi-arid parts of Kenya. The most productive hybrids and OPV lines were identified. Sufficiency of hybrid yield superiority to cover cost of hybrid technology with a surplus to induce farmers to go hybrid in sorghum was demonstrated. Therefore, the objectives set forth at the onset of the study were satisfied. Further research is necessary to identify farmers suitable candidate hybrids to replace OPV varieties in production. Similarly, research may be required to set up a hybrid sorghum seed sub-sector in the Kenya seed industry.

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CHAPTER SEVEN

OVERVIEW

7.1 Introduction

The study was conducted in phases to facilitate management. Constituent chapters have been discussed individually. Some issues could not be discussed from the chapters approach because they involved concepts from several chapters. It is therefore fitting to discuss this research in an integrated approach so that such issues can be explained fully. This is the objective of this chapter. Each of the objectives was conceptualized to deal with an issue. Some issues dwelt exclusively with setting the foundation for the actual research and were important in realization of the results that were obtained. At the chapter level, these broad objectives were too big to address. They became goals and were split into objectives at the chapter level. Each objective was addressed by research activities which had outputs (results). The outputs formed a discussion agenda in the chapters. Relationship between thesis objective, chapter objectives and activities pertaining to objectives and outputs (results) were overviewed in the appendix (Table 7.1).

The objectives of the study were:

1. To identify farmers' requirements for sorghum cultivars, constraints to sorghum production and why improved cultivars from research are not adopted by farmers (chapter two),
2. To characterize male and female parents and establish whether genetic distance can identify superior parent populations for the production of hybrids (chapter three),
3. To estimate genetic variance components of parents and explore feasibility of breeding for multiple environments (chapter four),
4. To test hybrids and OPV parents for stress tolerance to identify hybrids for further testing, and
5. To compare single cross hybrids and OPV varieties for yield performance (chapter six).

The foundation of chapters two through six was laid in chapter one, whose objective was to review literature on sorghum. Several issues pertinent to exploiting the sorghum crop came up in that review. Sorghum yield potential traces to sorghum's centres of origin, diversity and domestication. Areas of similar latitude, as the centres of origin, provide the most optimal sorghum growing conditions. Sorghum centres of origin and diversity are also centres of diversity for sorghum pathogens and an invaluable source of the resistance and tolerance genes required for high yield. Sorghum germplasm with tolerance or resistance to many major biotic and abiotic stresses has been found and characterized. Many sorghum OPV varieties have been acquired and tested in Kenya, but present varieties do not yield any better than older varieties. Sorghum varieties have reached a yield plateau in Kenya. Hybrid sorghum cultivars have been developed and released in various parts of the world. Hybrids between OPV lines that are genetically distant often gave the best hybrid vigour. Male sterile cytoplasms and nuclear fertility restorer genes are available in sorghum and are used to economically produce sorghum hybrids. The problem with sorghum hybrids previously developed in east Africa is they do not meet the local requirements of farmers in eastern Kenya. Participatory Rural Appraisal (PRA) approaches have been developed to incorporate farmer's preferences into variety development programmes. The research undertaken here attempted to identify farmer preferences, identify suitable parents and produce sorghum hybrids that were high yielding, stable over environments and met farmer requirement for yield.

7.2.1 The place of sorghum, production constraints and ideal plant and variety traits as perceived by farmers in semi-arid parts of Kenya

A study was conducted in chapter two, to assess farmer perceptions on the value of sorghum in a semi-arid farming system, production constraints and ideal variety characteristics at Kambu in eastern Kenya. Participatory rural appraisal methodologies were used to collect data from farmers and their semi-arid farming system. The findings were that women were dominant in agriculture of the farming system and education among farmers ranged from primary school to university level. Sorghum occupied the second position of biggest cropped land, had the lowest productivity, lowest market price and revenue compared to other crops. Thirteen crops were grown in the farming system and although the number grown varies with seasons and locations, sorghum was grown in the two seasons and in all the locations and was ranked number two in drought tolerance, after cowpea. Food, commerce, feed, nursing food and thatching were the most important uses of sorghum. In consumption for energy, sorghum was number two after maize. Production constraints were, seed, drought, lack of farm power, birds, termites, head worms, smut, chaffer grubs, stem borers, availability of storage chemicals, lack of diversity in sorghum products and marketing problems. Farmers preferred early maturity, high levels of tolerance to drought, and high nutrient content, good resistance to borers, smuts and bird damage. Farmers preferred high yield, large grain size and early maturity crop cultivars. Farmers could sacrifice some yield for a trait that was beneficial in the region, for example some yield to get an earlier maturity cultivar. The most popular sorghum cultivars among farmers were Kivila Kya Ivui", KARI Mtama-1 and Katengu. In a drought prone season, the preferred cultivars yielded one to one and a half tons per hectare and were grown in low plant population densities (30280 to 35 000 plants per hectare).

These findings have implication for future research; Sorghum's unique importance in the semi-arid farming system is a justification for further research on it for semi-arid parts of Kenya. Succeeding research aimed at adding value such as hybrid research (Chapter Six) for raising productivity of farming systems and alleviating the low yield constraint in the most preferred farmer cultivars. Indirectly, high yielding hybrids cannot be found without foundation research such as identification of parents for high yielding hybrids through genetic studies such as genetic distance and combining ability studies as reported in chapters three and four. This further fortifies the central position of genetic studies in addressing problems in farming systems.

Seed, drought, lack of farm power, birds, termites, head worms, smut, chaffer grubs and stem borers were important production constraints. Therefore, future research should aim to alleviate biotic and abiotic stresses with research such as the use of stress tolerant genotypes as reported in chapter five. Research to create comprehensive and wholesome screening environments would cut breeding time with fruitful results.

Non-biological constraints such lack of farm power, availability of storage chemicals, lack of diversity in sorghum products and marketing problems implied that future research should adopt a multidisciplinary and multi-industrial approach if farming constraints are to be "eliminated". Even within a discipline like plant breeding, diversified approaches must be adopted to find solution to the many and varied constraints. Breeders generally focus on yield. The finding that farmers can sacrifice some yield to accommodate another trait such as early maturity points to some delicate compromises that the breeder alone cannot make. The findings that among all the cultivars that have gone through the farming with rejection and retention of the most popular sorghum cultivars among farmers; Kivila Kya Ivui", KARI Mtama-1 and Katengu despite low yield potential (1 to 1.5 t ha^{-1}) and production at 30280 to 35 000 plant ha^{-1} against current recommendation of 66 000 plant ha^{-1}, should serve as lesson to breeders to respect farmers' perceptions. Any agricultural research that goes against this tide will not have any value and its finding will be a waste. This fact underscores the role of participatory plant breeding in future research. Ignorance of farmers' perceptions in future research may result in rejection of breeders' new technologies. From this experience, it is recommended that future research should be multi-sectored and have a component of participatory plant breeding. Future research should have diversity in disciplines, within disciplines and industries to have a visible impact. This research met many of these requirements and should have a great impact in addressing farmers' problems in the semi-arid farming systems in Kenya.

7.2.2 The use of genetic distance among sorghum populations to predict hybrid performance

A study was conducted in chapter three, to characterize parents and establish genetic relationships (distances) based on agronomic data between parent populations classified according to source of origin. From agronomic data on 68 R-lines, 53 A-lines and 27 pollen parents from five different sources that were tested over six environments in South Africa and Kenya, parents were characterized and genetic distance computed between 16 male and female population pairs.

There were significant differences among parents, test environments and parental populations (sources) and parental sexes (male steriles and male fertiles). Males were more variable than females. Male and female parents differed significantly in plant vigour, number of tillers, plant height, head exsertion, stem weight, head weight and days to 50% flowering. Male parent populations from different sources were similar in yield potential. Female parent populations of different sources also had similar yield. Female population sources did not exhibit differences in the two countries of testing. Males tended to yield higher in South Africa than in Kenya.

Relative genetic distances were determined between population combinations and the population combinations were ranked according to magnitude of genetic distance. There was a clear trend in both distance and relative heterosis. Zimbabwe males x Purdue females, Kenya males x Purdue females, Kansas males x Purdue females showed the greatest distance. Kenya males x Zimbabwe females, Zimbabwe males x Zimbabwe females had intermediate genetic distance and Texas males x Texas females, Texas males x Zimbabwe females had the least genetic distance between them. In high density, high potential environments, Zimbabwe parent population had the highest number of hybrids per male, while Purdue female population had the highest number of high yielding hybrids per female.

Correlation between population combinations' genetic distance in chapter three and head weight over environments in chapter six was significant ($p<0.05$). There was also significant ($p<0.05$) correlation between genetic distance and head weight in the LDLP environment. A frequency distribution of hybrids according to population source combinations genetic distance aggregated highest yielding hybrids in the population combinations' distances above the mean distance. Thus there is correspondence between findings in Chapter three where the high density high potential data was used and Chapter six where data from all trial was used. The population combinations: Texas males x Zimbabwe females, Texas males x Texas females, Texas males x Kansas females, Kansas males x Texas females, Kansas males x Zimbabwe females, Kenya males x Texas females, Zimbabwe males x Texas females or 7 out of the population combinations would have been eliminated without losing any of the top 40 highest yielding hybrids. Source combinations that were most distant genetically also produced the highest number of high yielding hybrids individually. Correlations among genetic distance of the combining population, relative heterosis, total GCA and total SCA components in the 40 hybrids with the highest head weight indicated that genetic distance estimated before hybridization and GCA of parents (component in the hybrids) were highly significantly ($p<0.01$) correlated. The genetic distance was uncorrelated with the total SCA component of the hybrids. Estimated relative heterosis was significantly correlated with head weight in the forty highest yielding hybrids. Relative heterosis was also significantly correlated with GCA. The actual SCA component in hybrids was significantly correlated with hybrids head weight as expected.

These findings have numerous implications for future research. The number of populations from which to draw parents from can be reduced by 50%. There is potential to rank combining parent populations by relative GCA component before hybridization. There is also potential to concentrate high GCA parents prior to selecting the ultimate parents for hybrid production, therefore, this research may have a far reaching impact in future breeding of new hybrid cultivars. The results in this research have implications on reduction of the hybrid breeding workload. Similarly it has great potential to reduce hybrid research budget and breeding time. One reason for low adoption of cultivars is prolonged time to cultivar release and losing farmers' attention. The findings herein may help reduce breeding time, in addition to retaining farmers interest in participatory plant breeding. Genetic distance was significantly correlated with head weights of low density, low potential populations. Single plant head weight potential in hybrids was correlated ($P<0.01$) with sensitivity to plant density, optimum plant density, yield at optimum plant density, total and average yield over a range of densities around optimum plant density. What is the link between population combination yield in LDLP and hybrid head weight singe plant potential? These questions require further research. It is recommended that genetic distance estimates be integrated in future research to increase precision of identifying superior hybrid parents. It is also recommended that the possibility of using genetic distance to identify stress tolerance be investigated in future research.

7.2.3 The role of combining ability estimates in the choice of parents for hybridization

From 41 male, 51 male sterile exotic parents and 27 local pollen parents, 722 hybrids were generated and subsequently tested for agronomic traits in four environments. The environments were low and high plant population density, and low and high moisture regimes. Deviations from the mean head weight of hybrids over the test environments were used to estimate female and male effects (GCAs) in those environments. The mean head weight of the hybrid and the male and female GCAs were used to estimate specific combining ability effects (SCA) of the hybrids. Male and female parents' differed significantly in GCA. Hybrids differed significantly in SCA. Combinations of parents having high GCA values generally gave high yielding hybrids. parents with intermediate GCAs tended to give moderately high yielding hybrids. Combinations of parents with low GCA gave low yielding hybrids. High SCA estimated generally resulted in high yielding, however, extremely high or extremely low SCAs did not result in very high yielding hybrids. General combining ability and SCA tended to be compensatory in hybrid performance, which could mean existence of an optimum balance between them. The regression coefficient of additive to non-additive genetic variance was roughly one and significant. Three female and five male parents were identified as being suitable for producing hybrids for multiple environments. Hybrids of parents that had positive GCA in all environments gave hybrids that were high yielding over the environments.

The significance of these findings is that the wide variation in GCA for yield would create a wide variation in hybrids when female and male parents are hybridized. Another implication is that variation in yield and other traits that are needed to address the many constraints in semi-arid farming systems can be created from the parents identified in this research. Therefore, future research will not be constrained by parental germplasm, at least in the short term. This view is supported by findings in Chapter Six that the best hybrid yielded 210% over the best Kenya OPV variety in low density, low potential environments. It is further fortified by the finding of Chapter Two that farmers in semi-arid parts of Kenya grow sorghum at low plant density and their region is low potential. Yields from low density, low potential environments were significantly correlated with low sensitivity to stress and high yield potential. Combinations of parents that have positive GCA in all environments are likely to impart high yield potential to hybrids in all environments, resulting in hybrids that give relatively dependable yield in all environments. Because such parents can be grown over a wide area, few parents would be required to produce seed for a large area resulting in good economies of scale. Parents with high GCA should be selected in conjunction with their hybrids so that the presence of SCA in the hybrids can be detected. Parents that combine the two gene actions should give higher yielding hybrids than OPV varieties due to exploitation of additive and non-additive gene actions.

The regression coefficient for additive to non-additive variance of one was a sign that hybrids were exploiting two gene actions with greater opportunity to break the previously impossible yield barrier attained by OPV varieties. Because of the delicate balance of SCA and GCA, it is recommended that GCA and SCA approach to parental selection be combined with the genetic distance approach to concentrate both additive and non-additive genes.

7.2.4 Population density and water stress tolerance in sorghum hybrids and open pollinated parental lines

Hybrids and parents differed significantly in head weight as a result of differential sensitivity to stress and single plant yield potential. Hybrids showed significantly less sensitivity to stress and significantly higher single plant yield potential than OPV lines. Single plant yield potential and yield in low density stands were significantly positively correlated with the highest yield, total and average yield over a range of densities in the study, and yield in the lowest and highest density conditions. Hybrids were more likely to provide high yielding genotypes for selection.

The significance of these results is that genotypes that were tolerant to stress and that have higher single plant yield potential could be selected to address the constraints of low yield potential identified in farmers model cultivars from the PRA area of study reported in Chapter Two. Hybrids were more tolerant to drought stress than OPV varieties because they could withstand this constraint and yield higher than OPV lines. Genotypes that are tolerant to stress will tolerate the drought stress identified and raise productivity in semi-arid parts of Kenya. The significant positive correlation between single plant yield potential and yield in low density stands with the highest yield, total and average yield over a range of densities in the study and yield in the lowest and highest density under crop conditions was indication that use of those two parameters can actually identify stress tolerant genotypes in future research. This is the impact of research under this section, to create a tool that could continually be used to alleviate constraints of semi-arid farming systems. Future research can use this too in the identification of stress tolerant genotypes. Selection of high population density tolerant genotypes is just but a stage in a selection process. Genotypic variation must continually be generated through research like genetic distance and combining ability then channelled through this stage for selection of stress tolerant genotypes. Participatory Research Appraisal (PRA) and hybrid testing stages are other selection stages. Future research must be organized this way to improve research efficiency while keeping research budget under control. This is the recommendation under this chapter.

7.2.5 Is there a place for sorghum hybrids in Kenya?

Seven hundred and twenty-two sorghum hybrids and 119 parents were tested in a triple square lattice design for agronomic performance in two densities x two moisture regime levels. Hybrids and OPV parents were compared in yield, heterosis, and the economic feasibility of hybrid technology was assessed. Hybrids and OPV parents differed significantly in head weight potential, head weight heterosis and all agronomic traits, except percentage of root lodging and number of leaves per plant. There was significant parental head weight x environment interaction. The highest yielding hybrid was 53% better than the best Kenyan OPV parent. The best hybrids had 210% yield superiority over the best Kenyan OPV variety in the low density, low potential environment. The yield superiority of the best hybrids over the best Kenya OPV varieties more than sufficiently covered hybrid cost. There is a place for sorghum hybrids in Kenya if a base for hybrid sorghum is established.

The significance of findings at this stage is that it was determined that there is variation for head weight and other agronomic traits as well as heterosis. These are indications that hybrids of high yield could be selected, and were actually selected, and genes that can address constraints to production are available. This is supported by the demonstration that the best hybrids could actually yield 210% better than the best Kenyan variety. Like many other stages in this research, it is a selection stage. Lines were sorted according to yield potential, heterosis in combination with other lines, agronomic superiority and economic feasibility of hybrids compared with OPV varieties. It may not have come out to light that the information generated could actually select lines into heterotic groups and into cytoplasmic reaction classes. The impact of this experiment is that it is the controls quality of research. It has feedback for research component areas that generated germplasm, that is, the genetic distance and combining ability stages of research. It is here that decision as to what must go for further quality assessment in the PRA must be made. Any defects in the germplasm used in generating hybrids must be detected here. A decision as to what can go for multiple environment testing must be made basing on results from this section. The impact to future research is that different research management activities can be created according to research being conducted to ease research and enhance efficient without making such activities routine.

7.2.6 **Conclusion and recommendation**

To conclude, this research identified constraints to sorghum production, farmers' preferred sorghum traits and model varieties on which hybrids can be based. Further, results demonstrated that parent populations containing parents to high yielding hybrids could be identified by genetic distance. High general combining ability in parents conferred high yield to hybrids and hybrids that had high specific combining ability were high yielding. The research demonstrated that genetic distance between combining male and female parent populations that produced the highest yielding hybrids and general combining ability component of the high yielding hybrids were significantly correlated. The cut-off point for populations giving high yield hybrids was seven out of sixteen populations (The seven lowest distance parents populations could be eliminated out of the sixteen population combinations used without losing any of the 40 highest yielding hybrids). Hybrid yield margin over OPV lines was sufficient to cover cost of hybrids with a surplus benefit. It was beneficial to grow hybrids instead of OPV lines. It was demonstrated that genotypes that are less sensitivity (more tolerant) to plant density stress are higher yielding than plant density stress sensitive genotypes and that in general hybrids are more tolerant of plant density stress than open pollinated varieties (OPVs). Hybrids were higher yielding and more tolerant of stress that OPVs. From the results, hybrids had substantial advantages over OPVs in yield and stress tolerance. Therefore Kenya should base sorghum production on hybrids. It is recommended that hybrids development should start with many male and female populations to maximise chances of high yielding hybrids. The parent populations should be narrowed to the most potent populations using genetic distance. To enhance accuracy of pinpointing parents, small population subsets should be used. General combining ability should then be used to identify the ultimate parents among the potent population. This way, breeders have been empowered to handle many more parents with a bigger chance of success than was possible before this research.

APPENDIX I

RELATIONSHIP BETWEEN THESIS OBJECTIVES, CHAPTER OBJECTIVES AND OUTPUTS

Table 7.1: Relationship between thesis objectives, chapter objectives and output (results)

Thesis level		**Chapter level**					
Thesis objective		**Chapter objectives**		**Activities**		**Results**	
1	To learn ideas and methods from literature and assess	1.1	to read available literature	1.1.1	literature acquisition from	1.1.1.1	Copies of journals,
	viability of proposed research	1.2	to analyze available literature	1.2.1	libraries and internet		books and book chapters
	(Chapter one was not a research objective)			1.1.2	Studying and analyzing literature of the literature	1.1.1.2	Knowledge, summaries and literature citation
		1.3	to compile a synthesis of the literature	1.1.3	Synthesis of the literature	1.1.3.1	A summarized literature write-up in chapter one
2	To identify farmers' requirements in sorghum cultivars and identify	2.1	to find out the position of sorghum in a multiple-cropping semi-arid farming system	2.1.1	to formulate a PRA discussion guide	2.1.1.1	a PRA discussion guide
	deficiencies in available cultivars			2.1.2	to mobilize farmers into a meeting to discuss their cultivars and requirements	2.1.2.1	a PRA meeting and discussion
	(Chapter two)			2.1.3	to record and analyze researcher /farmer discussion	2.1.3.1	PRA data analysis and results
		2.2	to identify strengths for expanding sorghum production	2.2.1	to formulate a survey questionnaire to survey and analyze survey on farmer strengths	2.2.1.1	a survey questionnaire and analysis
		2.3	to identify and prioritize sorghum	2.3.1	to examine farmers constraints	2.3.1.1	a prioritized list of

Thesis level		Chapter level					
Thesis objective		Chapter objectives		Activities		Results	
			production constraints in the system		and prioritize them in a discuss with farmers		sorghum production constraints
		2.4	to establish farmers sorghum variety models and quantify their agronomic traits	2.4.1	To discuss and rank farmers popular varieties	2.4.1.1	three most popular farmer varieties
				2.4.2	to survey, record and analyze agronomic traits of three most popular farmer varieties	2.4.2.1	Data on agronomic traits of most popular three farmer varieties
		2.5	to conceptualize practical sorghum breeding model for the farmer	2.5.1	Analyze farmer desired varieties and describe traits means and limits (S.E.D.)	2.5.1.1	A description of three most popular varieties
3	To characterize male and female parents and find out whether populations having the best parents could be identified without progeny test **(Chapter three)**	3.1	To explore variation in parents and infer variation in descendant hybrids	3.1.1	To test parents for yield and other traits in field trials and analyze the data for variation	3.1.1.1	Test data and results
		3.2	To estimate yield potential in parents and characterize them	3.2.1	test parents in yield traits and analyze data for potential	3.2.1.1	Report on the study
		3.3	To compute genetic distance between combining male and female populations sources	3.3.1	Finding appropriate literature, analysis of data for variances and computation of genetic distances	3.3.1.1	Literature, parental pair population distances
		3.4	To infer heterosis among expected hybrids and rank the population pairs according to expected heterosis in hybrids	3.4.1	Relate distances with performance and theory (literature)	3.4.1.1	Ranked list of population pairs
		3.5	To estimate yield range about	3.5.1	Relate hybrid performance to	3.5.1.1	Yield-good parent

Thesis level		**Chapter level**					
Thesis objective		**Chapter objectives**		**Activities**		**Results**	
			mean yield in good male and female parents		parental performance		relationship
4	To estimate genetic variance components of parents and explore feasibility of breeding hybrids that perform well over multiple environments **(Chapter four)**	4.1	to identify good OPV parents based on general and specific combining ability for yield	4.1.1	Yield trials in multiple simulated environments and computation of GCA and SCA	4.1.1.1	High GCA parents SCA hybrids
		4.2	to identify suitable parents for a satellite breeding programme	4.2.1	Computation of GCA and SCA over the environments	4.2.1.1	Positive GCA parents in all environments
		4.3	to identify high yielding and widely adapted hybrids for further testing	4.3.1	identification of consistently positive over environment GCA parents	4.3.1.1	consistently high yielding hybrids in all test environment
		4.4	to integrate GCA and SCA in selection of hybrid parents	4.4.1	Analyze how GCA and SCA affected performance	4.4.1.1	the optimum SCA and GCA balance in high performance hybrids in all environment
		4.5	to investigate whether there is a link between agronomic and homeostatic stability	4.5.1	Identify relationship between and SCA trends related GCA	4.5.1.1	hybrids performing highly in high potential and low potential environments
		4.6	to identify good germplasm source of hybrid parents	4.6.1	analyze performance of hybrids according to source of parents	4.6.1.1	ranking of source according to hybrids performance
5	To compare single cross hybrids and OPV varieties in yield performance **(Chapter five)**	5.1	To investigate heterotic response of sorghum hybrids	5.1.1	Crossing block, yield tests, recording hybrid and parental computation of heterosis	5.1.1.1	Report (part report in chapter 4)
		5.2	To compare hybrids with OPV sorghum varieties	5.2.1	Replicated yield trials comprised of test hybrids and their parents,	5.2.1.1	Test hybrids and parents performance data and

Thesis level		Chapter level					
Thesis objective		Chapter objectives		Activities		Results	
			in yield over environments		analysis of variance etc.		
		5.3	To appraise economical advantage of hybrids	5.3.1	Analysis and synthesis and discussion of trial data	5.3.1.1	Comparative test of Hybrids and OPV parents performance and
		5.4	To identify good hybrids for further testing	5.4.1	ANOVA, mean separation and ranking	5.4.1.1	part of chapter 4 results
6	To test hybrids and OPV parents for stress tolerance and identify tolerant hybrids for further testing **(Chapter six)**	6.1	Estimate single plant yield potential and sensitivity to plant density	6.1.1	Yield trials over multiple plant densities and regression analysis	6.1.1.1	Yield data according to plant densities
		6.2	Estimate optimum plant density, crop yield potential and mean yield over a range of densities	6.2.1	Computation following the yield/density relationships	6.2.1.1	Genotypic optimum plant densities
		6.3	Investigate if genotypic sensitivity to plant density is adaptive to high plant density	6.3.1	Regression analysis of the yield/ plant density trials	6.3.1.1	performance according to sensitivity
		6.4	Compare hybrids and OPV lines in sensitivity to plant density	6.4.1	regression analysis if hybrids and OPV lines	6.4.1.1	Trend on which are least sensitive
		6.5	Select density tolerant adapted genotypes (hybrids and OPV lines)	6.5.1	Ranking and t-test (SED)	6.5.1.1	Information of sensitivity Hybrids and OPV parents to density sensitivity

APPENDIX II

PRA GUIDE PART ONE: PARTICIPATORY IDENTIFICATION OF SSUES PATAINING TO SORGHUM IN GROUP DISCUSSIONS AND INTERVIEWS

A. Interview Details

1. Name of discussion leader-----------------------------

2. Name of discussion recorder---------------------------

3. Venue of PRA------------------Group-------------------

4. Date of discussion------------------------------------

5. Number of farmers in the group------------------------

B. Factors in farming

1. How many cropping seasons do you have in this area of Kambu? --

2. Which is the most promising of the seasons in crop production? --

3. Please list crops grown in each of the season (Table below)

	Season 1 crops	How many grow?		Season 2 crops	How many grow?
1			1		
2			2		
3			3		
4			4		
5			5		
6			6		
7			7		
8			8		
9			9		
10			10		
11			11		

4. In which of the season is most sorghum grown? ------------- --

5. What makes sorghum more suited to this season than the other season? Give reasons.

(a) --

(b) --

(c) --

(d) --

(e) --

6. How many are for reason (a) -------- How many are for reason (b) ------------- How many are for reason (c) --------------- How many are for reason (d) -------- How many are for reason (e) ---

7. How do you use sorghum in this area? (List)

	Uses of sorghum
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	
11	
12	
13	

8. What are the benefits of sorghum to human being in this area? (List them)

(a) --

(b) --

(c) --

(d) --

(e) --

9. How many are for benefit (a) -------- How many are for benefit (b) ------------ How many are for benefit (c) --------- How many are for benefit (d) -------- How many are for benefit (e) --

10. What are the benefits of sorghum to livestock in this area? (List them)

(a) --

(b) --

(c) --

(d) --

(e) --

11. How many are for benefit (a) -------- How many are for benefit (b) ------------ How many are for benefit (c) ---------- How many are for benefit (d) -------- How many are for benefit (e) --

12. In drought conditions, let us rank the order in which crops listed (No.7) would fail. (Use pairwise ranking)---------------
----

Crops season 1							

Crops season 2							

13. Is there need to improve sorghum grown in this area?--

How many think yes ----------- How many think No ----------

14. For those who think it should be improved, why? (List the reasons) (a) --- (b) ---(c) --- (d) --- (e) ---

15.For those who think it should be improved, how many support reason (a) -------- How many support reason (b)------------ How many support reason (c)---------- How many support reason (d)-------- How many support reason (e) -----

16.For those who feel it should not be improved, why? (List the reasons)(a) -------------------------------- (b) ----

--(c) ----

-- (d) ----------

-- (e) ---------------

----

17. For those who think it should not be improved, how many support reason (a) -------- How many support reason (b) ------------ How many support reason (c) --------------- How many support reason (d) -------- How many support reason (e) --

18. What aspects of sorghum crop should be improved? (List them)

	Name of Aspect	Increase/decrease?	To what level?
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			

19. What type of livestock do you keep in this area? (List in the table below)---

No.	Livestock Kept	How many Keep? (count hands)	Benefit to crop production
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			

20 What are the benefits of livestock to crop production in this area(List in the table above) ---------------------

---

SOCIO-ECONOMIC ACTIVITIES AND LIVELIHOOD

Besides food people need money to live a full life e.g. pay school fees, buy personal conveniences, travel, dress etc.

21. Please tell me ways in which you make money in this area.

(a) ---

(b) ---

(c) ---

(d) ---

(e) ---

22. How many of you make money through method (a) ------------ through method (b) --------------- through method (c) ----- through method (d) ---------- through method (e) -------

23. What are the sorghum products you sell?

Product (a) --------------------------------

Product (b) --------------------------------

Product (c) ------------------------------

Product (d) --------------------------------

24. What are the market outlets for your sorghum crop during the last two seasons? (List)

Outlet a. -----------------------------------

Outlet b. -----------------------------------

Outlet c. -----------------------------------

Outlet d. -----------------------------------

Outlet e. -----------------------------------

25. Please let us list all the prices you have ever received in each of the market outlets for the sorghum Products in the last two seasons

	Outlet (A) price	Outlet (B) price	Outlet (C) price	Outlet (D) price	Outlet (E) price
1					
2					
3					
4					
5					
6					
7					
8					
9					

26 How many of you think outlet (A) is most important? ---------

How many of you think outlet (B) is most important? -----------

How many think outlet (C) is most important? ------------------

How many feel outlet (D) is most important? -------------------

How many feel outlet (E) is most important? -------------------

27. You grow many varieties of sorghum; let us list the prices of different varieties sold regardless of market outlets in the last two seasons.

Variety Name	Long rains 2005		Short Rains 2004/5		Comments
	Minimum Price	Maximum Price	Minimum Price	Maximum Price	
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					

28. Rank the varieties according to market value. No. (1)-------

(2) --------- (3) --------- (4) ------- (5) --------

29.In which of the seasons do you receive a better price for sorghum? ---------------------- How many think long rains------

How many think Short rains -----------------------------------

30. Please list all factors that influence the price of your sorghum in the market (a)---

(b)---

(c)---

(d)---

(e)---

31.List ways of improving the price of your sorghum in the market (a)--

(b)---

(c)---

(d)---

(e)---

32.What would be ideal price for a unit weight of grain sorghum in the market, please suggest:

Suggestion 1-----------why? ---------------No. of farmers-------

Suggestion 2---------- why? ---------------No. of farmers-------

Suggestion 3--------- -why? ---------------No. of farmers-------

Suggestion 4---------- why? ---------------No. of farmers-------

33. What would be a fair price per unit of sorghum used as in the table below? (Participants indicate in cards)---------------

Use	Price
1 Certified Seed	
2 Farmer's preserved seed	
3 Consumption (grain sorghum	

34. Classification of sorghum growers by variety (Use table below)

	Sorghum variety	How many grow?	Why do you grow this variety?
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			

35. Which of these varieties is most preferred in the market?

(Use pairwise ranking matrix)

Variety Name									

36. Which of these varieties do you most prefer for your use?

(Use pairwise ranking matrix)

Variety Name									

37. Please give the characteristics of all the varieties grown?

(Use the table below)

Variety Name	Height	Earliness	Yield (grain)	Yield (stover)	Grain colour	Grain size

38. If you were given a variety with properties indicated in the table below, which would you, choose? Why? (Use the table below)

Trait	Level 1	No. of farmers	Level 2	No. of farmers	Level 3	No. of farmers
Height	Short		Medium		Tall	
Earliness	Early		Medium		Late	
Grain colour	White		Red		brown	
Grain size	Small		Medium		Large	
Yield (grain)	Low		medium		High	
Yield (stover)	Low		medium		High	

39. In your farming experience, what is the ideal for:

Height --No. of farmers--

Maturity-- No. of farmers ---

---Grain colour-- No. of farmers ---

----Grain size-- No. of farmers ---
-------Grain yield---
No. of farmers ---
----------Stover yield--
No. of farmers ---
----

40. Given the exhibits for the questions, which would you choose? (Use the plant exhibits provided)
Short-----------How many-------- why? ------------------------
Medium----------How many-------- why? ------------------------
Tall------------How many-------- why? ------------------------

41. Given the exhibits of the question, which would you choose in terms of grain colour?? (Use the grain exhibits provided)
Exhibit one ----------How many-------- why? -------------------
Exhibit two ----------How many-------- why? -------------------
Exhibit three --------How many-------- why? -------------------
Exhibit four ---------How many-------- why? -------------------
Exhibit five ---------How many-------- why? -------------------
Exhibit six ----------How many-------- why? -------------------

42. Given the exhibits of the question, which would you choose in terms of grain size? (Use the grain exhibits provided)
Exhibit one ----------How many-------- why? -------------------
Exhibit two ----------How many-------- why? -------------------
Exhibit three --------How many-------- why? -------------------
Exhibit four ---------How many-------- why? -------------------
Exhibit five ---------How many-------- why? -------------------
Exhibit six ----------How many-------- why? -------------------

Constraints to sorghum production, Processing, Utilization and Marketing

43. Please let us list all constraints to sorghum production in this area under the following groups

Constraints to crop production

1 Pre-planting to planting

2 Seedling to Harvesting

3 Post Harve

4 Cooking Problems

5. Consumption Problems

6. Marketing proble

44. Rank the sorghum constraints within each group according to seriousness (Use pairwise matrix ranking system)

45. putting all the constraints together, rank them in order of seriousness

CROP VARIETY DEVELOPMENT

46. In drought, what are the most frequently successful crops in this area? Please list them in order of success and give reasons. (Use table below)

Crop Rank	Reason	Remark

Crop Rank	Reason	Remark

ROLE OF SORGHUM IN THE COMMUNITY

47. What is the role of sorghum in the farming system of Kambu? --

48. What is the role of sorghum in the diet of Kambu people? --

49. What is the role of sorghum in feed/fodder of livestock in Kambu area? --

50. What is the role of sorghum in trade and commerce in Kambu? --

51. What are the market outlets of sorghum in Kambu? (Please list in order of importance)--

52. What would happen if sorghum production was greatly increased in the Kambu farming system? --

53. What would happen if sorghum was removed from the Kambu farming system? --

54. Please look at the sorghum plant provided and name the parts of the plant, to each part let us attach possible

uses to human and agriculture. (Use the table given below for the exercise)--
----

	Part	Uses	Remark
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			
16			

55. Please rank in order of importance for human use, the parts of a sorghum plant (Make pairwise ranking) ---------------
----
----

56. If you were to develop the best sorghum variety for this area, what parts would you enhance in your variety? -------
----

No.	Characteristic/Trait	Role in the plant

1		
2		
3		
4		
5		
6		
7		
8		
9		
10		
11		
12		
13		
14		
15		
16		
17		

Please list purposes of each part to the sorghum plant (Use the table above); what is the most important part to the plant? (Pairwise ranking) -- --

57. What is the most important part to both the plant and human being? -- --

58. Let us look at the characteristic in details (Jacob to prepare samples for each question, how many of you would want the head (panicle) to be:
Compact------------- Semi-compact ----------------loose-----
very loose--

59. How many of you would want the grain size to be: Small size ------------- medium size -------------- large size -------
very large size--

60. Why would you prefer this grain size?
Small ---
Medium ---
Large ---
Very large --

61. What colour would you want the grain to be? Completely white ------------ light brown ----------- dark brown---
-------------red --
----

62. How many of you would want the peduncle to be: Short ------
------ medium length -------------- long -----------very long ---

63. How many of you would want the peduncle to be: Goose-neck (curved) --------------------slightly curved-------- straight (non-goose neck) --

64. How many of you would want the plant to have: Few leaves (I) (6 to 9) ----------- (II) intermediate (10 to 13) -------------- (III) many (14 and more) --

65. Does number of leaves determine the total leaf size? --

66. How thick would you want the stem to be? (I) Slender ------------ (II) intermediate --------------- (III) Thick--

67. How many tillers would you want the plant to have? (I)Unniculm (zero tillers) ------- (II) two stems (one tiller) -------- (III) three stems (two tillers) ---------- IV) four stems---------- (V) (three tillers) --- ------ (VI) five stems (four tillers) ------------- (VII)six stems (five tillers) ---

68. How tall would you want the crop to be? (Plants of varying heights are produced to guide farmers)(I)Short (1 to 1.3 m) ----------- (II) medium height (1.4 to1.7m) ----------- (III) tall (1.8 m upwards) ---

69. How early maturing would you want the crop to be?(I)Very early (less than 90 days) ----------- (II) medium (90 to 100) ----------- (III) late (100-120)---

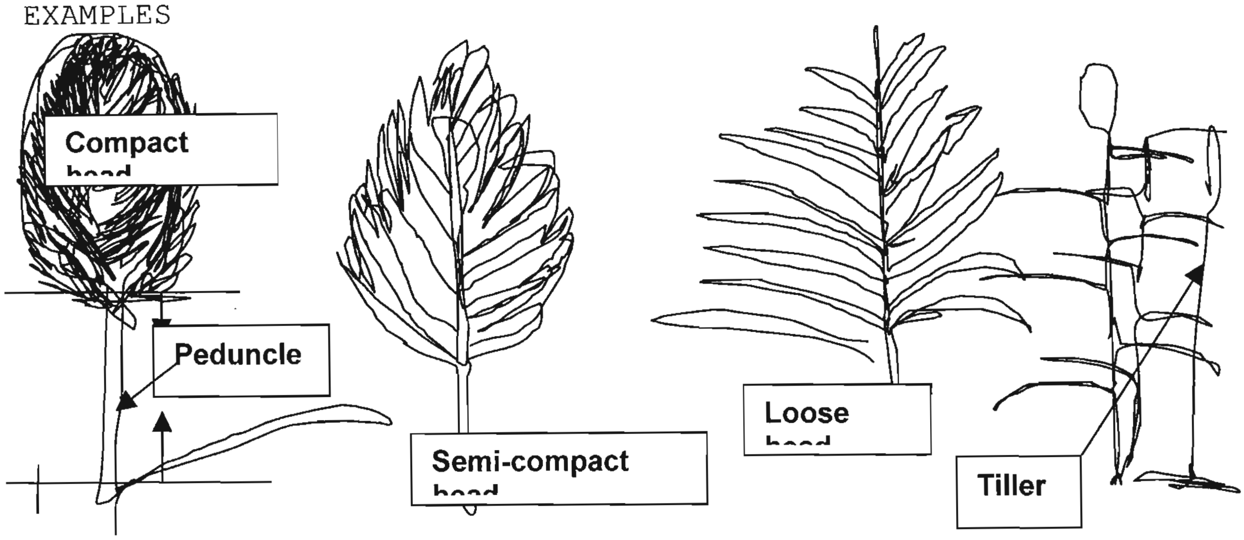
70. How deep rooted would you want the plants to be? (I)Deep rooted------------------- (II) moderately deep rooted ------------------ (III) shallow rooted --------------------------

Note: Peduncle is the stalk connecting the head with the rest of the plant, for further clarity, refer to the picture below.

71. Please let us rank the characteristics according to importance in your opinion. (Please perform pairwise ranking)--

Characteristics									

EXAMPLES



OTHER INFORMATION

ORGANIZATIONS AND INSTITUTIONS BASED IN KAMBU AREA

72. List organizations, government ministries and institutions that operate in Kambu and the problems they address in Kambu? (Use the table below)--------------------------------
----

	organization	Core activities	No. Participants	Cost sharing?
1				
2				

3				
4				
5				
6				
7				
8				
9				
10				
11				
12				

73. How many of you work with each of these organizations (non employees) --
----

74. How do they choose the people they work with? (State their criteria)---
----

----

75. What is your view on cost sharing? ------------------------
----

----

76. Which of the organizations would help expand sorghum production in this area? ------------------------------------
----
---77.How do organizations/ government ministries/government institutes affect you or your family? Please make a list

Organization	Effect on Community

Organization	Effect on Community

78. Do you believe farmers affiliated to organizations/ government ministries/government institutes are agriculturally more productive than non affiliate farmer? What is your feeling? -----------------------------------
----

----

79. Are affiliate farmers, the way they are because of the influence of the organizations or because the organizations choose farmer in that condition?---------------------------
----

----

80. How many feel because of the organization influence? ------
----

81. How many feel because of the organization choose the farmers the way they are? -------------------------------------

APPENDIX III

PART TWO OF PRA GUIDE: INDIVIDUAL FARMER PERCEPTIONS ON SORGHUM PRODUCTION, RESOURCE ENDOWMENT AND UTILIZATION ON IN KAMBU

INDIVIDUAL FARMERS INTERVIEWS AND DISCUSSIONS

HOUSEHOLD COMPOSITION

1. Name Mr. /Ms/Rev/Dr. /Prof. -----------------------------------

2. Gender (M/F) ---

3. Date of discussion-------------------Cluster --------------------

4. Level of education (Use table below) (Yrs) ---------------------

Please give the following information about members of your household (Table below)

Family member	Relationship	M or F Age (yr)s	Yrs of Education	Dependent(Y/N)	Independent(Y/N)
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					

3. Are you the one who makes decisions on the farm? (1)Yes------------- ------------------ (2) No-----------------------------------

4. Tell me about your residence particulars. Town --------------- Location -------------------- Sub location ------------------- Village ---

5. How many children are in your family? ---------------------

6. of the children, how many are dependent on you-------------

7. How many are independent of you ---------------------------

8. Of those dependent on you how many do you involve in farming? (1) Directly ----------- (1) indirectly -------

Crop Information

9. What sorghum varieties did you grow on your farm during the long and short rain seasons? (List them in the table below)

	Sorghum variety (Long rains season)	Sorghum variety (Short rains season)
1		
2		
3		
4		
5		

10. Why did you choose those varieties and not others? -------------

----

11. Which of these varieties do you like most? ---------------------

12. Name the attributes that make you like the variety more than the other varieties you grow.

Attribute (1) ---

Attribute (2) ---

Attribute (3) ---

Attribute (4) ---

13. Why did you choose to grow many varieties instead of only the variety you like most? (Provide reasons)

----

14. Please describe all the varieties you grow to me? (Use the table below)

Variety name	Height	Earliness	Yield (grain)	Yield (stover)	Grain colour	Grain size

15. Continue.

Variety name	Taste	flour color Flour quality	cooking quality

16. What products/foods do you make out of your sorghum? --------

----

----

17. Name your best variety---------------------------------

18. What is most striking about your best variety? ------------

----

19. Which of your varieties is most tolerant to drought? -------

----

20. Which of your varieties is most tolerant to diseases? ------

----

21. In your view, which tolerance do you consider more important? (1) Tolerance to disease--------------------- (2) tolerance to drought--------------------------------

22. Name the attributes you would like improved in your sorghum varieties---

---

Farm Information

What is the total size of your farm? (Use table below) -

Land owned	Cultivated area(acres)	Uncultivated area(acres)	Total land (acres)
Parcel 1			
Parcel 2			
Parcel 3			
Parcel 4			
Parcel 5			

23. How much of the land was under cultivation during the long rains and during the short rain seasons (Use the table below) (enumerator please measure if the farmer does not know)

24.

	Long rains season	Short rains season
Land owned	Area under crops	Area under crops
Parcel 1		
Parcel 2		
Parcel 3		
Parcel 4		
Parcel 5		

24. What sorghum varieties do you grow? (Give details for both short and long rain season in the table below)

25.

Varieties in the long Rains Season	Varieties in the long Rains Season

26. Please give details of sorghum production in your farm.

	Long Rains Season		Short Rains Season	
Variety	Area planted	Harvest (Kg)	Area planted	Harvest (Kg)

27. Give details of price by sorghum varieties

	Long Rains Season	Short Rains Season
Variety	Prices Received	Prices Received

27. For which varieties did you use improved seed? (Tick appropriate boxes)

	Long Rains Season		Short Rains Season	
Variety	Improved seed	Own seed	Improved seed	Own seed

28. How much of the total cultivated area was occupied by sorghum in the long and short rains seasons? (Use the table below)

29.

	Long rains season	Short rains season
Land owned	Area under sorghum	Area under sorghum
Parcel 1		
Parcel 2		
Parcel 3		
Parcel 4		
Parcel 5		

29. What quantity of sorghum was harvested during the long and short rains season respectively (Use the table below)

	Long rains season	Short rains season
Land owned	Total harvest of sorghum	Total harvest of sorghum
Parcel 1		
Parcel 2		
Parcel 3		
Parcel 4		
Parcel 5		

30. What was the market price of sorghum (1) during the short rains------------------ (2) during the short rains?-------- ----
----

31. In the long Rains season, what other crops did you grow and how much land did they occupy? What was the harvest? (Use the table below)

Crops grown	Area occupied by crop	Quantity harvested
1		
2		
3		
4		
5		
6		
7		

8		
9		
10		
11		
12		
13		
14		
15		

32. In the last Short Rains season, what crops did you grow and how much land did they occupy? How much was harvested? (Use the table below)

Crops grown	Area occupied by crop	Quantity harvested
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		
11		
12		
13		
14		

33. Do you fertilize your crops? Yes ------------No --------

34. How much of the sorghum land was fertilized during the long rains? --

35. How much of the sorghum land was fertilized during the short rains? --

36. What did you use to fertilize the sorghum crop in the long rains season? (1)Non----------(2) Boma manure------------(3) commercial fertilizer----------(4) compost manure -------------- (5) combinations--

37. Please state the type constituting the combination in the long rains season.---

38. What did you use to fertilize the sorghum crop in the short rains season? (1)Non----------(2) Boma manure------------(3) commercial fertilizer----------(4) compost manure -------------- (5) combinations (state the combinations)----------------------

Please state the type constituting the combination in the short rains season --

39. Did you spray your sorghum crop during the long rains season? Y/No? -------------- If yes, with which chemical? --

40. Did you spray your sorghum crop during the short rains season? Y/No? -------------- If yes, with which chemical? --

41. Do you practice any form of soil conservation? Y/No -------

42. What methods of soil conservation do you use? (1) Non ------------(2)Terraces--------------------(3)Trash lines -----------------(4)Tied ridges --------(5) Open furrows ----------------(6) Others (specify)------------------------------

43. How do you open up new land? (1)by oxen ----------(2) by tractor -----(3) by hand -----------------(4) by others methods --------

----

----

44. How do you plant your sorghum crop? (1)by oxen ---------- (2) by tractor ----(3) by hand ----------------(4) by others methods --

----

45. How do you plant? (1) by oxen ----------(2) by tractor -----(3) by hand ----------------(4) by others methods --------

46. How do you weed? (1)Oxen ---------- (2)tractor -----(3) Hand ----------(4) others ---------------------------------

47. Please provide the following information for a typical Long Rains season---

Crops grown	Output consumed	Output sold	Unit price	Remarks
1				
2				
3				
4				
5				
6				
7				
8				

9		
10		
11		
12		
13		

48. Provide the same information for a typical short Rains season---

----

Crops grown	Output consumed	Output sold	Unit price	Remarks
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				

49. Please provide the following information for a typical Long Rains season--

Crops grown	Area fertilized (acres)	Area not fertilized (acres)	Total Area (acres)	Reasons
1				
2				
3				
4				

5				
6				
7				
8				
9				
10				
11				
12				
13				
14				
15				

50. Please provide the same information for Short Rains season------
----

Crops grown	Area fertilized	Area not fertilized	Area (acres)	Reasons
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				
12				
13				
14				
15				

51. How many livestock do you own? (Use table below) ---------------

	Type of Livestock	How many owned (Number)	Remarks
1	Chicken		
2	Goats		
3	Sheep		
4	Cattle		
5	Oxen		
6	Donkeys		
7	Pigs		
8			
9			
10			
11			

52. How much manure do you get from the entire animal together in a season? (Please estimate in terms of oxen-carts, wheelbarrows etc)---

----

53. How many goats would give the same amount of manure as one cow?

----

54. How many sheep would give the same amount of manure as one cow?

----

55. How do you use the manure? (1) Sell the manure-----------------

(2)Apply to my crops--------(3) Both---------------------------

----

56. Do you sell your livestock to buy commercial fertilizer? (1) No------------------------------ (2) Yes -----------------------
----

57. What is the wage rate for casual work in this area? ------------
----
----

58. For what farm activities do you hire labour for? (List) --------
----
----

59. How many days do you hire labour in a season? -----------------
SR season ----------------------LR season ----------------------
----

60. How do you earn your livelihood in this community? ------------- (1)Farming within the community----------(2) Self employed within the community---------- (3) Non self employment within the community------------- (4) Employment outside the area e.g. government employee ----------(5) Other employment -------------
----

APPENDIX IV

ANALYSES OF VARIANCE TABLES FOR CHAPTERS TWO, THREE, FOUR AND SIX AND REGRESSION ANALYSIS FOR CHAPTER FIVE IN THE THESIS

Appendix IV table 1: Analysis of variance for location, seasons, crops grown and percentage of farmers growing each crop in the Kitengei and Nzambani areas (Chapter Two, Table 2.4)

Variable	Degrees of freedom	Wald/d.f.	Prob. of diff.
Locations	1	6.28	0.012
Crops	13	5.17	<0.001
Seasons	1	0.39	0.533
Locations x crops	12	2.60	0.002
Locations x seasons	1	2.28	0.131
Crops x seasons	13	11.07	< 0.001
Locations x crops x seasons	12	5.53	<0.001

< 0.05 means the difference is significant and applies in all tables

Appendix IV table 2: Analysis of variance in parental lines grown at Kiboko, Kenya, and University of Natal, South Africa (Chapter Three, Table 3.3)

Source of Variance	Degrees of Freedom	Mean squares	Prob. Level
Parents	119	2.32	0.005
Environment	5	183.47	<0.001
Country	1	6.01	0.998
Parent x environment	362	0.91	0.894
Parent x country	117	1.37	0.005
Source of parent	4	13.97	<0.001

Country x source	4	3.27	0.011
Environment x source	20	1.89	<0.001
Sex	1	26.48	<0.001
Country x sex	1	21.93	<0.001
Environment x sex	5	1.55	<0.001

Appendix IV table 3: Analysis of variance of parental head weight GCA, SCA, and yield in the study (Chapter Four, Table 4.4)

Source	df	Mean squares	Prob. of diff
Analysis of deviations from mean hybrid head weight			
Environments	3	0.78	All ns
Female parents (GCA)	43	12.47	**
Male parents (GCA)	63	3.83	**
Male parents (GCA)* Female parents(GCA)	581	2.67	**
Female parents (GCA)* Environments	129	1.79	**
Male parents(GCA) * Environments	189	1.31	**
Male parents (GCA)* Female parents(GCA) * Environment	1442	1.03	ns
Analysis of SCA for head weight			
Hybrids	709	1.61	**
Environments	3	22.86	**
Hybrids * Environments	1448	0.97	(0.161) NS
Analysis of yield (head weight)			
Hybrids	709	3.09	**
Environments	3	644.99	**
Hybrids * Environments	1448	1.05	ns
Parents * Environments	315	9.19	**

*, ** means the difference is significant at 0.05 and 0.01 respectively

Appendix IV table 4: Regressions of single plant head weight (gm^{-2}) on plant densities (plant m-^{2}) and plant densities on single plant head weights (Chapter Five, Table 5.3)

Group	Regression	d.f.	V:R	F pr.	% R-value	SED
Hybrids and parent	Single plant head wt on density	1431	7.75	**	61.8	56.9
Hybrids and parent	Plant density on Single plant head wt	1625	8.04	**	65.7	2.34

** indicates regression was significant at 0.05 level of probability

Appendix IV table 5: Analysis of variance of dry head weight of sorghum hybrids and parents as a group, and separately over the four environments used in the study (Chapter Six, Table 6.3)

Source of variation	Df	Wald/d.f.	Prob. of diff.
	Head weight		
Parents and hybrids	1	63.55	<0.001
Environments	3	212.22	<0.001
parents and hybrids * Environments	3	2.42	0.064
Hybrids	709	3.09	<0.001
Environments	3	644.99	<0.001
Hybrids * Environments	1448	1.05	0.111
Parents	117	1.89	<0.001
Environments	3	153.93	<0.001
Parents * Environments	318	1.19	0.010
	Percent hybrid heterosis over mid parent		
Hybrids	688	2.00	<0.001
Environments	3	0.31	0.822
Hybrids *Environments	1355	0.91	0.991