Combining Ability and Heterosis for Stem Sugar Traits and Grain Yield Components in Dual-Purpose Sorghum (*Sorghum bicolor* L. Moench) Germplasm

By

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Abstract

Sorghum is the fifth most important cereal crop in the world and ranks third in Africa, and it is potentially the number one cereal for the semi-arid environments in sub-Saharan Africa. Sorghum varieties have been developed specifically for grain, fodder or stem sugar but not for dual-purpose combining grain and stem sugar. Such varieties could be beneficial to the resource-poor farmers by providing grain for food and sugar rich stalks that can be sold for bioethanol production. However, there are no suitable dual-purpose cultivars on the market. There is also limited information about the combining ability, gene action and genetic effects and relationships between stem sugar and grain yield which is required in devising appropriate strategies for developing dual-purpose sorghum varieties. Furthermore, there is also lack of information about the perceptions of resource-poor, small-scale farmers and other important stakeholders on the potential of dual-purpose sorghum production and the value chain. Therefore, the objectives of this study were to: (i) investigate the awareness of the farmers, industry and other stakeholders on the dual-purpose sorghum varietal development and its feasibility, (ii) screen germplasm for use as source materials useful for grain yield and stem sugar traits, (iii) investigate the inheritance and heterosis levels attainable in grain yield components and stem sugar traits in dual-purpose sorghums, (iv) determine the relationships between stem sugar traits and grain yield components in dual-purpose sorghums, and (v) investigate the fertility restoration capacities of selected male-fertile lines used as male parents through the evaluating seed set in experimental dual-purpose hybrids.

Two surveys were conducted to establish stakeholders' level of awareness and perceptions on the potential and feasibility of developing and utilising dual-purpose sorghums in Southern Africa. One survey was carried out in the semi-arid tropical lowlands in Zimbabwe under the conditions of small-scale and resource-poor farmers while the other, which targeted sugar industries, plant breeders, engineers, political leaders, economists and extension workers, was conducted in South Africa and Zimbabwe. Data were analysed using SPSS computer package. Results showed that both farmers and the non-farmer stakeholders were in agreement on the view that dual-purpose sorghum would be a viable enterprise that could alleviate poverty, enhance food security, create rural employment and boost rural development in southern African countries. Farmers were willing to adopt the cultivars if they were made available. The stakeholders also suggested mechanisms to overcome the infrastructural, economic and technical challenges associated with the technology.

Screening of regional and international germplasm collection held at the University of KwaZulu-Natal in South Africa revealed high genetic variability for grain yield, stem brix and stem biomass yield that can be exploited in dual-purpose sorghum cultivar development. Ten lines were selected for inclusion as parents in the dual-purpose sorghum breeding programme. The selections were crossed to eight cytoplasmic male-sterile lines originating from the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) in accordance with a North Carolina Design II mating scheme. The 18 parents, together with the 80 experimental hybrids generated and two check varieties were evaluated for grain yield and stem sugar traits in six tropical low- and mid-altitude environments in Mozambique, South Africa and Zimbabwe. Stem sugar concentration and stem biomass were measured at the hard dough stage of each entry due to maturity differences between the genotypes. Grain yield was measured and adjusted to 12.5% moisture content. Data were analysed in GenStat computer package following a fixed effects model. Both additive and non-additive gene effects were important in controlling stem brix, stem biomass, grain yield and the associated traits in dual-purpose sorghum. This showed that breeding progress can be achieved through hybridisation and selection. Cultivars showing high stability, and high standard and better-parent heterosis for the three traits were identified implying that breeding for general adaptation was an option and that productivity could be enhanced by breeding hybrid cultivars.

The relationships between traits were estimated using correlation and path-coefficients analysis. Grain yield was found to be negatively and significantly associated with stem brix but was positively and significantly associated with stem biomass. This implied that breeding for high stem brix might compromise grain yield but selection for high stem biomass improved grain yield. Stem biomass and stem brix were not significantly correlated. The general negative relationship between grain and stem brix was attributed to the predominance of entries with contrasting performances for the two traits. However, the relationship between grain yield and stem brix of the top 20 performing entries showed a non-significant relationship between stem brix and grain yield suggesting that the traits were independent of each other. This finding was confirmed by the presence of crosses that combined high performance for both stem brix and grain yield as well as stem biomass among the hybrids. The relationships between stem brix and stem biomass for the top 20 performers remained non-significant while that between stem biomass and grain yield became stronger, positive and significant. Direct selection for stem brix and grain yield was shown to be more important than indirect selection, while selection for stem biomass improves grain yield but had no effect on stem brix. Therefore, it is possible to breed dual-purpose sorghum cultivars and the identification of genotypes combining the desirable traits is prudent in addition to general relationships information.

The study on fertility restoration capacities as evaluated through hybrid seed set showed that fertility restoration was under the control of genes with both additive and non-additive action. Since restoration is conferred by a single dominant gene (Rf_1), this could have arisen from the action of the modifier genes that have been previously reported to influence it. This showed that fertility restoration can be improved through breeding. Hybrid combinations showing complete seed set and high performance for grain, stem brix and stem biomass were identified and are potential dual-purpose sorghum cultivars. Overall, the study showed that development of dual-purpose sorghum cultivars would be feasible and genotypes identified as potential cultivars in this study will be forwarded for further testing across many sites and seasons in the target environments.

Declaration

I, Itai Makanda, declare that

1. The research reported in this thesis, except where otherwise indicated, is my original research.
2. This thesis has not been submitted for any degree or examination at any other university.
3. This thesis does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.
4. This thesis does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:
    a. Their words have been re-written but the general information attributed to them has been referenced
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5. This thesis does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the thesis and in the references sections.

Signed

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Itai Makanda

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

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Prof. Pangirayi Tongoona (Supervisor)

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Dr. John Derera (Co-Supervisor)

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Dedication

Kurangarira vakatungamira, vasina kumirira kuti vandisusukidze mberi, asi kusiri kuda kwavo.

1. Vabereki vangu Henry Chemerayi Makanda naSarah Tsirizani-Makanda.
2. Vasekuru Chari “Chimusoro” Makanda nambuya Norah Zvinorukwa Makanda.
3. Vasekuru Peter Tsirizani nambuya Gladys Tsirizani
4. Vanonditarisa pakufamba, ndinotenda.

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Introduction to thesis

Rationale for sorghum improvement

Sorghum (*Sorghum bicolour* L. Moench) total production ranks fifth among the important cereal crops worldwide and is second after maize in Africa (Chantereau and Nicou, 1994). In the sub-Saharan Africa, it is arguably the most important cereal. Most of the sorghums planted, especially in Africa, are grain sorghum cultivars. The world produces about 63,375,602t of sorghum grain from 46,928,023ha of which 26,065,312t comes from Africa (from 29,499,987ha) and 156,796t comes from southern Africa from an area of 219,090ha (FAO, 2009). Apart from grain, sorghum can be used for sugar production using the sweet stem types that accumulate fermentable sugars (≥8%) in their stems. These sweet sorghums provide an avenue for transforming sorghum into an industrial crop due to their potential use in bioenergy production. Stem sugar can be used for bioethanol production and the grain for food. This provides rural households with dietary energy as well as the much needed income for other requirements such as education and health from the small pieces of land from which they subsist. However, no effort has been made to combine grain yield and stem sugar in a single cultivar to produce a dual-purpose sorghum variety in southern Africa regardless of the presence of such varieties reported in other regions (FAO, 2002; Reddy *et al*., 2005). The potential for both grain yield, stem sugar accumulation and stem biomass yields in dual-purpose sorghum cultivars for the region is not known. This is evidenced by the non-availability of the dual-purpose sorghum cultivars on the market. Generating information on the behaviour of the traits after combination is important for a dual-purpose sorghum breeding programme. An ideal dual-purpose sorghum should achieve acceptable grain yields, stem brix and stem biomass. Although there are no set values of these traits, minimum grain yield of 1.5t ha^{-1}, stem brix of 11ºbrix and stem biomass of 30t ha^{-1} can be arbitrarily set to achieve about 3000l $ha^{-1}$and food security. Assuming a farmer plants two hectares, 3t of grain and 6000l of ethanol can be produced based on studies by Woods (2000) and Tsuchihashi and Goto (2004).

The potential for generating bioethanol from sweet sorghum has not been quantified in most countries and environments in southern Africa. However, stem sugar values of between 10% and 25% (10ºbrix and 25ºbrix) have been reported in the literature (Woods, 2000; Reddy *et al*., 2005; Tsuchihashi and Goto, 2004, 2008). Stem sugar can be processed into jaggery or distilled to produce ethanol (FAO, 2002). Bioethanol yield of 3000l to 7000l ha^{-1} have been reported from biomass levels of between 30t to 120t ha^{-1} in Zimbabwe (Woods, 2001); Romania (Roman *et al*., 1998); Italy (Dolciotti *et al*., 1998); United States of America (Anderson, 2005); China (FAO, 2002); and various European union countries (Claassen *et al*., 2004). Mean grain yield potentials of between 1.0t and 6.5t ha^{-1} have been reported with improved grain sorghums in Zambia, Zimbabwe and Botswana (Obilana *et al*., 1997). However, most African farmers use unimproved cultivars with productivity of less than 1.0t ha^{-1}.

The potential of dual-purpose sorghum in rural economy

The potential use of sweet sorghum for bioethanol production has been demonstrated in southern Africa by Woods (2001) working in Zimbabwe. Sweet sorghum can be successfully incorporated into the sugarcane processing system. Countries in southern Africa, for example Malawi, Mozambique, South Africa, Swaziland, Zambia and Zimbabwe, which have viable sugar industries based on sugarcane (*Saccharum officinarum* L.), the major sugar producing crop, can benefit from dual-purpose sorghums. These countries can exploit the sugar mills by using sweet sorghum stalks thereby maximising output. The dual-purpose sorghums thus complement sugarcane. Sweet sorghum is widely adapted; can be grown under dryland conditions where sugarcane cannot grow and have rapid growth (Reddy and Sanjana, 2003). Further, sorghum can be ratooned thereby obtaining more than one biomass harvest from a single planting, although research has shown diminishing yields and increased disease pressure from a ratooned crop. Overall, provision of dual-purpose sorghums can lead to sustainable rural development, enhanced renewable energy production, higher health standards through cleaner fuels, and improved food security (Woods, 2001). Farmers in most parts of southern Africa already grow sorghum, for example, in Musikavanhu, a dryland communal area in Zimbabwe. Chivasa *et al*. (2001) reported that sorghum was grown by 94% of the farmers in the area and occupied 82% of the land. Derera *et al*. (2006) reported similar findings in the same area.

On the food security aspect, many world bodies express reservations on the use of bioenergy crops due to potential competition for land with food crops, thereby pushing food prices beyond the reach of many. This necessitated the search for alternative non-food security crops for bioenergy production. Guiying *et al.* (2000) reported that sorghum cultivars with high stem sugar and high grain yield were required for China. This creates the niche for dual-purpose sorghum where farmers can harvest the grain for food and sell the stalks for sugar extraction, reaping twice from the same crop and same piece of land. According to the FAO (Gnansounou *et al.*, 2005) dual-purpose sorghums can give a yearly gross margin of US$1300 ha^{-1} compared to only US US$1054 ha^{-1} for grain sorghum reported by Hagos *et al.* (2009). With specialised sweet sorghum, farmers can earn between US$40 to US$97 ha^{-1} more than for grain sorghum (PSciJourn, 2010). Thus, dual-purpose sorghum development would not only increase income for the household, but improve food security as well. The challenge that may arise is the development of appropriate technologies and markets for the stems. However, with the projected future fossil fuel shortages and the increasing global call for cleaner environments, adoption of sweet sorghum as a raw material for the production of alternative fuel is inevitable. This will potentially increase the demand for sweet stem sorghum, making the enterprise viable.

In Zimbabwe, the cost of producing a litre of bioethanol from sweet sorghum was reported at US$0.19 compared to the then global prices of ethanol of US$0.30 to $0.35 a litre (Woods, 2000). Roman *et al*. (1998) reported 2000-3000TOE (tones of oil equivalence) per hectare of sweet sorghum and 6-9TOE of fuel from bagasse. Up to 9000l ha^{-1} of ethanol has been reported in China (FAO, 2002) and Greece (Sakellariou-Makrantonakai *et al*., 2007). Woods (2000) reported the production of 12.6GJ electricity (3.5MWhe at 15% conversion efficiency) from 46t ha^{-1} of fresh stem weight was achieved using sweet sorghum cultivars identified in Zimbabwe. High grain yield potential of 2.0t to 6.0t ha^{-1} has been reported for sweet sorghum (FAO, 2002; Reddy *et al*., 2005). The ethanol yields of up to 7000l ha^{-1} combining with grain yield of up to 6.0t ha^{-1} can potentially make the bioethanol industry, using sweet sorghum, viable at the same time contributing towards food security and social sustainability (Zhao *et al*., 2009). Therefore, introducing dual-purpose sorghum is likely to impact positively on both food security and rural development.

Exploitation of the off-season production

Successful production of dual-purpose sorghum might entail expansion of production to include off-season production in tropical lowlands that have optimum temperatures and water supply throughout the year. These areas include the Zambezi basins covering parts of Zimbabwe, Mozambique, Zambia and Malawi, Makhathini flats in South Africa and Chokwe in Mozambique. Off-season production in Chokwe and Makhathini flats was demonstrated to give optimum grain yield, stem biomass and stem sugar percentage with dual-purpose sorghum experimental hybrids. Off-season production for grain was reported to significantly contribute to food security in Somalia (Food Security Assessment Unit, 1998) and India (Patil, 2007), while all year round production of sweet sorghum was demonstrated in Indonesia (Tsuchihashi and Goto, 2008). There is potential to use the off-season in addition to the traditionally used in-season production environments for dual purpose sorghum. The limitation is the non-availability of appropriate dual-purpose sorghum cultivars for this purpose and cultivar development is viewed as key strategy. Therefore, it is important to generate the information required towards the devising of an appropriate strategy to develop dual-purpose sorghum cultivars that are also adapted to the off-season production environments.

The need for appropriate breeding source germplasm

Cultivar development relies on the presence of genetic variability for the traits under consideration. This makes it imperative to evaluate germplasm collections for grain yield potential, stem sugar accumulation and stem biomass potential to select the appropriate parents for the breeding programme. The next step is to understand the gene action controlling the traits of interest. This information can be obtained by conducting combining ability studies that entails systematic crossing of the selected parents using appropriate mating designs and subsequent hybrid evaluation. Information on general combining ability (GCA) and specific combining ability (SCA) effects is critical in cultivar development, either through selection or inbreeding then cross breeding (Goyal and Kurmar, 1991; Cruz and Regazzi, 1994; Kenga *et al*., 2004). Variation due to GCA is attributed to additive genes, and that due to SCA is attributed to non-additive gene action. Lack of this information limits research under African dry-land sorghum growing conditions (Kenga *et al*., 2004). For dual-purpose sorghums, knowledge of the inheritance of the major traits, grain yield, stem sugar content and stem biomass, is important. Although a lot of work has been done on the inheritance of these traits separately, no work has been reported on the traits combined in dual-purpose sorghums. In the long run, the development of parental lines (base population) with high performance in stem sugar, grain yield potential and stem biomass is key to the dual-purpose sorghum cultivar breeding programme. These can be used as parents in hybrid cultivar development programmes or as pure line varieties where high performance is demonstrated.

Is southern Africa ready for sorghum hybrids?

The promotion of hybrid cultivars is one way of enhancing productivity in southern Africa without expanding the area under production. There is already a high pressure on pressure, in Malawi and Zimbabwe for example, with serious political consequences. Hybrid cultivars have been shown to be more productive than pure line varieties in sorghum (Li and Li, 1998). Many researchers are now advocating for hybrid sorghum deployment in Africa. Haussmann *et al*. (1999) concluded that hybrids could boost sorghum production in Kenya. Hybrids can also bring the private sector into the sorghum industry, which can result in the supply of high quality seed and agronomic support services for the farmers. Farmers in southern Africa, especially Zimbabwe and South Africa, have been purchasing maize hybrid seed for years and are familiar with the benefits of hybrid cultivars. These farmers are likely to adopt hybrid sorghum cultivars easily, given the economic benefits of dual-purpose sorghums. The Malawi, Zambia and Mozambique governments also have seed and other agronomic input distribution programmes called the Input Voucher systems that can be exploited to promote sorghum hybrids production (Mangisoni *et al.*, 2007). Given the foregoing, it is most likely that hybrid sorghum deployment in the region, especially with an added industrial trait such as stem sugar, can increase sorghum production. It is, therefore, necessary to evaluate the levels of heterosis attainable and stability of the traits. However, effective hybrid development programmes in sorghum are dependent on the identification of heterotic fertility restorer (male) and cytoplasmic male-sterile (female) lines. Production of grain on the hybrids is important in dual-purpose cultivars. There is need to evaluate hybrid fertility from crosses using male-sterile parents because hybrid fertility restoration has been shown to be influenced by the genetic background and the environment in which the restorer genes are operating (Sleper and Poehlman, 2006).

Rationale for studying the inheritance of grain yield and stem sugar in dual-purpose sorghum

Knowledge of the mode of inheritance of the dual-purpose sorghum traits, mainly grain yield, stem sugar and stem biomass, would be useful for developing a viable breeding programme. A survey of the literature did not identify any source of such information. However, in studies involving sweet stem sorghum, genes with partial dominance, additive effects, and both major and minor effects were reported to control stem sugar in sorghum with trait heritability estimates ranging between 40% and 96% (Schlehuber, 1945; Baocheng *et al*., 1986). Many studies reported significant GCA and SCA effects for grain yield in sorghum with heritability estimates ranging between 10% and 86% (Haussmann *et al*., 1999; Kenga *et al*., 2004; Bello *et al*., 2007). This information suggests that the two traits are controlled by genes with both additive and non-additive effects and can, therefore, be improved through hybridisation and selection. However, the behaviour of the genes in dual-purpose sorghum cultivars when grain yield and stem sugar are combined in one cultivar is not known. This information is important in formulating a breeding strategy. For example, if it is found that the behaviour of the genes in dual-purpose cultivars is the same as in the specialised grain and sweet sorghums, then hybridisation and selection can be used in cultivar development. The development and use of parents with high GCA and identification of heterotic crosses showing high SCA effects is expected to maximise breeding gain. However, unless this information is generated, it is difficult to formulate such breeding strategies, hence it is crucial to study the gene action for the traits in dual-purpose sorghum cultivars.

Is high grain yield mutually exclusive of high stem sugar and high stem biomass?

Development of dual-purpose sorghum cultivars entails the combination of high grain yield potential, high stem sugar accumulation and high stem biomass potential in one cultivar. This activity is based on the understanding of the relationships between the traits to devise appropriate selection criteria. There are no conclusive reports regarding the relationships between grain yield components and stem sugar traits in the literature surveyed on specialised cultivars. No reports were found on dual-purpose sorghum. This information is crucial in developing dual-purpose sorghum cultivars and its generation is viewed as an important activity. Guiying *et al.* (2000) reported a general negative relationship between stem brix and weight of 1000 seed in sorghum. It can be argued that 1000 seed weight alone does not give a clear picture of the relationship because it is not representative of grain yield per plant or per unit area. In other studies, Ferraris and Charles-Edwards (1986) found stem sugar concentration to increase as a function of growth duration. Although they reported low grain yields in their cultivars, they also found remobilization of stem sugars to the grain to be negligible. Although the high stem sugar after seed initiation and the resultant low yields may seem to suggest a negative association between stem sugar content and grain yield, the negligible remobilisation of stem sugar to grain after grain initiation suggests otherwise. It is important to conduct detailed studies on the relationship because it influences the selection strategy during cultivar development. Correlation and path coefficient studies have been shown to establish trait relationships in crops (Ofori, 1996; Makanda *et al*., 2009).

Rationale for stakeholders involvement and situational studies in dual-purpose sorghum cultivar development

Southern Africa is dominated by small-scale and resource-poor farmers living in the semi-arid low and mid-altitude environments, producing about 80% of the total sorghum crop. These areas account for about 35% of the cereal mega environments (Vivek *et al*., 2005). Until recently, breeding has been conducted by researchers without involving the farmers and usually at research stations which are not necessarily representative of the conditions in the small-holder or resource-poor farmers' conditions. This meant a complete marginalisation of the farmers from setting of the research agenda to the formulation of the solutions. This approach has been demonstrated not to be effective due to the uniqueness of the small-scale and resource-poor farmers' situations. Many researchers have reported on the negative consequences of not including farmers in setting up research and policy agenda (Derera *et al*., 2006). This led to breeders shifting from the traditional approaches of scientist-centred research agenda to the inclusion of the farmers in problem identification and research agenda formulation (Dixon *et al.,* 2001). Understanding the farmers is an initial step towards the search for an effective and sustainable way to make agricultural research more relevant to them (Kudadjie *et al.,* 2004).

Although cases in dual-purpose sorghum were not found in the literature, cases of different preferences between farmers and researchers are well documented in specialised sorghum cultivars. In Ethiopia, farmers selected only three varieties from the eight that researchers considered the best (Mulatu and Belete, 2001). In the same study, the farmers also proved wrong the notion that existed among researchers that they were not willing to grow short season varieties. In Malawi, the use of farmer participation in cultivar evaluation has resulted in the selection of high yielding sorghum landraces in farmers fields (Nkongolo *et al*., 2008). In both cases, the cultivars were well received by the farmers. This demonstrates the breeding success that can be realised if farmers' views and preferences are taken into consideration during cultivar development.

Situational studies are very important as a first step in new cultivar development. They generate information about the farmer and their socio-economic conditions that impact on cultivar adoption. Important information should be established about the levels of knowledge, age, labour, land holding, resource availability, constraints to production, possible competing cropping enterprises and access to produce markets. If not clearly identified, the factors can impact negatively on the dual-purpose sorghum adoption and production. In situations where the farmers and other stakeholders are not familiar with the technology, as is the case with dual-purpose sorghum cultivars in the lowland areas of Zimbabwe, interacting and discussing with the farmers also helps to create awareness. This information can be gathered using participatory research techniques used to gather information prior to, during and after technology deployment (Matata *et al*., 2001). These techniques give farmers an avenue for participation in decision-making, especially on the type of cultivars they prefer in the case of dual-purpose sorghums. This increases cultivar adoption rates as was the case in Ethiopia and Malawi. The situational studies can also help to explain the anticipated adoption pattern, which aid future breeding projects for the farmers. Given the foregoing, it is prudent to include all stakeholders, from farmers to industrial end users, in dual-purpose sorghum cultivars development if acceptable cultivars are to be bred and adequate production is to be sustained to boost the rural economies.

Research objectives

Given the foregoing, this study aimed at:

i. Appraising the farmer situation to obtain information on factors that might impact on dual-purpose cultivar production;

ii. Soliciting farmers and non-farmer stakeholders' views and perceptions on dual-purpose sorghum and the feasibility of their utilisation;

iii. Screening sorghum germplasm for grain yield potential and stem sugar traits;

iv. Investigating the gene action involved in the inheritance of grain yield potential and stem sugar in dual-purpose sorghum cultivars in selected tropical low and mid-altitude environments in Mozambique, South Africa and Zimbabwe;

v. Determining the levels of heterosis and cultivar stability for grain yield components and stem sugar traits in dual-purpose sorghum cultivars in selected tropical low and mid-altitude environments in Mozambique, South Africa and Zimbabwe;

vi. Investigating the relationship between grain yield potential and stem sugar traits in dual-purpose sorghum cultivars across selected tropical low and mid-altitude environments in Mozambique, South Africa and Zimbabwe; and

vii. Determining fertility restoration capabilities of introduced and regional sorghum germplasm used as male parents in hybrids formed from crosses with male sterile female lines from ICRISAT in selected southern African environments.

Research hypotheses

The research tested the following hypotheses:

i. Farmers and non-farmer stakeholders' are aware of the dual-purpose sorghum cultivars and their potential benefits;

ii. There is high genetic diversity for grain yield potential and stem sugar traits among the germplasm collection held at the African Centre for Crop Improvement in South Africa;

iii. Grain yield potential and stem sugar traits in dual-purpose sorghum are controlled by genes that act predominantly in an additive manner;

iv. There are high levels of heterosis for grain yield and stem sugar traits that can be exploited to increase mean performance for the traits in dual-purpose sorghum hybrid cultivars;

v. Grain yield potential and stem sugar traits are independent of each other in dual-purpose sorghum cultivars; and

vi. Introduced and regional sorghum germplasm used as male in hybrid combination with male-sterile lines have the capacity to restore hybrid fertility in selected tropical low- and mid-altitude ecologies in South Africa.

Structure of the thesis

This thesis consists of eight distinct chapters in accordance with a number of activities related to the afore-mentioned objectives. Some overlap and repetition may exist between the chapters as they were written as independent journal papers containing all the necessary information, some of which might have been presented in other chapters. Some of the papers have already been published or accepted for publication and they are indicated in the thesis.

Chapter	Title
-	Introduction to thesis
1	A review of the literature
2	An appraisal of the factors impacting on crop productivity of small-scale farmers in the semi-arid environments in Zimbabwe and their implication for crop improvement goals and policy interventions
3	Development of sorghum for bio-energy: a view from stakeholders in Zimbabwe and South Africa
4	Variability for grain yield components and stem sugar traits for the development of dual-purpose sorghum cultivars for grain and bioenergy
5	Heterosis, combining ability and cultivar superiority of sorghum germplasm for stem-sugar traits across six environments
6	Combining ability, heterosis and cultivar superiority of sorghum germplasm for grain yield traits across tropical low and mid altitude environments
7	Relationship between grain yield components and stem sugar traits in dual-purpose sorghum germplasm
8	Fertility restoration capacities of southern African and introduced sorghum lines as measured by hybrid seed set across tropical low- and mid-altitude environments
9	An overview of the research findings

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CHAPTER 1

A Review of the Literature

1.1 Introduction

This chapter reviews the literature on topics that are important in the development of dual-purpose sorghum cultivars. It starts by introducing the crop, followed by reviews on the development of dual-purpose sorghums focusing on grain yield and stem sugar content. The inheritance of the crucial traits such as grain yield and stem sugar and methods used to evaluate stem sugar concentration are also emphasised in the review. The next section reviews breeding for high yield potential focusing on hybrid cultivar development and the use of the male sterility systems. Heterosis in sorghum follows with emphasis on its basis and its mechanisms with examples cited in the literature. The interaction between genotype and environment in sorghum is also reviewed. The need to consult stakeholders and the importance of situational studies as a way of gathering information on factors that may impact on cultivar acceptance and adoption of new cultivars is also reviewed.

1.2 Sorghum

Sorghum is a self-pollinating cereal crop thought to have originated in north-eastern Africa around Ethiopia, Sudan and East Africa (Dogget, 1988, de Wet and Harlan, 1971; Kimber, 2000; Acquaah, 2007). Some researchers argue for multiple centres of origin for the crop (Snowden, 1936; de Wet and Huckabay, 1967). Its distribution around the world is attributed to movement of people and its diversity to disruptive selection in different habitats, especially in northeast Africa. For example, it is argued that as *S. bicolor* moved west, it crossed with the wild *S. arundinaceum* giving rise to the type known as the durra sorghum (Kimber, 2000). There are four wild (*S. bicolor* subspecies *verticilliflorum*) and five cultivated (*S. bicolor* subspecies *bicolor*) races in sorghum differentiated by head type, grain size, yield potential, and adaptation, among other traits (Acquaah, 2007). The cultivated races are bicolor, guinea, kafir, caudatum and durra (Kimber, 2000; Acquaah, 2007). In commercial breeding programmes, there are established working groups in cultivated sorghums, namely kafir, milo, margaritiferum, feterita, hegari, shalu, kaoliang and zera-zera (Menz *et al*., 2004; Acquaah, 2007). Some intermediate races resulting from inter-mating are also recognised. The significance of the working groups is in differences in adaptation, yield potential and their implications to crop improvement. Researchers argue that the races are the best basis for grouping sorghum into heterotic groups for hybrid programmes (Menz *et al*., 2004) although breeders use other methods (Acquaah, 2007). This will be discussed in a later section in detail under hybrid sorghum development.

1.3 Development of dual-purpose sorghum cultivars

1.3.1 Grain yield in sorghum

1.3.1.1 The genetic variability and potential for grain yield in sorghum

Genetic variability in yield components is important for yield improvement programmes in sorghum (Warkad *et al.*, 2008). Abdi *et al*. (2002) reported that sorghum farmers in north-eastern coastal regions of Africa prefer the durra (compact head) types due to its high grain yield and quality. Head type is chiefly determined by the rachis and branch lengths, distance separating the whorls, and the angle of the branches from the rachis (Dogget, 1988). There are semi compact elliptic, compact elliptic, semi loose primary branches, very loose primary branches, very loose drooping primary branches, and half broomcorn head types in sorghum (Dogget, 1988; Abdi *et al*., 2002) all of which bring variation for grain yield potential. Therefore, head architecture is correlated with grain yield potential. The guinea sorghums have been described as lowland sorghums and are generally low yielding compared to the durra types adapted to the high rainfall highlands (Dogget, 1988). Warkad *et al.* (2008) reported variation in the grain yield and its components namely days to maturity, days to 50% flowering, plant height, number of leaves, head length and width, weight of 1000 seeds, and dry fodder weight. The authors used both phenotypic coefficient of variation (PCV) and genotypic coefficient of variation (GCV) to study variability. It has been demonstrated that genetic variation for yield is available, which can be exploited for breeding high yielding cultivars. Many African countries have a rich collection of sorghum germplasm. Such collections are important because the more diverse the genetic base, the more distant the lines developed and consequently the higher the hybrid vigour that can be realised and maintained on crossing (Li and Li, 1998). In this regard, quantification of this variation is important if it is to be exploited in breeding programmes.

1.3.1.2 Inheritance of grain yield and its components in sorghum

In self-pollinating crops, advances in grain yield have been made through selection alone. Whereas selection followed by hybridisation was confined to cross pollinating crops like maize. In recent developments, hybridisation has been successfully used to develop hybrid cultivars in self-pollinating crops like rice and sorghum (Li and Li, 1998; Kenga *et al*., 2004). This has enabled the exploitation of both gene additivity and non-additivity with the computation of combining abilities and heritabilities becoming more important in sorghum breeding. Kenga *et al*. (2004) reported significant variation due to GCA and SCA effects in sorghum for grain yield, days to anthesis, plant height, threshing percentage, and seed weight. Liang and Walter (1968) and Haussmann *et al.* (1999) reported similar results. The significance of these findings is that additive and non-additive gene action is important for these traits. Furthermore, Kenga *et al*. (2004) reported variance due to SCAs to be higher than that due to GCAs for grain yield but Haussmann *et al*. (1999) reported the predominance of additive gene action for grain yield.

Further, Warkad *et al.* (2008) reported high heritability in the broad sense (H^2) and expected genetic advance over mean values for grain yield, dry fodder yield, stem diameter, and head length and width implying that gene additivity played a major role in these traits. Selection is therefore important for improving these traits. In the same study, days to maturity and number of leaves per plant had high H^2 but lower expected genetic gain over the mean, implying the predominance of non-additive gene action. Thus hybridisation was important in increasing performance. Different heritability values for yield and its components reported for sorghum in literature are summarised in Table 1.3-1. The differences in the H^2 estimates from different studies can be attributed to the use of different sets of germplasm and environments. For example, grain yield H^2 ranged from 0.10 to 0.86 in different studies with a mean of 0.65. The same trend can be seen for 1000 seed weight (Table 1.3-1). This demonstrates that both the H^2 and inheritance information cannot be generally applied to all sorghum germplasm and environments, hence the need to conduct separate studies in the target environments using the required germplasm.

The importance of both GCA and SCA effects and the moderate to high heritability estimates for grain yield suggests that grain yield can be improved through both selection and hybridisation. Selecting heterotic parents that are good general and specific combiners is thus key to yield improvement in sorghum. However, the studies were conducted on specialised grain cultivars, not dual-purpose sorghums combining grain and stem sugar traits. It is therefore important to study the gene action controlling the traits in dual-purpose sorghums to aid cultivar development.

Table 1.3-1: Estimates of heritability in the broad sense (H^2) for grain yield and its components in sorghum

Trait	[β]**Warkad *et al.* (2008)**	[α]**Bello *et al.* (2007)**	[†]**Biswas *et al.* (2001)**	[‡]**Lothrop *et al.* (1985)**	[∞]**Haussmann *et al.* (1999)**	
					Lines	Hybrids
Grain yield	0.86	0.10	0.52	0.81	0.79	0.84
Days to flowering	0.91	0.95	-	-	0.93	0.88
Days to maturity	0.91	0.99	-	-	-	-
Dry fodder weight	0.92	0.71	-	-	0.75	0.74
Stem width	0.94	-	-	-	-	-
1000 grain weight	0.49	0.24	0.67	0.78	0.96	0.91
Plant height	-	0.93	0.41	-	0.97	0.97
No. of leaves/plant	0.52	0.95	-	-	-	-
Panicles/plant	-	-	0.59	0.69	-	-
Panicle length	-	0.96	0.91	-	-	-
Panicle width	-	0.58	-	-	-	-
Seeds/panicle	-	-	-	0.78	-	-

β - experiment conducted in Kharif, India in 2006; α - experiment conducted in Yoal and Mubi, Nigeria in 2001; † - experiment conducted in Dinajpur, Bangladesh in 1998; ‡ - experiment conducted at Ames and Castana, Iowa, USA in1978-80; ∞ - experiment conducted in eight environments in Kenya in1992-3

1.3.2 Stem sugar in sorghum

1.3.2.1 Genetics of stem sugar and biomass in sweet sorghum

Many reports have been made on the inheritance of stem sugar in sorghum. Earlier reports suggested partial dominance with Schlehuber (1945) reporting hybrids intermediate between the two parents in total solids and sucrose. Later on, a single gene "X" was reported to control sugar accumulation (Baocheng *et al*., 1986). New evidence suggests sugar accumulation to be under the control of recessive genes acting in an additive manner with broad sense heritability (H^2) estimates of 0.65 to 0.81 in different populations (Guiying *et al*., 2000), results that are consistent with Schlehuber (1945). From part of this study, GCA and SCA effects were found to be important for stem brix in sorghum (Makanda *et al*., 2009). Baocheng *et al*. (1986) reported GCA effects to be more important (10-26 times) than SCA effects and narrow sense heritabilities (h^2) of between 0.40 and 0.96. Overall, this further provided evidence for a quantitative inheritance of stem sugar in sorghum. Crosses between sweet and non-sweet sorghums provided transgressive segregants in the F_2 for stem sugar content in sweet sorghum (Guiying *et al.*, 2000). Crosses between low sugar types resulted in negative heterosis for stem sugar accumulation, giving evidence for gene additivity for low sugar (Guiying *et al.*, 2000). In recent QTL analyses no significant segregation for genes with major effects on sugar percentage were found (Natoli *et al*., 2002) but Ritter *et al*. (2008) reported QTL alleles from some entries to increasing sucrose content, sugar content and ^{o}brix. The moderate heritability estimates, significant GCA and SCA effects and reports of QTL controlling stem sugar suggest that the trait can be improved through traditional breeding. However, plant biomass is known to be controlled by four dwarfing genes, Dw_1, Dw_2, Dw_3 *and* Dw_4, with tall being incompletely dominant to short (Rooney, 2000). The height differences are brought about through the control of internode length with plants with zero dwarfing genes ($Dw_1Dw_2Dw_3Dw_4$) growing up to 4.00m while those with the four recessive dwarfing genes ($dw_1dw_2dw_3dw_4$) are less than 0.50m (Rooney, 2000; Acquaah, 2007). Single ($Dw_1Dw_2Dw_3dw_4$), double ($Dw_1Dw_2dw_3dw_4$) and triple ($Dw_1dw_2dw_3dw_4$) recessive dwarfs average around 1.20-2.07m, 0.82-1.26m, and 0.52-0.61m, respectively (Rooney, 2000; Acquaah, 2007). Some interaction effects have also been reported to influence plant biomass accumulation in photosensitive cultivars with Rooney and Aydin (1999) reporting duplicate recessive epistasis for plant height. However, the applicability of these findings on dual-purpose sorghum needs investigation because these reports were based on specialised sweet sorghums. Plant height is positively associated with plant biomass and breeding tall dual-purpose cultivars translates to high biomass yields per unit area which increases stem sugar yields.

1.3.2.2 Structural and temporal sugar distribution in sweet sorghum stalks

Stem sugar variations in sweet sorghum have been reported along and across the stem as well as in time during the plant's growth cycle. Rose and Botha (2000) reported a sharp gradient in sugar increases between internode three and six in sorghum stems and slower increase between internode six and nine. This seems to imply that sucrose content of the core bottom tissue is lower compared to the upper tissues along the stem. This can be because the bottom tissue is concerned with non-sucrose storing metabolism, that is, metabolic processes involving respiration and growth hence more assimilates are committed and transported to the younger actively growing upper tissue (Rose and Botha, 2000).

Across the stem, the bark contains less sugars (glucose and sucrose) compared to the inner pith (Billa *et al.*, 1997). As a percentage of dry weight, Billa *et al.* (1997) reported the bark to contain 32.2% sucrose and 2.4% glucose whereas the pith contained 67.4% and 3.7%, respectively. However, the bark had more lignin, cellulose and hemicelluloses compared to the pith. Ferraris and Charles-Edwards (1986) found stem sugar concentration to be a function of growth duration. They reported higher sugar concentration in one of their cultivars after grain initiation, particularly sucrose concentration. However, they reported low grain yields in other cultivars although remobilization of stem sugars to the grain was negligible. Zhao *et al*. (2009) reported ethanol production from stalk sugars to increase with increases in time after anthesis. This demonstrated an increase in stem sugars during the grain-filling period, implying that photo-assimilate translocation to the developing grain at the expense of the stems was absent. This suggests that dual-purpose sorghum cultivars that have the potential for both high grain yield and stem sugar can be developed.

In developing dual-purpose sorghums, remobilisation of photo-assimilates from the stem to the grain is not desirable because the ideal cultivar must retain high stem sugar and grain yield. The possible complication that can arise is that lack of remobilisation might result in lower grain yield. The fore mentioned studies showed that it is possible to identify genotypes with negligible remobilisation of photo-assimilates from the stem to the grain. Therefore, in dual-purpose cultivar development, it is necessary to screen materials to identify genotypes that combine both negligible or non-remobilisation of stem photo-assimilates and high grain yield. These can be used as parental or source germplasm in a breeding programme for dual-purpose sorghums.

Overall, it has been shown that there is variation in sugars along the sweet sorghum stem and therefore, in the absence of whole stem crushers, taking sugar measurement at different points along the stem gives a better representation of the sugar performance compared to taking single measurements. The temporal variation necessitates the need for sampling sorghum stalks at the correct time during the growth cycle, and in dual-purpose sorghum, the sampling time must be the hard dough stage of the grain because it is a major component.

1.3.2.3 Screening for stem sugar accumulation potential in sorghum

There are many techniques used to quantify soluble sugars in plant tissues. These methodologies, which are well developed, are described by many researchers including Chow and Landhäusser (2004) and Reed *et al.* (2004). Most of these techniques follow common steps of drying plant samples, grinding it into powder, and then homogenising a sub-sample of the powder in a carbohydrate solvent (Hendrix, 1993) then using various chemicals and steps to determine the amount of sugars in plants. The commonly used quantification methods when high levels of specificity and discrimination between the sugars is required include the high performance liquid chromatography (HPLC), calorimetry using anthrone reagent (Chow and Landhäusser, 2004; Reed *et al.*, 2004), gas chromatography (GC), liquid chromatography (LC), and the enzyme methods based on NADPH absorption (Chow and Landhäusser, 2004). Each of these has its advantages and disadvantages ranging from cost, hazardous chemicals, low throughput, reagent stabilities, digestion of target compounds and others. The disadvantages common to all the methods are the low throughput, the need for sophisticated equipment, lack of adaptation to field conditions where the screening takes place and being expensive.

Researchers are now advocating for more specific, time saving, and less hazardous methods (Hendrix, 1993). With large samples to be screened in the field, the refractometer is the most widely used instrument for stem sugar quantification. It measures the sugars in degrees brix (°brix), which is a quantification of soluble sugar-to-water mass ratio of fluid (Wikipedia, 2009). For example, if a 100g solution is 15°Bx, it means that 15 grams of the 100g is made up of the sugars. This scale is used to approximate the amount of sugars in many plant juice extracts for example from fruits, vegetables, sugarcane and sweet sorghum or in beverages like wine and soft drinks (Wikipedia, 2009). The refractometer offers a cheap, time saving, and less hazardous method with high throughput. It can be used for screening a lager sample in the field. This method was adopted in this study. Recent improvements have seen the development of portable simple and easy to use digital refractometers with automatic temperature compensation (ATC) ranging from 0.0 to 50°C. This is the type used in this study (Figure 1.3-1). The refractometer has the disadvantage of inability to sample the whole stalk juice reading in the field as it depends on sectional cuttings. This can be addressed by measuring brix readings at different points along the length of the stalks so as to sample variation along the stem.

Figure 1.3-1: The Atago PAL-1 digital hand-held pocket refractometer used to screen sorghum entries for stem sugar accumulation in the study

1.4 Breeding sorghum for high yield potential

Sorghum breeding history is not as long and successful as that of other grain cereals such as maize, wheat, rice and barley. However, the past years have seen significant advances with the advent of hybrid seed production as a result of the discovery and use of the male sterility system.

Using hybrid sorghum, India has achieved an 80% yield increase in sorghum in the last 20 years on a 37% background decline in area under the crop (Kenga *et al*., 2004). The authors also reported that in the same period, Africa's area under sorghum had nearly doubled but yields have not increased. Apart from genetic research, the success story of Indian sorghum has been attributed to hybrid use (Kenga *et al*., 2004). Elsewhere in China, production of hybrid varieties has become predominant in sorghum breeding programmes, although traditional population improvement procedures are still in use (Li and Li, 1998). About 90% of China's sorghum growing land is under hybrid sorghum cultivars (Li and Li, 1998). The authors reported that hybrid production has led to several fold yield increases in China. Haussmann *et al*. (1999) concluded that hybrid production had the potential to increase yield in semi-arid areas of Kenya.

1.4.1 Cytoplasmic-genetic male sterility and cultivar development in sorghum

Commercial hybrid cultivar development in sorghum is difficult due to the self-pollinating nature of the crop. Hybridisation has been achieved through many techniques including hand emasculation, anther dehiscence control, gametocides, hot water emasculation and male sterility (Rooney and Smith, 2000). Of these techniques, commercial hybrid production has been successfully done using the male sterility system. Male sterility is based on some genetic and cytoplasmic intrinsic systems that result in the production of plants that have non-viable male gametes (male-sterile) (Schertz, 1973) believed to have arisen due to compatibility problems between nuclear and mitochondrial genes (Hanson, 1991). It was identified as a result of the interaction between the sorghum race kafir nuclear genes with the cytoplasm of race milo, which was observed to result in male sterile sorghums (Stephens and Holland, 1954). Use of male sterility was first reported and proposed in 1937 and used about 20 years later (Stephens and Holland, 1954). Male sterility can be conferred by recessive nuclear genes where the phenomenon is referred to as genetic male sterility (gms) or cytoplasmic factors with a genetic basis in which case the phenomenon is cytoplasmic-genetic male sterility (cms) (Rooney, 2000; Schertz, 1994; Sleper and Poehlman, 2006). The later is the most useful system in sorghum breeding.

Genes responsible for this phenomenon were described by Maunder and Picket (1959) and Erichsen and Ross (1963) and were designated ms_1 and ms_2, respectively. Sterility in milo cytoplasm is conferred by the homozygous recessive conditions at any one of the two loci, that is, either ms_1ms_1 or ms_2ms_2. Fertility restoration is fully conferred by a dominant gene Rf_1 identified by Brengman (1995) and the relationship between Rf_1 and Ms_1 is not fully understood to date. However, the fertility restoration in hybrids was reported to vary depending on modifier gene Pf_1 and Pf_2 described by Miller and Picket (1964) and Sleper and Poehlman (2006) which act in an additive and also with both inter-allelic and intra-allelic epistatic interaction manner (Rooney, 2000). This explains the observations of complete fertility restoration by R-lines on some A-lines but partial restoration on others (Andrews *et al*., 1997). Although this presents a seemingly simple phenomenon, the variations in fertility restoration in sorghum are evidence to the complexity of the inheritance of the trait.

Four groups of male sterile cytoplasms have been identified in the cms system in sorghum (Schertz, 1973; Hanna, 1989). These were designated A1, A2, A3, and A4 based on hybrid fertility after crossing to lines containing the fertility restorer gene (Sane *et al*., 1996). The male sterile (A) lines lack the Rf_1-gene in their nucleus which restores fertility and the fertile cytoplasm. It is identical genetically to its maintainer, the B-line, that has a fertile cytoplasm hence produce pollen. The A-line and B-line are genetically identical, the only difference is that the A-line has a male sterility inducing cytoplasm whereas the B-line has a male fertile cytoplasm and the two lines are said to be “iso-cytoplasmic" (Rooney and Smith, 2000). The male-fertile B-line is used to maintain the seed of the male-sterile A-line because the male parent does not transmit its cytoplasm to the progeny. The resulting offspring from the cross between an A-line and a B-line is a male-sterile A-line. The male-fertile B- and R-lines are maintained by self-pollination in isolated plots or through the use of paper bagging to avoid cross pollination. The only role of the B-line in the breeding programme is to perpetuate the A-line. The R-line is the male parent in commercial hybrid seed production. It is genetically different from the iso-cytoplasmic A- and B-lines and it carries the dominant fertility restorer Rf_1 gene necessary in the restoration of male-fertility in its hybrids with the A-lines (Acquaah, 2007). The Rf_1-gene’s presence in the nucleus results in male fertility whether the cytoplasm is male sterility-inducing or not. In selecting the male parent (R-line), Sleper and Poehlman (2006) and Acquaah (2007) gave three factors that must be put into considerations; (i) the line must be a good combiner with the male-sterile female (A-line); (ii) the line must be heterotic to the A-line to give high-yielding hybrids; and (iii) the line must contain the dominant restorer Rf_1 gene and be able to restore complete fertility and give seed in the F_1 hybrid if seed is the trait of importance.

Table 1.4-1 summarises the various possibilities resulting from using pollen sources with and without the Rf_1-gene. This usually arises when materials of unconfirmed restoration capacities are used as male parents with A-lines, for example, when landraces are to be used to evaluate heterosis with improved A-lines.

Table 1.4-1: Possible situations arising from using male parents whose restoring ability is not confirmed

	Male fertile male		Male sterile female		Hybrid		Hybrid fertility status
	Genotype	Cytoplasm	Genotype	Cytoplasm	Genotype	Cytoplasm	
1	Rf_1Rf_1	F	msc_1msc_1 *or* ms_2ms_2	S	Rf_1-	S	All male fertile
2	Rf_1Rf_1	S	msc_1msc_1 *or* ms_2ms_2	S	Rf_1-	S	All male fertile
3	Rf_1rf_1	F	msc_1msc_1 *or* ms_2ms_2	S	½ Rf_1- :½ *rf1rf1*	S	½ male fertile: ½ male sterile
4	Rf_1rf_1	S	msc_1msc_1 *or* ms_2ms_2	S	½ Rf_1- :½ rf_1rf1	S	½ male fertile: ½ male sterile
5	rf_1rf_1	F	msc_1msc_1 *or* ms_2ms_2	S	rf_1rf1	S	All male sterile

Where Rf_1 = male restorer gene; rf_1 = the non restorer recessive to Rf_1; F = the fertile cytoplasm; and S = the sterile cytoplasm

The cms system is useful to produce almost the entire commercial sorghum hybrid seeds in the world. Within the cms system, the A1 system is the most commonly used out of the four because the other three systems (i) lack 100% sterility in unfavourable environments, (ii) give lower yields, and (iii) exhibit other adverse traits (Andrews *et al*., 1997; Sleper and Poehlman, 2006). Under unfavourable conditions, fertility levels in the A1 system can be enhanced by additional modifier genes present in some parental genotypes (Miller and Picket, 1964).

1.4.2 Commercial hybrid sorghum development using the A1 cms system

Commercial hybrids production requires the development of parental lines referred to as inbred or pure lines with high *per se* performance and combining ability (Andrews *et al*., 1997; Rooney and Smith, 2000). In the initial stages of the hybridisation programmes, superior commercial pure lines and advanced breeding lines are identified and selected for use as commercial pure line varieties or as parental lines (Sleper and Poehlman, 2006). Currently, parental lines are developed specifically for the purpose of hybrid seed production. These can be developed in three ways; (i) inter-crossing among B-lines and R-lines then select superior segregants; (ii) using the backcross procedure to add superior genes to an already established parental line; (iii) recurrent selection programmes of improving quantitative traits, and (iv) from hybridisation using the pedigree breeding method (Andrews *et al*., 1997; Sleper and Poehlman, 2006). The specific approaches vary but they are basically based on self-pollination (Rooney and Smith, 2000; Acquaah, 2007). The developed female parental lines have cms incorporated into them using the backcrossing method (Sleper and Poehlman, 2006) with the developed lines being the recurrent parent and the cms line the donor parent.

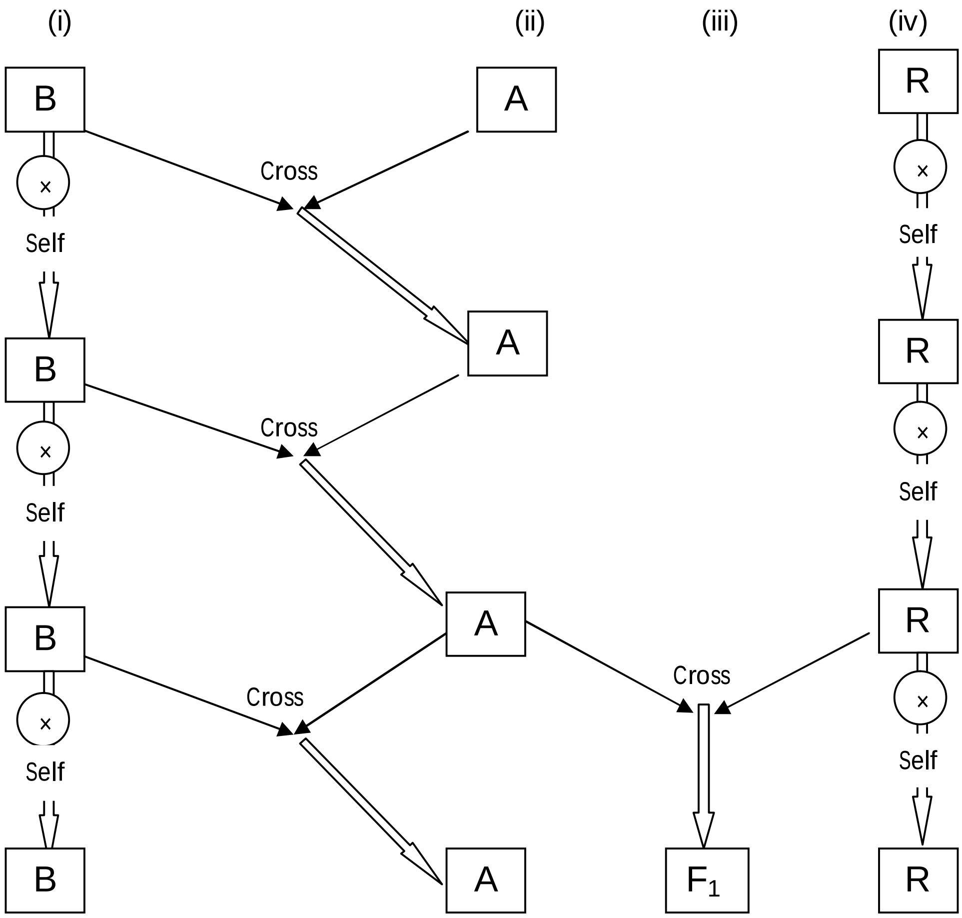

Figure 1.4-1: Maintenance of (i) the maintainer (male-fertile) B-line , (ii) its iso-cytoplasmic male-sterile A-line and (iii) F_1 hybrid seed production scheme and (iv) the male fertility restoring R-line maintenance in a sorghum breeding programme

Commercial hybrid seed is then produced by the A-, B- and R-lines as shown in Figure 1.4-1. At the commercialisation stage, environments that ensure quality seed production are selected and used for F_1 hybrid seed production purposes. The first cross between the iso-cytoplasmic A and B lines serves to increase seed of the female parent, the A-line. Seed harvested from these crosses are male-sterile, perpetuating the A-line. This seed is planted in a commercial set-up with between 12 and 18 rows of A-lines inter-planted with two rows of the R-lines (Rooney and Smith, 2000). However, this male to female ratio varies with company and with the environment in which seed production is conducted. Pollen from the R-line contains restorer genes making the seed harvested from the A-lines male fertile. This seed is the commercial hybrid seed. The male R-lines may be harvested first or cut down prior to harvesting and off-types are rouged out from the A-line female parents of the hybrid seed to avoid contamination. Seed from the A-lines is then harvested, cleaned, treated, bagged, and sold to farmers as the hybrid seed for grain production (Rooney and Smith, 2000).

1.5 Heterosis in sorghum

1.5.1 The basis of heterosis in sorghum

Heterosis has been studied and explained from both a genetic and physiological point in sorghum (Blum *et al.*, 1990). Genetic variability is key to hybrid sorghum development programmes. It determines genetic gain from selection and the grouping of the materials into heterotic groups, the basis of any hybrid cultivar development programme (Menz *et al.*, 2004). Attempts to group sorghum into heterotic groups have so far been inconclusive (Gilbert, 1994) and breeding programmes use the A/B and the R lines as the heterotic groups. The female lines in the A/B groups must be heterotic to the R group for a successful hybrid programme and one group is used as a tester for the other during line development (Acquaah, 2007). Following a cluster analysis, Menz *et al*. (2004) reported that diversity was mainly due to sorghum working groups, that is, Kafir, Feterita, Zera-zera, Kafir-Milo, Durra, Caudatum, Margaritiferum, and Guinea. Based on this study, Menz *et al*. (2004) concluded that sorghum heterotic groups are better determined by working groups and were of the opinion that interracial crossings dilute potential heterotic patterns. Earlier reports supported this notion (Ahnert *et al.*, 1996). In this regard, actual heterosis studies may need to be conducted to conclusively determine whether the diversity based on working groups or even races are the basis of heterosis in sorghum. Although the explanation of heterosis is based on theories, with the actual genetic mechanisms yet to be understood, crosses between genetically diverse genotypes have been demonstrated to give high heterosis in plants (Hallauer, 1999). From these studies, it can be concluded that heterosis in sorghum might be realised from crosses between different working groups.

However, the limitation to commercialising sorghum hybrid cultivars based on working group heterosis is the presently used male sterility system. The currently used A1 system is basically based on two races, the Kaffir and Milo. This means that all the R-lines have to be heterotic to these working groups, which reduces the heterotic grouping to two, that is, the males (R group) which must all be heterotic to the male-sterile lines based on the Kaffir/Milo group (A/B group). Therefore, at present, unless other effective large scale male sterilisation mechanisms are discovered, it might still not be feasible to base heterosis in commercial sorghum hybrids on working groups. Nevertheless, with continued research into the male sterility systems and other sorghum hybridisation techniques, it might be feasible to use the working groups or even races as the basis of heterotic groups in commercial hybrid sorghum programmes. As for now, the A/B and R grouping currently used by breeders might still be the most feasible option based on current trends in breeding programmes such as those described by Acquaah (2007) and Sleper and Poehlman (2006).

1.5.2 Explanations and levels of heterosis attained in sorghum

Information is available on the causes of heterosis for grain yield but not on stem sugar in sorghum. Grain yield heterosis in sorghum was explained by (i) higher numbers of grains per panicle, especially in the lower branches (Stickler and Pauli, 1961; Quinby, 1963; Blum *et al*., 1990), (ii) increased net photosynthetic rates per unit leaf area per unit time due to the presence of a bigger sink, the larger head (Hoffmann *et al*., 1984), (iii) larger leaf area (Liang, 1967; Quinby, 1970), and (iv) greater stomatal conductance and transpiration hence more carbon dioxide fixed per unit time over a larger range of temperature (Blum *et al*., 1990). Also suggested for positive heterosis were; (v) increased plant height (Chiang and Smith, 1967; Kirby and Atkins, 1968); (vi) increased biomass with constant harvest index (Patanothai and Atkins, 1971) and (vi) many vigorous and long roots (Blum, 1977). Haussmann *et al*. (2000) reported mid-parent heterosis values of between 13 and 88%. For grain yield, Blum *et al*. (1990) reported grain yield heterosis of 23.9 to 39.6% whereas Haussmann *et al*. (1999) reported relative hybrid superiority for grain yield of 47.1%. Although no literature was found for stem sugar heterosis, improved plant size in hybrids can result in higher sugar yields from the crop, provided there is high stem sugar content in the stems. It is suspected that crossing sweet sorghums diverse in stem sugar content can result in heterosis based on the reports of the importance of gene additivity and non-additivity for the traits (Baocheng *et al*., 1986; Natoli *et al*., 2002; Guiying *et al*., 2000; Schlehuber, 1945; Ritter *et al*., 2008). Heterosis for stem sugar can also be a result of improvements in the associated traits such as biomass and net photosynthetic rates (Chiang and Smith, 1967; Kirby and Atkins, 1968; Hoffmann *et al*., 1984).

Expression of heterosis for stem sugar and grain yield in one cultivar has not been reported in the literature. Only information on the traits studied separately in specialised cultivars is available. Examples of these will be cited. Haussmann *et al.* (1999) observed that heterosis for 1000-seed weight contributed the most to grain yield heterosis results which emphasise the need to take into account yield components when breeding from higher yield potentials. They reported that low mid-parent heterosis values were associated with crosses between adapted parents, whereas higher values were obtained for exotic materials or under stressed conditions. Majisu and Dogget (1972) reported heterosis values (over the trial mean) of between 113 and 130%.

Haussmann *et al.* (2000) further cited other researchers who reported values of around 1.0% hybrid superiority where blends were used and heterosis measured in comparison to pure stands in Kansas and Ghana. However, regardless of heterosis on the lower side, hybrid blends were reported to be more productive and stable populations (Reich and Atkins, 1970). Programmes have to include crosses involving populations obtained locally crossed to exotic materials to produce stable hybrids with maximum heterosis in line with reports of high heterosis from diverse genotypes (Hallauer, 1999).

1.6 Genotype stability and Genotype × Environment Interaction (G × E) analyses in sorghum

1.6.1 Genotype by environment interaction and its quantification

Quantification of genotype by environment interaction (G × E) is important to assess genotypic adaptation and stability across environments. Basically two types of stability have been described, (i) biological or homeostatic stability where a genotype maintains a relatively constant yield over many environments, and (ii) agronomic stability where a genotype has the ability to respond to its environment, that is, a genotype has the ability to perform well relative to the production potential of its environment (Becker, 1981). An agronomically stable genotype is therefore consistently well ranked across the production environments. If this happens for a wide range of environments, the genotype has a general or wide adaptation, and if it happens for a limited number of environments, it has specific adaptation (Fox *et al.*, 1997). Many methods have been used to quantify G × E in crops. These include analysis of variance, risk assessment, ranking, biplots (Fox *et al.*, 1997), and cultivar superiority (Lin *et al.*, 1985; Lin and Binns, 1985; 1988). Of these methods, the ranking method and the cultivar superiority methods are simple but effective in studying the stability of cultivars across the environments. The ranking method gives information of general good performers across environments as these ranked high across environments whereas the cultivar superiority gives information on the stability of performance differentiating between general and specific stability among cultivars.

The ranking method addresses G × E of a crossover nature, that is, one involving changes in the rankings of genotypes across environments, and does not require assumptions of additive main effects, homogeneity of variance across sites, linear response to raising environmental potential and it is robust to extreme environments (Fox *et al*., 1997). The cultivar superiority is based on the computation of a cultivar superiority index (P*i*), defined as the distance mean square between a cultivar's observed value and the maximum value observed in a given environment (Lin and Binns, 1988). It follows that cultivars displaying high P*i* values are specifically adapted to certain environments whereas those with low P*i* values show general adaptation. The index was first defined in 1985 (Lin and Binns, 1985) and improved in 1988 (Lin and Binns, 1985) due to the shortcomings of the preceding method's computation. The 1988 method uses the highest yield observed in an environment as the potential of that environment and the P*i* is computed as mean square deviations from that value as opposed to the use of the standard check mean. This removes the need for repeating the same check varieties in all environments thereby reducing the trial and subsequent cost associated with large trials (Lin and Binns, 1985). Standard check are also not necessarily the same across environments, thus the use of highest yield per environments is ideal. The cultivar superiority index is therefore a measure of both performance and stability, a characteristic that makes it simple and ideal for use in cultivar comparison and selection.

1.6.2 Evidence of G × E in sorghum

There are many reports on G × E and stability studies in sorghum (Majisu and Dogget, 1972; Alagarswamy and Chandra, 1998; Chapman *et al.,* 2000; Haussmann *et al.,* 2000; Kenga *et al.,* 2004). The strong presence of G × E as depicted by genotypic inconsistencies across environments in sorghum has necessitated multi-location evaluation of materials, especially those intended for the semi-arid tropics (Alagarswamy and Chandra, 1998). In these areas, poor soil fertility, plant establishment, and drought are major constraints to production and contribute to the ubiquitous G × E observed (Haussmann *et al.,* 2000). Stability of sorghums, be they homozygous or hybrid materials, depend on individual buffering capacity (Majisu and Dogget, 1972). However, stability of a population was found to be improved by the heterozygosity of cultivars and heterogeneity of populations (Léon, 1991; Hill *et al*., 1998; Helland and Holland, 2001). Genotype by environment interaction has manifested itself as either a change in ranking (lack of correlation among environments), or by changes in differences between entries without changing the ranks, which shows heterogeneity of variances (Alagarswamy and Chandra, 1998). The crossover type G × E is the most important during selection whereas changes in differences without changes in ranks among entries become important when disseminating improved materials.

Studying G × E for yield using 12 sorghum genotypes of diverse origin across 25 environments, Alagarswamy and Chandra (1998) found that 12% of the variation was due to genotypes, 61% due to environment while G × E accounted for 27%. Their results were consistent with earlier reports in wheat (DeLacy *et al.,* 1990; Cooper *et al.,* 1996). Rattunde *et al.* (2001) reported substantial G × E interaction in dual-purpose (grain and stover yield) between *in vitro* gas production of stems and leaves and concluded that multi-environment testing was necessary during selection. The authors also reported variations in biomass yield over seasons (6.19t ha^{-1} in 1995 and 9.79t ha^{-1} in 1996) mainly due to an 11-day delay in planting in 1995 and previous cropping history because the climatic conditions did not differ significantly during the two years. Based on results from 75 hybrids and 20 parents in Kenya, Kenga *et al.* (2004) concluded that selection for superior yields must precede stability in sorghum hybrids. Selection for superior yields is even more desirable when breeding for stress environments. Chapman *et al.* (2000) reported that most of the G × E in sorghum was a result of the genotype by location by year, but suggested breeders to deal with the genotype by location type over a fixed number of seasons. The authors advised that, given enough resources and reduced risks of failure, programmes should evaluate materials in a single season over many locations for higher throughput of test materials. Haussmann *et al*. (1999) suggested that instead of multi-season testing, G × E could be evaluated by using appropriate artificial stress factors that are characteristic of the intended growing areas. Studies in sorghum and other grain cereals have demonstrated the strong presence of G × E for all traits from grain yield (Alagarswamy and Chandra, 1998) to the less obvious like the *in vitro* gas production analysed by Rattunde *et al.* (2001). It is therefore important to conduct multi-location testing, quantify G × E and conduct stability analyses to select superior materials in sorghum.

1.7 The need involve farmers and other stakeholders in dual-purpose sorghum cultivar development

Development of dual-purpose sorghum cultivars with high grain yield and high stem sugar will require an engagement with relevant stakeholders from farmers, scientists and political leaders because the technology is relatively new. Farmers are a very important component in cultivar development because they are the users of the varieties, regardless of the views of the researchers (Röling *et al.,* 2004). The farmers' agronomic practice, storage, processing, and marketing preferences influence their decisions on cultivar adoption and these must be understood and taken into consideration during cultivar development (Dixon *et al.,* 2001; Kudadjie *et al.,* 2004; Danial *et al.*, 2007). Even the micro differences like taste and culinary characteristics can affect dissemination and adoption of a variety (Conroy and Sutherland, 2004). This information can be gathered by conducting situational studies to appraise the farmers and generate information that impact on production such as the levels of knowledge, age, labour, land holding, resource availability, production constraints, possible competing cropping enterprises and access to produce markets.

Although there are no reports of farmer acceptance on dual-purpose sorghum, incidences have been reported with grain sorghums. For example, in sorghum, various preferences have been given by Mushonga *et al*. (1992) reporting farmers in Zimbabwe as preferring white grain. Gupta and Lagoke (2000) reporting low tannin levels to be preferred by farmers in Nigeria, where small-scale farmers have rejected high yielding cultivars due to high tannin levels and adopted low yielding ones with low tannin levels. Mulatu and Belete (2001) reported incidences where farmers selected about 40% of the cultivars regarded as good by researcher in Ethiopia while Nkongolo *et al*. (2008) reported that including farmers' views and having them participate in the selection process improved selection and adoption rate of grain sorghum in Malawi. In the latter case, landraces were even selected by farmers over the improved lines from research stations. The negative consequences of not including farmers in setting up research and policy agenda are well documented (Gupta and Lagoke, 2000; Bänziger and Cooper, 2001; Snapp, 2002; Danial, 2003; Kamara *et al.*, 2006; Derera *et al.*, 2006; Ceccarelli and Grando, 2007). There has been a gradual shift from the traditional "top-down" view of agriculture to a more holistic approach that encompasses all facets of rural agricultural development with the farmer as the major component (Dixon *et al.,* 2001). Therefore, improving cultivar productivity alone is not the solution and a poor farmer is not synonymous with a low producer. Understanding the farmers' situation and involving them in research improve the impact of activities aimed at improving their conditions because they enhance appropriate technology development. In this regard, Kudadjie *et al.* (2004) pointed out that understanding the farmers is the initial step towards the search for an effective and sustainable way to make agricultural research more relevant to the farmer. Farmer participation in research can be achieved through participatory research methods such as questionnaires interviews, group discussions, transect walks and matrix ranking in cases where choices are to be made between alternatives. Detailed discussions on the methods can be obtained from many authors (FAO, 1990; Burkey, 1993; Anyaegbunam, 1998; Matata *et al.*, 2001).

1.8 Research gaps identified from the review of the literature

This review of the literature established that:

- there is lack of information on the gene action involved for grain yield and stem sugar traits in dual-purpose sorghum cultivars,
- there are no suitable dual-purpose sorghum cultivars in southern Africa,

- no studies have been done to determine the expression and levels of heterosis attainable for both grain yield and stem sugar traits in dual-purpose sorghum cultivars,
- the relationship between grain yield components and stem sugar traits in cultivars combining both traits has not been determined conclusively,
- there are no suitable dual-purpose sorghum parental lines and germplasm for use in a dual-purpose sorghum breeding programme,
- restoration capacities vary according to crosses and environments and the restoration capacities of the germplasm collection at the University of KwaZulu-Natal has not been evaluated, and
- farmers' situation that may impact on dual-purpose sorghum cultivar adoption and production has not been appraised or reported on.

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CHAPTER 2

[1]An appraisal of the factors impacting on crop productivity of small-scale farmers in the semi-arid environments in Zimbabwe and their implication on crop improvement goals and policy interventions

2.1 Abstract

The study was aimed at (i) surveying and appraising the factors that impact on small-scale crop production and (ii) determining socio-economic factors that might affect dual-purpose sorghum cultivar adoption and production in the semi-arid environments in Zimbabwe. Stratified random sampling was used to select 108 households in three districts within two provinces, Masvingo and Manicaland provinces. These districts represent tropical dryland environments with high frequency of mid season and full season drought, and frequent crop failure. Data generated from the questionnaire were validated by conducting focus group discussions, and observations were made during transect walks in the areas. Results showed significant variation in household structure, education, crops grown and farming systems. There was gender balance in Chipinge South, while at least 67% of farmers were male in Chivi and Chipinge North. Major cereal crops grown were maize and sorghum while groundnuts dominated among legumes. These were primarily produced for home consumption but surplus were sold to generate income for the household. Cotton and maize were the major cash crops that can potentially compete for resources with dual-purpose sorghum cultivars. Thus, dual-purpose sorghums had to be more economically attractive for wide adoption. Cattle were the chief source of draught power and they also supplied organic fertiliser. The major production constraints were low soil fertility, drought, limited access to seed, inappropriate crop cultivars, inadequate labour, poor logistical support and lack of market access. Choice of farming enterprises was not influenced by level of education, household structure or wealth status, but primarily influenced by climate. This suggested that sorghum could be more attractive than the competing enterprises in the areas due to its drought tolerance. Landholdings were generally small, ranging between 2.8 ha and 6.85 ha which can imply that crop enterprises such as dual-purpose sorghums that get the farmer food and income might be more attractive. From these results, policy intervention is needed on sufficient supply of resources, improved seed availability and improved market access to boost and sustain high dual-purpose sorghum production.

Keywords: Crop production, farming systems, resource-poor farmers, household data, production constraints, semi-arid environments

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2.2 Introduction

The gap between population growth and food production remains wide in sub-Saharan Africa (SSA) because crop productivity remains low resulting in high levels of poverty. The major economic activity in this region is agricultural production, mainly by the small-scale and resource poor farmers who farm with few resources in predominantly marginal zones. Sustainable development could be attained by boosting agricultural productivity in the semi-arid areas in SSA. However, despite many decades, probably more than 100 years of investment in agricultural research in these areas, poverty levels remain high and food insecurity is rampant. Crop yields are very low even for the small-scale farmers near the research facilities in the area. Seemingly, research efforts have not been focused on generating relevant technologies that are adaptable to these areas or proper consultation with the local people have not been done prior to establishing research programmes. Several factors, which include poor links between researchers and the resource-poor farmers on the ground, have been pointed out as contributory to the continued poor crop productivity. Ideally, the scientists should form an important component of the link between resource-poor farmers and science in the region.

To be successful in transferring technologies to the farmers, there has to be an appreciation of the farmers' situations and knowledge to better understand their choices, views and preferences for agricultural technologies. Most of the resource-poor farmers in SSA are in the semi-arid areas classified as Lowland Tropical Dry environments (≤800m.a.s.l.) by the International Maize and Wheat Improvement Centre (CIMMYT), which accounts for about 15% of the crop production area in southern Africa (Vivek *et al.,* 2005). The areas are characterized by variable and usually harsh agro-ecological, socio-economic, and climatic conditions. Thus farmers face huge challenges presented by a complex of stresses and increased production risks in both time and space (Almekinders and Elings, 2001; Conroy and Sutherland, 2004), which compromise productivity with serious negative impact on food security and poverty reduction. Among other factors, there are limited crop varieties options that farmers can grow in this environment, and other than agriculture, there are limited economic activities that the households can pursue except agriculture.

In these areas, small-scale farming is the major economic activity and households have many farming enterprises ranging from crop production to animal husbandry. These enterprises are designed to minimise or spread the risk of failure due to drought and other constraints to production. Apart from food, the crops also provide other needs such as beverages, household income, construction material, livestock fodder, and medicines (Almekinders and Elings, 2001) with implications on generation of new crop variety and policy interventions that are designed to alleviate poverty. The enterprise heterogeneity brings constraints, resulting in differences in farmers' needs even within a region (Conroy and Sutherland, 2004), making it difficult to implement new and broad strategies that would enhance crop productivity. Some researchers even argue that, with such heterogeneity, the recommendation domain can be limited to as little as an individual farm (Okali *et al*., 1994) yet research programmes such as plant breeding goals are aimed at generating crop varieties for a wide geographical deployment. For development to take place, research has to address these issues in consultation with the farmers because they are the users of the crops (Röling *et al.,* 2004). In this regard, understanding farmers' agronomic practice, storage, processing, and marketing preferences is an important step before any intervention efforts are made (Danial *et al.*, 2007). The levels of knowledge, age, labour, land holding, and resource availability are very important in determining the farmers' choice of varieties and enterprise mix.

The first major decision by the farmers is assessing the potential impact of the new cultivars to their economies and the reliability and commitment of the researchers (Röling *et al.,* 2004). In this regards, it is prudent for researchers and policy makers to understand the farmers' situation as they influence decision making by both the farmers and researchers (Dixon *et al.,* 2001). Although increasing productivity alone leads to poverty reduction, other interventions like promoting market growth or creating awareness on alternative enterprises can be equally valuable. This implies that a poor farmer is not synonymous with a low producer; other factors may be contributory and have to be taken into account to help formulate intervention avenues. Therefore an understanding and involvement of the farmer helps to develop appropriate technologies adapted to their situation. It also helps to improve the impact of farmer support activities by government, non-governmental organisations (NGOs) and the private sector.

Factors that might impact adoption and production of dual-purpose sorghum include land availability, labour limitation, other production constraints, other crop enterprises that can compete for resources with the dual-purpose sorghums and the expertise of the farmers in crop production. These factors have to be appraised through situational studies to understand the farmers and better devise a solution with the farmers with the background understanding of factors influencing their choices and perceptions. The negative consequences of not understanding or including farmers in setting up research and policy agenda are well documented (Gupta and Lagoke, 2000; Bänziger and Cooper, 2001; Snapp, 2002; Danial, 2003; Kamara *et al.*, 2006; Derera *et al.*, 2006; Ceccarelli and Grando, 2007).

Information about the factors that impact on crop productivity has been collected using participatory approaches which emphasise broader community participation (Anyaegbunam, 1998; Matata *et al.*, 2001). Participatory methodologies and their application have been discussed in detail by many authors (FAO, 1990; Burkey, 1993; Anyaegbunam, 1998; Matata *et al.*, 2001), and have been reported to be successful in obtaining vital information and shown to be effective in boosting crop productivity and adoption of new crop varieties (Kudadjie *et al.,* 2004; Derera *et al.*, 2006). Given the foregoing, this study aimed at appraising the various factors that impact on crop productivity in the semi-arid regions in an effort to get an intimate understanding of the farmers and intrinsic factors that could affect dual-purpose sorghum adoption and production. Other areas of possible policy intervention were also explored from the surveys and data synthesis to assist stakeholders in formulating other poverty alleviation programmes through crop farming. This was achieved by analysing among other factors the household structure, farming systems, and crop production constraints in two provinces of Masvingo and Manicaland in the southern to the south-eastern Zimbabwe, respectively. The information was generated by critically engaging with small-scale farming communities in the two provinces through both formal and informal approaches. The formal interviews formed the core of the participatory rural appraisal (PRA) and informal techniques of focus group discussions and transect walks helped observe some physical indicators that could have been easily passed unnoticed if the researchers had used formal interviews alone. Therefore, a combination of PRA methods helped solicit more information.

2.3 Materials and Methods

2.3.1 The study area

The study was conducted in Chivi (20°05′S; 30°50′E**)** and Chipinge North and South (20° 11' S; 32° 37' E) districts in Zimbabwe. The area stretches from Masvingo to Manicaland provinces in the southern to the south-eastern Zimbabwe, respectively. The area is representative of the semi-arid regions in sub-Saharan Africa, which occupies 15.9% of the total land in southern Africa according to mega-environment classifications by CIMMYT (Vivek *et al.*, 2005). In Zimbabwe, the area represents Natural Regions III to V, which are characterised by low, erratic and unimodal annual rainfall starting in November and ending in March with a high probability of a mid-season dry spell, mid season drought or a full season drought (Vincent and Thomas, 1961). The districts have medium grained sandy-loam soils (Mugabe, 2005; Clark *et al.,* 2001).

In Chipinge district, the North and South regions are under different traditional authorities which have implications for the farming systems. Chipinge South is under the jurisdiction of Chief Musikavanhu, while Chipinge North is under Chief Mutema hence the two regions were treated separately in the study.

2.3.2 The survey study and data analysis

Initial visits, to develop rapport with farmers and other development practitioners in the area, were made three months prior to the study. These provided opportunities for informal interactions with farmers and key stakeholders. During these initial visits, secondary data for the area were also obtained from provincial and district offices. In addition, enumerators, who spoke the local languages, were identified, trained and made to pre-test the questionnaires. Stratified random sampling was used to select districts within the provinces, while random sampling was used to select (i) wards within districts, (ii) villages within wards, and (iv) farmers within the villages. At each level of selection, the units in the sampling frame were numbered and selection was done using computer generated random numbers. The formal study was then conducted during February to March 2007 using a structured questionnaire, and other participatory rural appraisal tools including focus group discussions and observations made during transects walks across the area.

In Chivi, 44 farmers from five villages were interviewed whereas in Chipinge North and Chipinge South 34 and 30 farmers were interviewed from 12 and four villages, respectively (Table 2.4-1). Information on the general household structure, education level, wealth status (as judged by property owned), cropping enterprises, and production constraints were obtained using the structured questionnaire. Group discussions were done on completion of the questionnaire interviews to confirm data obtained and to solicit new information that was not obtained during the formal process. After the group discussions, the researcher, enumerators, key informants and farmer participants conducted transect walks across each village to make observations and further discussions were held in the process. Three key informants were selected per village on the basis of their knowledge in farming and the village. Extension workers and district office employees helped identify the key informants. During the transect walk, discussions were held and all participants were free to contribute, and bring out any issues. Data were summarised and subjected to analysis of variance using SPSS 15.0 computer package (SPSS Inc., 2006).

2.4 Results and Discussion

2.4.1 Household and demographic information

The majority of the farmers in Chivi, Chipinge North and Chipinge South were in the age groups of 31-40, 41-50 and 51-60 years, respectively (Table 2.4-1). Kajoba (2002) reported similar results in small-scale farming community in central Zambia. It may be argued that Kajoba's (2002) study focused on women, results of which might not necessarily be reflective of the general community. However, in the current study, although men dominated the respondents list, women (spouses of respondents) were observed to actively participate in the discussions during the interviews, hence Kajoba's (2001) finding might be comparable to the current findings. In Chivi, 70% of the respondents were male, whereas the percentage of male was 73% in Chipinge North and 53% for Chipinge South were men (Table 2.4-1). The percentage of women in Chipinge South (47%) is consistent with Gladwin *et al*. (1997) who reported that 45% of the small-scale farmers in Zimbabwe were female, and Dixon *et al.* (2001) who reported that women constitute 47% of the agricultural labour force in SSA. The percentage of women in farming has not changed have changed probably due to lack of changes in customary land ownership laws in which men are regarded as the custodians of wealth including land. The predominance of male farmers in Chivi and Chipinge North suggested lack of gender balance and contrast the average statistics for the country and SSA. The lack of gender balance in this study can be attributed to the fact that in the Zimbabwean traditional culture, and especially in Chipinge North (the "*Ndau*" people under the jurisdiction of Chief Mutema), men are the household heads and are the custodians of common household wealth. In a few cases, women even refused to be interviewed and suggested to the researchers to wait for the husbands. This was consistent with reports by Kajoba (2002) who reported that land was a common property in traditional Africa and that policies favour men than women. Therefore, although land was a common property, men were the custodians of it, making them the decision makers within households. However, during the interviews, it was observed that women would intervene to expand or correct some inaccuracies. This observation is quite consistent with most Zimbabwean culture where women always contribute to the debate but the men, as the household heads, will eventually make the decision and take full responsibility.

Table 2.4-1: Farmer and household information for Chivi and Chipinge districts in Zimbabwe

			Masvingo	Manicaland		P-Value
			Chivi	Chipinge North	Chipinge South	
General information						
Number of households interviewed (n)			44.00	34.00	30.00	
Number of villages sampled (yr)			5.00	11.00	4.00	
Modal age range of farmers	1	<30	0.02	0.15	0.07	0.23
	2	31 – 40	0.40	0.17	0.27	
	3	41 – 50	0.23	0.15	0.33	
	4	51 – 60	0.19	0.21	0.13	
	5	61 – 70	0.16	0.15	0.20	
	6	>70	-	0.17	-	
Sex of respondents	1	Males ratio	0.70	0.73	0.53	0.16
	2	Females ratio	0.30	0.27	0.47	
Demographic data per household						
Mean number of males below 18 years			1.50	1.47	2.23	**0.02**
Mean number of females below 18 years			1.68	1.56	1.89	0.50
Mean number of males above 18 years			1.61	2.03	1.85	0.22
Mean number of females above 18 years			2.07	1.82	1.96	0.57
Labour data per household						
Mean number of male family members providing farm labour			2.32	2.54	2.33	0.77
Mean number of female family members providing farm labour			2.48	2.31	2.07	0.44
Mean number of male hired labour			0.23	0.29	0.67	0.08
Mean number of female hired labour			0.16	0.07	0.11	0.70
Farming experience						
Mean number of years in farming			19.28	25.63	20.48	0.22
Mean number of years growing sorghum			8.89	20.16	14.23	**0.00**
Education and training background						
Ratio of respondents in each of the educational qualifications category	1.	Grade 1 – 7	0.21	0.12	0.03	**0.00**
	2.	†Sub A –B	0.14	0.03	0.00	
	3.	Standard 1 – 7	0.27	0.35	0.23	
	4.	"O" Level (form 1 – 4)	0.36	0.38	0.47	
	5.	"A" Level (form 5 – 6)	-	-	0.13	
	6.	Tertiary	-	-	0.13	
Ratio of respondents in each of the educational agricultural training category	1.	Master Farmer	0.16	0.09	0.27	
	2.	Certificate	-	-	0.13	
	3.	#Non	0.34	0.78	0.00	
	4.	‡Other	0.50	0.13	0.60	
Wealth data per household						
Mean number of goats			3.10	3.24	5.93	**0.02**
Mean number of cattle			3.30	2.61	4.50	0.16
Mean number of modern houses			2.90	0.79*	1.03**	**0.00**
Number of radio sets			0.33	0.33	1.20	**0.00**
Method of land preparation	1.	Ox-drawn plough	0.86	0.47	0.67	0.11
	2.	Hand digging	0.14	0.44	0.33	
	3.	Zero tillage	-	0.09	0.00	

*, ** within area (by village) significant at 0.05 and 0.01 probability levels, respectively; † = equivalence of grade 1-2; # = No agricultural training; ‡ = training including short courses from government, NGOs, and other such sources.

Significant differences were observed among the districts for demographic data with implications on farm labour availability. The number of male household members below 18 years differed significantly ($P \leq 0.05$) between the three districts with Chipinge South averaging 2.2 compared to Chipinge North and Chivi both averaging 1.5 (Table 2.4-1). The number of females below 18 years ranged from 1.56 to 1.89 across the districts. According to the Zimbabwean laws, persons below 18 years are considered as children with no voting rights. Generally, this is considered to be school going age with no family responsibilities. The number of males and females above 18 years averaged 1.61 - 2.03, and 1.82 - 2.07, respectively. The results suggest gender balance, with at least one adult member per household. This indicates that there was gender balance only that men dominated the respondents' list as is consistent with tradition. Individuals above 18 years are considered adults with full voting right and responsible for their actions. Family size is very important as it determines the amount of labour available per household. Results show that farm labour is mainly provided by family members with at least four people per household, comprising two males and two females, but about 25% of the households hire an extra person to boost their labour force (Table 2.4-1). Women (family members and hired) contributed 50.9% of the labour force in Chivi, 45.7% in Chipinge North and 42.1% in Chipinge South (Table 2.4-1). This gender balance in farm labour is in sharp contrast to previous reports from central Zambia by Kajoba (2002) who reported women to be the major contributors to farm labour. However, these findings are generally in agreement with Gladwin (1997) and Dixon (2001).

There were significant differences ($P \leq 0.05$) among the farmers for education level and experience in farming. Generally, experience and education levels are expected to influence knowledge and the farming enterprises undertaken in rural areas. Experience in farming ranged from 19.28 years in Chivi to 25.63 years in Chipinge North and was not significantly different between the three areas. This indicates that farmers had sufficient experience in farming and would therefore provide reliable information about farming in the area, which is useful in capturing local and indigenous knowledge. In Chivi, experience in farming was positively and significantly ($P \leq 0.05$) correlated ($r = 0.511$) to the number of cattle owned whereas in Chipinge South, it was also positively and significantly ($P \leq 0.05$) correlated to the number of cattle ($r = 0.587$), goats ($r = 0.618$), and modern houses ($r = 0.664$) a farmer owned. This could be because farmers accumulate wealth over the years and therefore, the more experienced the farmer is the more the wealth accumulated. The majority of the farmers had gone to school up to Standard 6 (standard 6 is primary level equivalent to grade 8 level or eight years of primary education) (Table 2.4-1). Although the data shows that most farmers had no formal agricultural training, a sizeable portion had attended short courses given by government agricultural extension officers, non-governmental organizations (NGOs), and other sources (Table 2.4-1). The most common certificate awarding training received by farmers was the Master Farmer Certificate.

2.4.2 Wealth status

The wealth status of the household was assessed using the number of livestock owned and ownership of radios and modern houses. Households in Chipinge North had significantly ($P \leq 0.01$) more modern houses (made of baked brick wall and roofed with asbestos or corrugated iron sheets or tiles) than Chivi and Chipinge South (Table 2.4-1). Households in Chipinge South had more goats ($P \leq 0.05$) and radio sets ($P \leq 0.01$) with an average of 1.2 radios per household than in Chivi and Chipinge North both of which averaged 0.33 radio sets per household. There are many training courses offered on national radio stations in Zimbabwe, therefore, possession of radios give farmers access to information. Goats are a source of food (meat and milk) and they are adapted to drier conditions where they feed on branches of drought tolerant bushes and occasionally on crop residues. They also provide manure for field and garden crops. In addition to owning large numbers of goats, most households owned between 2.61 to 4.50 heads of cattle (Table 2.4-1). Cattle are a sign of wealth by rural standards and are the dominant source of draught power in rural Zimbabwe. Like goats, they also provide meat, milk, and manure for the crops. In Chipinge South, there was a negative significant ($P<0.01$) correlation between agricultural training and the age of the farmer ($r = -0.594$), cattle owned ($r = -0.690$), goats owned ($r = -0.675$), and the number of radio sets owned by a farmer ($r = -0.419$). In Chivi significant ($P<0.05$) correlation was only with the age ($r = -0.337$). This implied that young farmers received more agricultural training and owned more wealth compared to their older counterparts. This could be because they were putting their training into practice thereby improving productivity. It can also be speculated that they might also have inherited some wealth from their aging parents as is the tradition in the Zimbabwean and most Africa cultures.

2.4.3 Cropping enterprises

Crops grown included sorghum, maize, pearl millet, finger millet, groundnuts, beans, cowpea, bambara groundnuts, and cotton (Table 2.4-2). Less than two farmers grew sunflower and paprika (data not shown). The majority of the farmers grew sorghum, maize and groundnuts every year and cowpea also frequented the cropping systems. Groundnuts and cowpeas were sometimes grown as intercrops with maize or sorghum and therefore, the area per household for these crops does not necessarily represent a monoculture crop. Generally, no significant differences were observed within districts between years except for cotton in Chivi which showed a significant increase during 2006 (Table 2.4-2). The national average yield for these crops are generally low with sorghum being around 340kg ha^{-1}, maize 660kg ha^{-1}, groundnuts (unshelled) 454kg ha^{-1}, and millets 200kg ha^{-1} (Figure 2.4-1) (FAOSTAT, 2008). Nationally, areas under these crops is around 222 500ha, 1 445 800ha, 275 100ha and 221 703ha respectively (Figure 2.4-1) (FAOSTAT, 2008). Given the low national averages for these crops, it is expected that productivity in the semi-arid lowlands would even be lower, necessitating serious policy intervention to ensure food security and raised standards of living.

Table 2.4-2: Crop history over five years (2002-2006) showing the area planted (ha) to each crop per household in Chivi and Chipinge districts in Zimbabwe

	Crop	Year	Area (ha) in each district				P-Value†
			Chivi	Chipinge North	Chipinge South	Mean (±S.E)	
Cereals	Sorghum	2006	1.03	0.82	0.56	0.84 ±0.06	**0.02**
		2005	0.89	0.90	0.53	0.79 ±0.06	**0.02**
		2004	0.84	0.92	0.51	0.78 ±0.06	**0.04**
		2003	1.09	0.89	0.45	0.75 ±0.07	**0.00**
		2002	0.91	0.86	0.45	0.68 ±0.08	**0.02**
		Mean	0.95	0.88	0.50		
	Maize	2006	1.60	0.16	0.75	1.07 ±0.09	**0.00**
		2005	1.38	0.17	0.76	1.07 ±0.08	**0.00**
		2004	1.40	0.17	0.74	1.07 ±0.09	**0.00**
		2003	1.67	0.24	0.83	1.13 ±0.11	**0.00**
		2002	1.67	0.21	0.92	1.10 ±0.12	**0.00**
		Mean	1.54	0.19	0.80		
	Pearl Millet	2006	0.35	0.74	0.20	0.48 ±0.10	**0.02**
		2005	0.40	0.76	0.18	0.49 ±0.09	**0.01**
		2004	0.40	0.76	0.20	0.50 ±0.09	**0.02**
		2003	0.27	0.46	0.15	0.28 ±0.06	0.06
		2002	0.00	0.36	0.16	0.24 ±0.06	0.09
		Mean	0.35	0.62	0.18		
	Finger Millet	2006	0.55	-	0.07	0.33 ±0.07	**0.00**
		2005	0.51	-	0.11	0.37 ±0.06	**0.00**
		2004	0.51	-	0.09	0.30 ±0,09	**0.01**
		2003	0.50	-	0.12	0.29 ±0.08	**0.01**
		2002	0.37	-	0.04	0.16 ±0.07	**0.01**
		Mean	0.49	-	0.08		
Legumes	Groundnut	2006	0.60	0.20	0.10	0.39 ±0.04	**0.00**
		2005	0.51	0.19	0.11	0.34 ±0.04	**0.00**
		2004	0.45	0.19	0.10	0.30 ±0.03	**0.00**
		2003	0.41	0.22	0.11	0.27 ±0.04	**0.00**
		2002	0.49	0.22	0.09	0.25 ±0.05	**0.00**
		Mean	0.49	0.21	0.10		
	Beans	2006	0.08	0.20	0.12	0.12 ±0.01	0.23
		2005	0.07	0.20	0.10	0.10 ±0.01	0.20
		2004	0.07	0.23	0.10	0.11 ±0.01	**0.00**
		2003	-	0.20	0.10	0.11 ±0.01	**0.01**
		2002	-	0.20	0.10	0.11 ±0.01	**0.02**
		Mean	0.07	0.21	0.10		
	Cowpea	2006	0.73	0.34	0.14	0.51 ±0.13	0.20
		2005	0.58	0.34	0.14	0.43 ±0.11	0.36
		2004	0.54	0.34	0.14	0.39 ±0.12	0.51
		2003	1.40	0.16	0.11	0.77 ±0.38	0.27
		2002	1.24	0.16	0.11	0.69 ±0.34	0.30
		Mean	0.90	0.27	0.13		
	Bambara groundnut	2006	0.02	0.20	0.12	0.12 ±0.04	0.50
		2005	0.15	0.20	0.12	0.14 ±0.03	0.72
		2004	-	0.20	0.12	0.13 ±0.04	0.50
		2003	-	0.20	0.13	0.15 ±0.05	0.67
		2002	-	0.20	0.13	0.15 ±0.05	0.67
		Mean	0.09	0.20	0.12		
Fibre	Cotton	2006	2.30	0.86	0.86	1.03 ±0.20	**0.01**
		2005	1.80	0.82	0.82	0.93 ±0.16	**0.02**
		2004	1.80	0.72	0.72	0.85 ±0.17	**0.04**
		2003	-	0.78	0.78	0.73 ±0.11	0.12
		2002	-	0.76	0.76	0.71 ±0.11	0.13
		Mean	1.97	0.79	0.79		
Mean land holding			6.85	3.37	2.8		

†Bold faced figures show significant differences at P<0.05

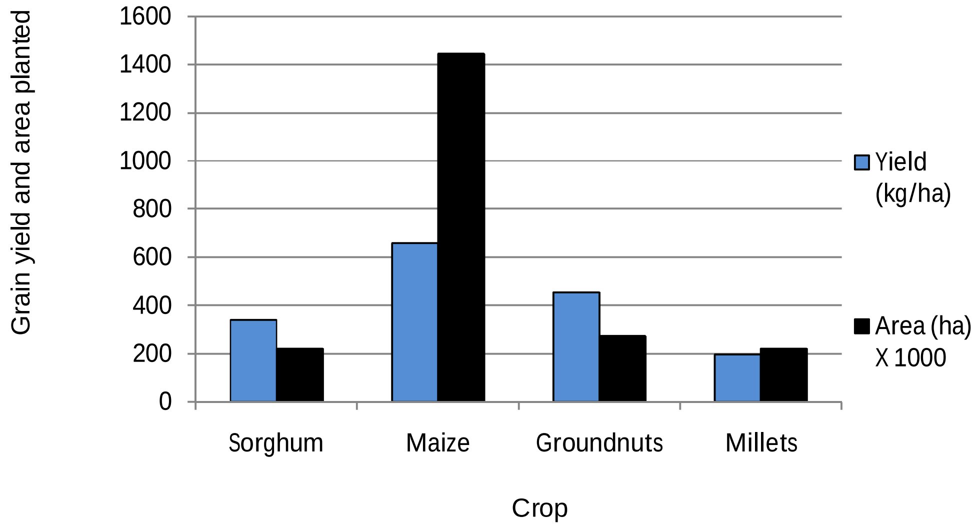

Figure 2.4-1: National crop productivity and production figures for Zimbabwe (Source: FAOSTAT, 2008)

Chivi had a significantly ($P \leq 0.05$) larger area under finger millet, whereas farmers in Chipinge North did not grow any finger millet during the past five years which could be due to differences in cereal crop preferences among the areas. Finger millet, apart from being a food security crop in drought years, is usually planted for purposes of brewing and making dishes for traditional ceremonies. This might explain its strong presence in Chivi (0.49ha per household) where it is planted on a larger scale than pearl millet. Chivi had the largest land allocation to groundnuts (0.49ha). Beans were allocated the least area, and were grown by very few farmers in Chivi and Chipinge North and by half of the farmers in Chipinge South. Chivi and Chipinge North are more drought-prone than Chipinge South; hence the farmers in these areas received more food aid which included beans to supplement their protein requirements. Seemingly food aid acted as a disincentive to production of legumes such as beans. However, because cereals are known to be deficient in the important nutrients such as proteins, iron and vitamins, an expansion of the area allocated to legumes would be recommended wherever possible to improve on the nutrition.

2.4.4 Crop management practices

2.4.4.1 Planting dates

Appropriate timing of planting is a critical success factor in the semi-arid environments because farmers need to capture the scarce soil moisture once the rains come. Farmers planted their crops as early as possible after the onset of the rainy season to capitalize on the high temperatures which support rapid growth, and to avoid the coincidence of crop flowering with the mid-season dry spell, which is usually experienced during the last half of December to early

January in semi-arid Zimbabwe. All the crops, except beans, were planted during October to November (Table 2.4-3) which is the onset of summer in Zimbabwe. A similar strategy was reported to be followed by farmers in Ghana (Kudadjie *et al.,* 2004). Beans were planted during January to March as it can grow with residual moisture after harvesting the main crop.

2.4.4.2 Seed system

Apart from maize and the other high value crops, most crops were raised from unimproved seeds of landraces or farm-retained seed (Table 2.4-3), which might partly explain problems of low productivity for these crops. Sorghum, pearl millet, groundnuts, cowpea and bambara groundnuts were mainly planted from retained seed in Chivi and Chipinge North. In Chipinge South, NGOs, government handouts, and the official seed markets were the major sources of seed for these crops. Maize, beans, and cotton were mainly purchased from the official market. This could be attributed to the fact that maize is a staple crop whereas beans and cotton are high value cash crops and therefore farmers seek high quality seed for these crops. Further, these crops have a well developed crop improvement and seed distribution systems in Zimbabwe. There are many crop improvement programmes at Seed Co Ltd, Crop Breeding Institute (CBI), Pannar and Pioneer Seeds and other small programmes that are involved in crop improvement. However, these companies devote greater attention to maize than the legumes; only soybean receives reasonable attention at Seed Co and CBI (about 10%). In the same vein there is a cotton improvement programme at the Cotton Research Institute, and Quton Seeds Ltd produces high quality seeds which are distributed to farmers through input schemes to ensure that high standards of the crop are maintained. Thus, there are opportunities to develop breeding programmes for legumes (cowpeas, beans, bambara groundnut, etc) and for seed companies to distribute seed of these crops. It was observed that small scale farmers very well understood the need to buy new maize seed every year to avoid yield reductions associated with retaining seed because hybrids dominate the market in Zimbabwe. This shows that, once the market is developed or access to it is improved, these farmers would be willing to purchase improved seeds of legumes and other small cereals with high positive impact on crop production.

2.4.4.3 Fertiliser application

One way of improving crop productivity in the smallholder sector is through enhanced use of fertiliser. There were differences in the levels of fertiliser application for all crops and among the districts. Application of fertilisers reflected the importance and value placed on each crop. Data indicates that maize received significantly ($P \leq 0.05$) higher rates of fertilisation than sorghum, for example (Figures 2.4-2a and b).

Table 2.4-3: The proportion of people who planted various crops at particular times of the year, sourced seed from various sources and marketed their produce to particular markets

Area			Sorghum	Maize	Pearl Millet	Finger Millet	Groundnut	Beans	Cowpea	Bambara groundnut	Cotton
Chivi											
Time of planting	1.	September	0.00	0.00	0.00	0.00	0.00	0.00	0.04	-	0.00
	2.	October	0.43	0.18	0.94	0.95	0.20	0.00	0.91	-	1.00
	3.	November	0.52	0.50	0.06	0.05	0.80	0.00	0.04	-	0.00
	4.	December	0.05	0.32	0.00	0.00	0.00	0.00	0.00	-	0.00
	5.	January	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-	0.00
	6.	February	0.00	0.00	0.00	0.00	0.00	1.00	0.00	-	0.00
	7.	March	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-	0.00
Source of seed	1.	Retained	0.70	0.02	0.69	0.81	0.68	0.00	0.82	0.00	0.14
	2.	Official Market	0.16	0.91	0.19	0.10	0.15	1.00	0.05	1.00	0.86
	3.	NGO Handouts	0.07	0.07	0.12	0.09	0.07	0.00	0.13	0.00	0.00
	4.	Friends/Relatives	0.07	0.00	0.00	0.00	0.10	0.00	0.00	0.00	0.00
	5.	Government	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Market	1.	Do not sell	0.02	0.05	0.08	0.29	0.27	0.25	0.65	-	0.00
	2.	Official market	0.84	0.93	0.42	0.18	0.49	0.75	0.35	-	1.00
	3.	Informal market	0.14	0.02	0.50	0.53	0.24	0.00	0.00	-	0.00
Chipinge North											
Time of planting	1.	September	0.00	0.00	0.15	-	0.12	0.00	0.13	0.00	0.00
	2.	October	0.20	0.38	0.15	-	0.16	0.00	0.13	0.00	1.00
	3.	November	0.62	0.38	0.59	-	0.40	0.00	0.33	0.50	0.00
	4.	December	0.06	0.19	0.07	-	0.28	0.50	0.33	0.38	0.00
	5.	January	0.12	0.00	0.04	-	0.00	0.00	0.04	0.15	0.00
	6.	February	0.00	0.00	0.00	-	0.00	0.00	0.04	0.00	0.00
	7.	March	0.00	0.00	0.00	-	0.00	0.50	0.00	0.00	0.00
Source of seed	1.	Retained	0.53	0.34	0.50	-	0.52	0.33	0.52	0.67	0.00
	2.	Official Market	0.23	0.53	0.19	-	0.17	0.67	0.17	0.33	1.00
	3.	NGO Handouts	0.12	0.16	0.15	-	0.13	0.00	0.17	0.00	0.00
	4.	Friends/Relatives	0.12	0.00	0.15	-	0.17	0.00	0.13	0.00	0.00
	5.	Government	0.00	0.00	0.00	-	0.00	0.00	0.00	0.00	0.00
Market	1.	Do not sell	0.93	0.89	0.96	-	0.88	0.00	0.87	0.80	0.00
	2.	Official market	0.03	0.06	0.00	-	0.08	1.00	0.00	0.00	1.00
	3.	Informal market	0.03	0.05	0.04	-	0.04	0.00	0.13	0.20	0.00
Chipinge South											
Time of planting	1.	September	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2.	October	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.36
	3.	November	0.38	0.66	0.18	0.18	0.00	0.00	0.00	0.00	0.64
	4.	December	0.59	0.31	0.71	0.82	0.08	0.00	0.18	1.00	0.00
	5.	January	0.03	0.03	0.12	0.00	0.92	1.00	0.82	0.00	0.00
	6.	February	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	7.	March	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Source of seed	1.	Retained	0.10	0.10	0.17	0.25	0.37	0.48	0.50	0.75	0.00
	2.	Official Market	0.43	0.53	0.28	0.16	0.37	0.22	0.00	0.00	1.00
	3.	NGO Handouts	0.30	0.07	0.39	0.42	0.15	0.22	0.42	0.25	0.00
	4.	Friends/Relatives	0.03	0.03	0.00	0.00	0.07	0.04	0.00	0.00	0.00
	5.	Government	0.13	0.26	0.17	0.17	0.04	0.04	0.08	0.00	0.00
Market	1.	Do not sell	0.39	0.35	0.82	0.82	0.78	0.89	0.92	0.88	0.00
	2.	Official market	0.35	0.62	0.06	0.09	0.04	0.11	0.00	0.00	1.00
	3.	Informal market	0.28	0.03	0.12	0.09	0.19	0.00	0.08	0.12	0.00

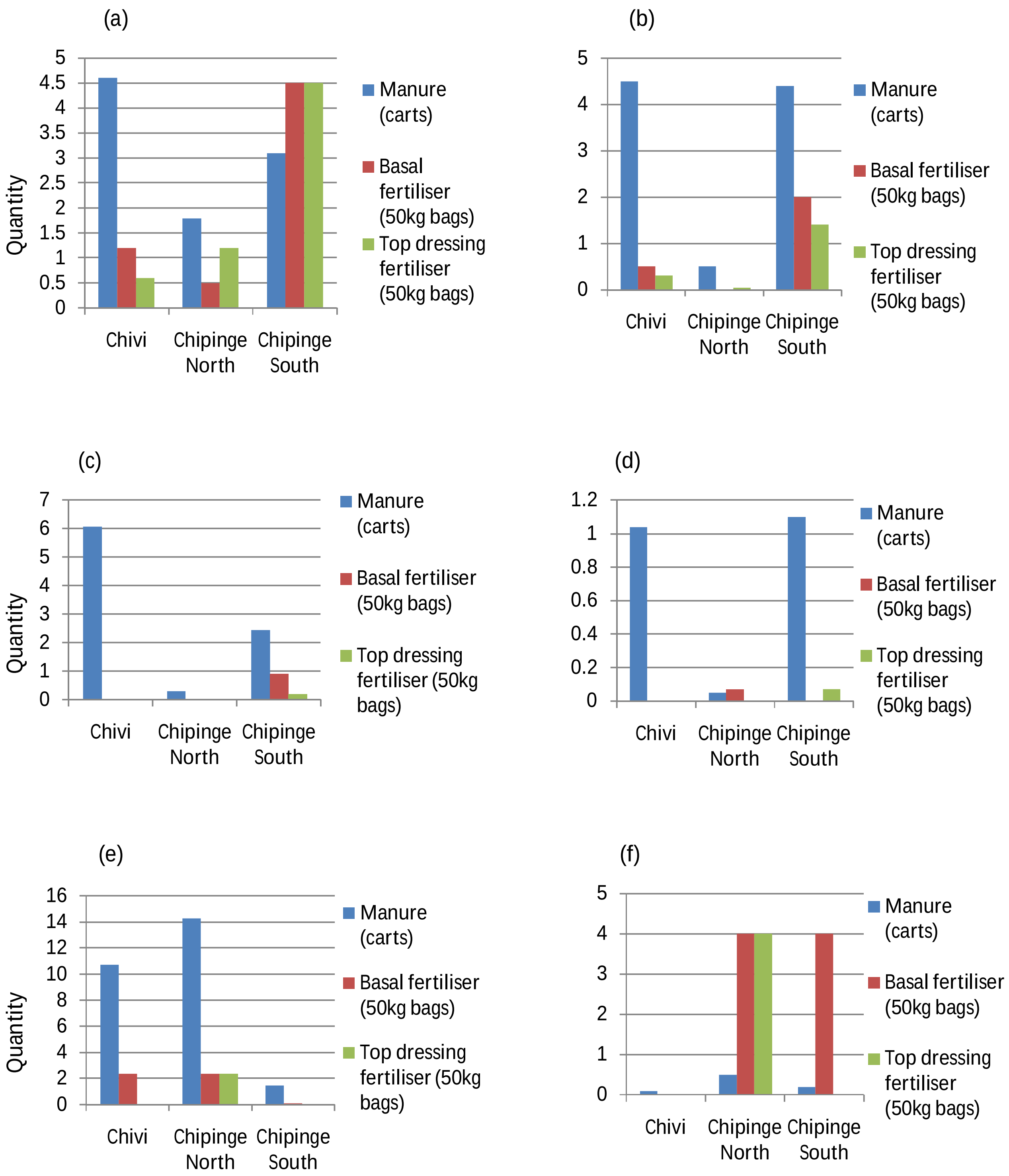

Figure 2.4-2: Levels of fertiliser application for the major crops grown by the communities in Chipinge and Chivi districts in Zimbabwe: (a) Maize, (b) sorghum, (c) pearl millet, (d) groundnut, (e) beans, and (f) cotton

Farmers in Chipinge South applied more basal and top dressing inorganic fertilisers to maize, sorghum, pearl millet, groundnuts, and cotton than those in Chipinge North and Chivi (Figure 2.4-2a to f). For beans, the fertiliser rate was the same for both Chivi and Chipinge North (Figure 2.4-2e). In addition to government input schemes, Chipinge South and Chivi had many NGO supplying farming inputs, among them seed and fertilisers. This might be the reason for the higher rates of fertiliser application in the area. Groundnuts and cotton received more fertiliser in Chipinge North the other two Chipinge South and Chivi (Figure 2.4-2d). The observation of the use of inorganic fertiliser in semi-arid Zimbabwe is in agreement with Murwira *et al.* (1995) who reported 98% of the farmers in Mutoko (Zimbabwe) and 40% of the farmers in Shamva (Zimbabwe) to be using fertilisers in their fields. Farmers in Chipinge South and Chivi put more carts of manure in sorghum and maize than farmers in Chipinge North (Figures 2.4-2a and b). Farmers in Chipinge South had significantly ($P \leq 0.05$) higher mean numbers of goats and cattle per household and therefore could afford to apply more manure on their fields. Farm manures are an important source of crop nutrients in the rural Zimbabwe. Murwira *et al* (1995) reported that manure was used by 85% of farmers in Mutoko and 65% in Shamva.

2.4.4.4 Crop marketing

There were differences among districts for the use of crops. Maize was mainly sold in Chipinge South and Chivi but was largely consumed at home in Chipinge North (Table 2.4-3). Farmers in Chipinge North and Chipinge South produced sorghum for home use whereas those in Chivi sold most of it (Table 2.4-3). All the other crops, except cotton and beans, which were sold at the official market, were either mainly consumed at home or sold to the informal market (Table 2.4-3). Beans and cotton are high value crops and their sale brings the much needed income for household requirements. Therefore, they were sold to the official markets for higher returns. Crop residues were mainly used as livestock feed and manure, and farmers correctly pointed out that they, especially legume residues, were a rich source of animal and plant nutrition. Discussion on the importance of legumes in farming systems was presented by many authors including Amede (2003) and Sheaffer and Seguin (2003). Maize and sorghum stalks were also used for thatching granaries, houses and home gardens. Sweet sorghum stalks were chewed at home or sold to increase household income. The many uses of crops were also reported by Almekinders and Elings (2001) among the small-holder and resource-poor farmers. Thus breeding programmes aimed at servicing these farmers entails a different approach from the conventional procedures for commercial varieties targeting commercial farmers. For example, in sorghum, traits such as stem thickness and tensile strength for constriction, leaf nutritional qualities for livestock feed, sweet stems for chewing and sale and other non-traditional traits need consideration for subsistence farmers.

2.4.5 Production constraints

The study identifies maize and sorghum as the major crops, and constraints to these have a huge impact on agricultural production and food security. All the constraints except animal damage and weeds were a problem for maize in Chivi (Table 2.4-4). In Chipinge North, however, drought, diseases and pests had more than 10% of the farmers acknowledging them as problems (Table 2.4-4). Although the study did not focus at identifying the pests and diseases, these constraints featured prominently and it could be worthwhile to initiate another study aimed at identifying the pest and disease problems in the area. In Chipinge South, drought, poor soil fertility, diseases, pests, seed availability, markets, and labour shortages were reported as major production constraints (Table 2.4-4). This was not surprising because farming is rain-fed, soils are sandy with low water and nutrient retention; maize seed is usually expensive since the Zimbabwean market is dominated by hybrids, and given the low and erratic rainfall in the area. Drought stress has been identified as one of the major constraints to most rain-fed crops throughout the world (Ludlow *et al*., 1994; Haussmann *et al*., 1999; Borrell *et al*., 2000). Among other factors and interventions, problems of drought and low productivity can be addressed through breeding for higher yields under drought stress conditions. In Kenya, addressing poor soil fertility through credit schemes was identified as key, with potential to improve maize production six-fold (Achieng *et al.,* 2001).

The major constraints to sorghum production in Chivi and Chipinge South were poor soil fertility, diseases, pests, seed, poor cultivars, lack of markets, labour, bird damage, lack of transport, and land availability (Table 2.4-4). In Zimbabwe and other Southern African Development Community (SADC) countries, low sorghum yields have been attributed to lack of improved seeds among other constraints such as lack of information, marketing and utilisation, poor grain quality, and fertility management issues (Chisi, 1997). In Zambia, the availability of improved seed and information on agronomic recommendations were identified as the major limiting factors to the adoption of available sorghum varieties (Chisi *et al.,* 1997). Drought, together with poor soil fertility, pests, and bird damage were cited as the major problems for sorghum in Chipinge North. Bird damage was ranked first in Chivi and Chipinge South and second after drought in Chipinge North (Table 2.4-4). Drought was ranked lowest among the constraints for sorghum in Chivi and Chipinge South (Table 2.4-4). In a similar study in Ghana, farmers ranked low rainfall and poor soil fertility as major constraints to sorghum production (Kudadjie *et al.,* 2004). Apart from yield performance, it was noted that a considerable proportion of the farmers' sorghum varieties were late maturing which could result in reduced yield if rainfall onset is delayed and hence farmers in

Chivi (63%) regarded poor varieties as a major constraint. A similar observation was reported in Ghana (Kudadjie *et al.,* 2004). These findings suggest that the sorghum improvement programme should be boosted with resources to develop new varieties and hybrids that are more productive and tolerant to the prevailing stresses. Currently, there are only a few sorghum breeding programmes in sub-Saharan Africa despite the established fact that sorghum is the ideal crop for the tropical dry regions.

Groundnuts had similar constraints to maize and sorghum with drought, poor soil fertility, diseases, pests, seed availability, and poor varieties being top on the farmers' list in Chivi and Chipinge South (Table 2.4-4). Those in Chipinge North only reported drought and poor soil fertility as constraints to groundnut production. Drought, poor soil fertility, diseases, and insect pests were the major problems for the rest of the crops in Chipinge South (Table 2.4-4). Drought was only important for pearl millet and cowpea in Chipinge North and for cowpea and cotton in Chivi. At least 10% of the farmers in Chivi acknowledged seed availability and poor cultivars as production constraints. Transport featured for most crops in Chivi and Chipinge South but not Chipinge North. All the cotton farmers in Chivi cited small land holdings as a major limitation to production (Table 2.4-4). These results indicate the significance of land related problems in Zimbabwe. There is need to make more land available to the productive cotton farmers in the region since it is the main source of cash with possible multiplier effects on other enterprises and poverty reduction in the region.

Table 2.4-4: Proportion of farmers who acknowledged the production constraints and how they ranked them

		Crop									
	Constraint	Sorghum	Maize	Pearl millet	Finger millet	Groundnut	Bean	Cowpea	Bambara groundnut	Cotton	Mean Rank
Chivi	Drought	0.07	0.91	0.00	0.00	0.51	0.00	0.47	-	0.50	7.07
	Poor soil fertility	0.37	0.84	0.22	0.14	0.44	0.67	0.22	0.00	0.00	8.48
	Diseases	0.26	0.49	0.11	0.07	0.27	0.00	0.56	0.00	0.50	7.02
	Insect Pests	0.42	0.33	0.11	0.07	0.22	0.33	0.22	0.00	0.00	5.95
	Seed availability	0.67	0.44	0.11	0.29	0.22	0.67	0.11	0.00	0.50	6.18
	Poor varieties	0.63	0.52	0.33	0.50	0.15	0.33	0.17	0.00	0.50	5.98
	Market availability	0.58	0.33	0.33	0.50	0.15	0.00	0.00	0.00	0.50	5.87
	Labour availability	0.84	0.54	0.78	0.71	0.32	0.00	0.00	0.00	0.50	3.84
	Bird damage	0.91	0.02	1.00	0.71	0.00	0.00	0.00	0.00	0.00	1.68
	Transport	0.86	0.86	0.78	0.50	0.39	0.00	0.00	0.00	0.00	7.45
	Land	0.86	0.77	0.44	0.36	0.17	0.33	0.00	0.00	1.00	6.55
	Theft	0.09	0.79	0.00	0.07	0.17	0.67	0.06	0.00	0.00	11.95
	Weed	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-
	Animals	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-
Chipinge North	Drought	0.82	0.77	0.35	0.00	0.38	0.00	0.22	0.00	0.00	2.09
	Poor soil fertility	0.21	0.10	0.07	0.00	0.24	0.00	0.00	0.14	0.00	9.85
	Diseases	0.09	0.29	0.04	-	0.00	0.33	0.00	0.00	1.00	10.11
	Insect Pests	0.53	0.24	0.32	-	0.08	0.00	0.23	0.00	0.00	7.64
	Seed availability	0.09	0.14	0.07	0.00	0.00	0.00	0.00	0.00	0.00	9.20
	Poor varieties	0.00	0.00	0.00	-	0.00	0.00	0.00	0.00	0.00	9.85
	Market availability	0.21	0.00	0.00	-	0.04	0.00	0.05	0.00	0.00	10.62
	Labour availability	0.12	0.00	0.00	-	0.00	0.00	0.00	0.00	0.00	11.40
	Bird damage	0.68	0.00	0.83	0.00	0.00	0.00	0.00	0.00	-	2.94
	Transport	0.03	0.05	0.00	-	0.00	0.00	0.00	0.00	0.00	11.35
	Land	0.03	0.00	0.00	-	0.00	0.00	0.00	0.00	0.00	11.70
	Theft	0.00	0.00	0.00	-	0.00	0.00	0.00	0.00	0.00	11.90
	Weed	0.09	0.10	0.07	-	0.00	0.00	0.05	0.00	0.00	-
	Animals	0.09	0.10	0.11	-	0.04	0.00	0.00	0.14	0.00	-
Chipinge South	Drought	0.00	0.97	0.06	0.08	0.70	0.70	0.42	0.43	0.00	8.23
	Poor soil fertility	0.40	0.70	0.53	0.58	0.22	0.19	0.23	0.27	0.25	5.73
	Diseases	0.38	0.38	0.42	0.33	0.48	0.59	0.50	0.43	0.75	4.77
	Insect Pests	0.48	0.43	0.44	0.33	0.37	0.30	0.17	0.00	0.50	4.03
	Seed availability	0.53	0.68	0.28	0.42	0.19	0.19	0.33	0.29	0.08	3.37
	Poor varieties	0.13	0.17	0.28	0.25	0.15	0.19	0.17	0.29	0.08	5.70
	Market availability	0.23	0.27	0.11	0.08	0.15	0.23	0.00	0.13	0.27	5.47
	Labour availability	0.13	0.27	0.11	0.08	0.07	0.04	0.08	0.14	0.33	7.66
	Bird damage	0.97	0.03	0.33	0.33	0.19	0.04	0.00	0.14	0.08	2.10
	Transport	0.03	0.13	0.06	0.08	0.04	0.04	0.08	0.00	0.17	9.25
	Land	0.20	0.13	0.17	0.25	0.11	0.11	0.25	0.14	0.08	8.47
	Theft	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	11.53
	Weed	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-
	Animals	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-

Farmers in the study area are resource-poor, not only in accessing agricultural inputs, but also in the timely acquisition. Some farmers were not even aware of methods that could be used to deal with the problems of pests and diseases and in most cases could not afford the chemicals needed for the control. This could be the reason pests and diseases were ranked among the major constraints, well above drought. Access to fertiliser was also difficult despite the concerted effort from the government and NGOs to ensure availability. As a result, poor soil fertility continues to be one of the major limitations to crop production among the resource-poor farmers. Access to improved varieties was hindered by lack of income to buy and transport them. Farmers resorted to using farm-saved seed from previous harvests. Whilst this approach works with self-pollinating crops like sorghum, and the legumes, yields progressively decline in cross-pollinated crops such as maize and pearl millet. The seed maize market in Zimbabwe is dominated by hybrids and planting the second generation seed results in drastic reductions in yields. In legumes, such as beans, systemic diseases such as viruses and seed borne bacteria also accumulate resulting in reduced seed yield with time. Therefore, as they may seem as standalone problems, the production constraints all form a web of problems that depress yield for the small-scale and resource-poor farmers. The way farmers ranked the constraints among the three areas were correlated and the correlation coefficients were positive but only significant ($P \le 0.05$) between Chivi and Chipinge South ($r = 0.68$). This might imply that intervention in alleviating these constraints can be accomplished using similar approaches in Chivi and Chipinge South and a different one might be necessary for Chipinge North.

2.4.6 Possible areas of intervention

2.4.6.1 Crop variety improvement

The study showed that notwithstanding the knowledge of the small-scale farmers in agriculture, external factors pose a serious limitation to increased productivity. The call to improve farmers' access to agricultural inputs, appropriate crop varieties and extension services cannot be over-emphasised. The story of sorghum can demonstrate how improved varieties, if accompanied by inputs and extension services, can benefit farmers. At present, most sorghum breeding programmes are based on hybrid commercial seed production (Li and Li, 1998; Kenga *et al.*, 2004). Sorghum hybrids have been demonstrated to be very beneficial to farmers. India has achieved an 80% yield increase in sorghum production in the last 20 years with a 37% decline in area under the crop (Kenga *et al.*, 2004). The success story of Indian sorghum has been largely attributed to the use of hybrid cultivars (Kenga *et al.*, 2004). In China, Li and Li (1998) reported that production of hybrid varieties has become predominant in the sorghum breeding programme. Up to 90% of China's sorghum growing land is under hybrid varieties and the country has realised several folds yield increases from adopting hybrid sorghum. Similarly, Haussmann *et al.* (1999) concluded that hybrid production had the space and potential to increase yield in semi-arid areas of Kenya. The sorghum story demonstrates that research has the potential to boost agricultural production in SSA. Therefore, sorghum might immensely benefit the small-scale farmers through food security, income from the sale of sweet stalks if dual-purpose hybrids are developed, with local seed companies helping in the production and distribution of the improved seed.

2.4.6.2 Improving access to agricultural inputs and facilities

Crop input schemes are presently available and increasing the scale of these operations can enhance productivity in semi-arid areas. A concerted effort is needed from government, NGOs, and the private sector in this regard. Timely supply of the inputs is an important factor raised by the farmers. Timely supply of fertiliser alone increased maize productivity six-fold in Kenya (Achieng *et al*. 2001) and this can be replicated in the region for all crops. Another way of intervention is through building dams for home gardens and irrigation schemes. Farmers usually grow vegetables in small home gardens located around water sources and get revenue from the sale of produce such as tomatoes, leafy vegetables and beans. Training on water management, soil and plant health, and the correct and timely use of inputs such as fertilisers and chemical (where available) is also important. Training of farmers in pest and disease management practices through cost effective means such as use of resistant varieties as part of an integrated pest management strategy is also important and could boost crop productivity given the farmers' limited access to plant health chemicals.

2.4.6.3 Access to produce markets

The issue of markets is usually overlooked but the present study clearly indicates that improved access to markets can boost productivity given that farmers are likely to buy crop chemicals and improved seeds. The critical section is grain marketing because grain, especially maize and to a lesser extent sorghum, are the most traded crops by resource-poor farmers in Zimbabwe. There are tendencies among grain buyers to exploit farmers through holding prices at unrealistically low levels; this leaves the resource-poor farmer in more poverty. Achieng *et al*. (2001) reported a similar situation in Kenya where maize grain price was held at a low level when fertiliser prices rose by 150% between 1980 and 1993. Röling *et al.* (2004) reported the same state of affairs in West Africa where cheap imports from industrialised nations undermine the profits of local farmers.

2.5 Conclusions and implications of the findings on dual-purpose sorghum cultivars

The study showed that farming was an important economic activity in the semi-arid regions surveyed, suggesting that farmers might be willing to adopt crop enterprises that improves returns from investments on their land. Therefore, dual-purpose sorghums could be a viable option for the farmers. Farmers were found to be of active age between 31 and 60 years which can mean availability of effective labour, however there were fewer adults (about 3) implying that there were labour limitation for a commercial type of agriculture. The fact that some household could hire additional labour is an indication that when economically justified, labour could be hired given high economic returns. The predominance of maize was testimony to the need for food security in the areas and income from the sale of surpluses, which could mean that farmers were able to analyse and decide on the cropping enterprises that satisfied their needs, namely food and household income. Production of cotton in some areas is testimony to that fact. However, the farmers faced problems of access and timely acquisition of inputs, lack of markets for most crops, poor seed quality, inappropriate varieties, moisture limitations, bird damage in sorghum and pearl millet, and poor soil fertility. The finding that climate was the major determinant of choice of crop suggest that dual-purpose sorghum cultivars might be adopted by the farmers in these areas. Sorghum is one of the most drought tolerant grain cereal and with drought and limited access to market listed among the major constraints, dual-purpose sorghums are better placed as they are expected to have ready market in the biofuel industry. The fact that dual-purpose cultivars provide both food from grain and income from the sale of sweet stalks makes it more ideal for production in the area with limited land holding, the latter was cited as a major constraint by farmers in Chivi. The potential high returns from dual-purpose sorghum can potentially attract the seed industry which can result in the supply of quality seed.

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CHAPTER 3

Development of sorghum for bio-energy: a view from stakeholders in Zimbabwe and South Africa

3.1 Abstract

Dual-purpose sorghum, which can be used for both grain and bio-ethanol production, would be preferred to maize and sugarcane for energy production amid concerns for food insecurity and increasing frequency of drought in southern Africa. Currently there are no suitable sorghum varieties, and there is limited knowledge on the use of sorghum for bioethanol production in the region. Surveys were, therefore, conducted to solicit views and perceptions of resource-poor farmers in marginal areas in Zimbabwe where there is potential to enhance sorghum production. The other stake-holders were drawn from Zimbabwe and South Africa. Results show that small-scale farmers in Zimbabwe have limited knowledge of the use of sorghum for bio-ethanol production. However, there is a high level of awareness (>50%) and optimism among the non-small-scale farmer stakeholders, which is attributed to more access to information, and experiences from the sugar industry. All the interviewed stakeholders acknowledged potential benefits of dual-purpose sorghums with farmers willing to adopt them. The stakeholders were also of the view that current sugarcane processing plants could be adjusted to handle sorghum stalks. Perceived problems included seasonal supply and current low grain productivity of sorghum ranging between 0.5 to 1.3t/ha. Among other traits, farmers' ideal sorghum variety would combine high yield potential with early to intermediate maturity and high stem sugar content. Unfortunately high yield and earliness as well as earliness and high grain yield might compromise stem sugar yields. Further, earliness sacrifices stem biomass and hence there is need for a compromise when breeding dual-purpose sorghum cultivars. The non-farmer stakeholders further pointed out that infrastructural development and access to capital by farmers are important if the use of dual-purpose sorghums for food and bioenergy is to succeed. Therefore, there is need for a concerted effort from farmers, breeders, agronomists, policy makers, governments, non-governmental organisations and other stakeholders to make the production and utilisation of dual-purpose sorghums a success. In this regard, cultivar development is viewed as the starting point.

Key words: bio-ethanol; dual-purpose sorghum; grain sorghum; stakeholder survey; sweet sorghum

3.2 Introduction

The search for alternative fuel sources has led researchers to investigate various renewable energy sources most of which are biomass-based. Sorghum, a drought-tolerant cereal, has been identified as one source for industrial bio-ethanol production. Sweet stem sorghum cultivars that can accumulate high levels of stem sugars with potential for bio-ethanol production have been reported (Prasad *et al.*, 2007; Gnansounou *et al.*, 2005; FAO, 2002; Woods, 2001). But they are currently not available to small- and large-scale farmers in southern Africa. The "ideal" varieties should combine high biomass and high stem sugar content (Prasad *et al.*, 2007), but to be adaptable to marginal areas in southern Africa, they must (i) be drought tolerant, (ii) be able to fit within the short rainy seasons (a characteristic that sacrifices biomass), and (iii) not be photosensitive. Small-scale farming is characterised by a complex of stresses and production risks (Almekinders and Elings, 2001) which is the case in the lowveld agricultural natural regions IV and V with little and poorly distributed rainfall in Zimbabwe (Vincent and Thomas, 1961). In addition the ideal, varieties should have high and adequate grain yield to sustain their commercial production, and to also guarantee household food security. With the projection that drought will become a major constraint to agriculture in the near future (Ryan and Spencer, 2001); sorghum can complement the narrowly adaptable sugarcane for sugar and bio-ethanol production and maize for dietary energy production (Reddy *et al.*, 2005). Bio-ethanol can replace a considerable portion of the petroleum-based fuel used by vehicles and is imported by most of the poor countries in the region (Kammen, 2006).

Although the use of sorghum for bioenergy has not been implemented in southern Africa, there are examples from other regions. Currently, Brazil produces bio-ethanol [99.6% (vol.) ethanol and 0.4% (vol.) water] from sugarcane and is used as 20-24% blends with petroleum fuels or anhydrous ethanol (95.5% ethanol and 4.5% water) used directly by ethanol fuelled vehicles (Gnansounou *et al.*, 2005). In the US, bio-ethanol is mainly produced from maize (Kammen, 2006). Both options are not viable in southern Africa where, apart from the dry conditions that result in restrictions to sugarcane production, there is a perpetual deficit of maize. Local maize supplies are mostly augmented by importing from the USA, Brazil and Argentina. As a result the regional policy makers are not keen to approve maize as a suitable bio-energy crop which might compromise regional food security. Therefore, sorghum provides an alternative to maize for bio-ethanol production and can complement sugarcane, which requires enormous investment in irrigation infrastructure for expansion in area. Given the benefits, sorghum production might increase resulting in improvements in food security and household incomes. Sorghum is highly adapted to the marginal and drought-prone and semi-arid areas where both maize and sugarcane would not give economic yield.

Survey of the literature indicates that currently there are specialised sorghum cultivars for either stem sugar or grain supply, but there are no cultivars that combine both traits. Apart from improving the current enterprises, there is need for cropping enterprises that can supply both household food security and income with limited investment in additional resources need is necessitated by the small land holdings (usually ±2 ha of arid land) for farmers in the semi-arid parts of southern Africa. Dual-purpose sorghum cultivars, which combine high grain yield and high stem sugar content, can be used to generate both grain for food and stem sugar for bio-ethanol production with possible multiplier effects in marginal areas. This can lead to sustainable rural development, renewable energy production, improved health standards through cleaner fuels, and improved food security (Woods, 2001). This alternative has not been extensively explored by research and the cultivar options are not available in southern Africa in spite of the potential to boost rural income. According to the FAO (Gnansounou *et al.*, 2005) the sweet stem sorghums for grain and stalks can give a yearly gross margin of US\$1300ha^{-1} compared to only US\$27ha^{-1} for maize. Further, supplying hybrids for this purpose can increase the benefits as they are more productive than open pollinated cultivars (Li and Li, 1998; Haussmann *et al.,* 1999; Kenga *et al.*, 2004). There are no hybrid varieties, which are also more uniform and suitable for industrial production, that are available and affordable to the small-scale farmers in southern Africa. This has prompted the need to develop new sorghum cultivars.

Appropriate cultivar development requires a holistic approach that includes all stakeholders to facilitate adaptation and subsequent adoption. The information on availability of genetic variability for traits to be considered during breeding of the ideal cultivar is also important. The views and perceptions of the stakeholders with regard to bio-ethanol production from sweet sorghum or dual-purpose varieties remain very scarce. Such ventures would entail a long-term investment in science, economic and political resources, and require the intervention of farmers, policymakers, and ordinary citizens who will use the product (Kammen, 2006). The stakeholders include all the users of the breeding products from breeders and farmers to processors (Lançon *et al.*, 2006), and end-users of the technology. The chief stakeholders are the farmers and the other stakeholders include scientists, marketers, policy makers, opinion leaders, non-governmental organizations in food security, environmentalists, and others impacted by the technology. The consequences of not involving the farmers in cultivar development are well documented (Gupta and Lagoke, 2000; Ceccarelli and Grando, 2007; Danial, 2003; Kamara *et al.*, 2006; Derera *et al*., 2006). Although the involvement of farmers in the breeding process might result in a longer time to release cultivars and fatigue, it may considerably increase the chances of adoption of the cultivars (Danial, 2003). Adoption of improved sorghum varieties might fail if farmers' preferences are not seriously considered as was observed in maize and wheat by Banziger and Cooper (2001) and Derera *et al*. (2006), and the comparative advantage of sorghum over the competing crops and technologies are not clearly identified.

This investigation was conducted to solicit views, preferences, and perceptions on the use of sorghum for bio-ethanol production and the possibility of developing dual-purpose sorghum for both food and bio-ethanol production among stakeholders in Zimbabwe and South Africa. The study highlights the awareness and willingness of farmers to adopt new dual-purpose sorghum cultivars in particular, preparedness of other stakeholders, and possible challenges that should be overcome to be able to use dual-purpose sorghums for bio-ethanol production. The study also aimed to identify the traits of a "model" dual-purpose cultivar that is desired by small-scale farmers.

3.3 Materials and Methods

3.3.1 Small-scale farmers' survey

Surveys were conducted in Chivi (20°05′S 30°50′E), Chipinge North and Chipinge South (20°11'S 32°37'E) in southern Zimbabwe, which stretches from Masvingo province to south-eastern lowveld in the Manicaland province. The area represents low rainfall and drought-prone environments in the Natural Regions III to V of Zimbabwe (Vincent and Thomas, 1961). In this area sorghum is expected to have a comparative advantage over maize, which is the predominant cereal crop in Zimbabwe and southern Africa. Sorghum production is dominated by small-scale farmers. The surveys involved 44 households in Chivi, 34 in Chipinge North and 30 in Chipinge South, during February to March 2007. Data were collected using formal questionnaires and informal survey comprising PRA tools: matrix ranking, focus group discussion, and transect walks. This was done with assistance of trained enumerators and local extension staff who spoke the local languages to eliminate errors associated with translation. Stratified random sampling was used to select districts within the provinces, while random sampling was used to select (i) wards within districts, (ii) villages within wards, and (iv) farmers within the villages. At each level of selection, the units in the sampling frame were numbered and selection was done using computer generated random numbers. During the formal survey, information was solicited on sorghum production, cultivars grown, the preferred traits, farmers' awareness and perceptions on use of sorghum as a bio-energy crop, and farmers' preparedness to grow dual-purpose sorghum cultivars. Focus group discussions were then conducted to confirm information obtained during the formal surveys. This was followed by transect walks with key informants in the study areas to observe sorghum crops in the field. Key informants comprised farmers selected on the basis of their general knowledge of the area and crop production systems. During the transect walk, issues were discussed and any new information was recorded.

3.3.2 Non small-scale farmer survey

The non-farmer stakeholders' surveys were conducted during March to July 2007 in South Africa and Zimbabwe. Participants were selected from the agricultural research and extension (25%), seed industries (plant breeders and agronomists, 6.3%), sugar and petroleum fuel industries (including engineers, 25%), farmers' unions and community leadership (12.5%), government and non-governmental organisations (6.3%), and academic institutions (18.8%). These were selected based on their knowledge and influence on policy, food security, crop research and specialist services, and expertise in their areas. Overall 25 stakeholders participated with 17 in Zimbabwe and 8 in South Africa. The non-farmer questionnaire and informal discussions were used to solicit the following information the potential of dual-purpose sorghum cultivars in the small-holder sector, potential of sweet sorghum for bio-ethanol production, and challenges and opportunities for bio-ethanol production in southern Africa.

3.3.3 Data analyses

An analysis of variance was conducted for quantitative survey data using SPSS computer package (SPSS Inc., 2006). All qualitative data from both the formal and informal surveys were summarised using frequency tables.

3.4 Results and discussion

3.4.1 Farmers views on dual-purpose sorghums

Results show that a significant number of farmers were not aware that sweet sorghum can be used for bio-ethanol and sugar production (Table 3.4-1), indicating that the technology requires a sustained promotion through demonstrations and workshops in the area. Less than 10% of the farmers were aware of the use of sorghum for bio-ethanol and sugar production. Although the technology is not new, the use of sweet sorghum for bio-ethanol production has not received serious attention until only recently. Among other factors, the rising petroleum prices and the search for cleaner and environmentally-friendly fuels has given the impetus to consider sorghum as a potential crop for bio-energy. Regardless of the low awareness, a significant number (74-82%) of the farmers in the three areas were willing to grow special sweet sorghum varieties for the stalks alone, and to adopt dual-purpose sorghum cultivars (Table 3.4-1). It can be inferred that farmers realised the benefits of converting sorghum into a cash crop. The economic benefits of sorghum as both a food and cash crop have been reported by FAO (Gnansounou *et al.*, 2005). A significant number of farmers in each district (41-53%) are willing to trade off grain yield with elevated stem sugar levels, provided prices are lucrative. However, the study identified that farmers' training should be emphasised by establishing local demonstration trials to market the improved cultivars. Farmers demonstrated their understanding of the importance of training agricultural extension officers and NGOs on new technologies.

Table 3.4-1: Percentages of farmers responding to questions on dual-purpose sorghum in three areas studied in Zimbabwe

Area	**Chivi (n = 44)**	**Chipinge North (n = 34)**	**Chipinge South (n = 30)**
	% saying yes		
Farmer awareness on the use of sweet sorghum to produce fuel	9	0	0
Farmer awareness on the use of sweet sorghum to produce sugar	11	0	7
Farmer willingness to grow sweet sorghum for sale of stalks only	43	50	33
Farmer willingness to grow dual-purpose sorghum	80	94	50
Farmer willingness to forego some grain yield for high stem sugar	41	53	47
Farmer willingness to adopt dual-purpose sorghum cultivars	82	79	37

3.4.2 Non-farmer stakeholders' views

A significant number of non-farmer stakeholders were aware of the potential use of sweet sorghum for bio-energy and sugar production (Table 3.4-2). These stakeholders were generally educated with more access to information compared to the small-scale farmers. Thirty-one percent thought farmers would be willing to adopt sweet sorghum whereas 44% were of the opinion that farmers could adopt dual-purpose sorghums (Table 3.4-2). A few stakeholders (25-31%) were of the opinion that the necessary technology to produce ethanol and sugar from sweet sorghum was available.

Table 3.4-2: Percentage of the other stakeholders responding to questions on the use of dual-purpose sorghum for bio-fuel production in Zimbabwe and South Africa (n = 25)

	Yes	No	Maybe	Not sure
General views		(%)		
Awareness on the use of sweet sorghum to produce fuel	52	36	12	0
Awareness on the use of sweet sorghum to produce sugar	64	28	8	0
View on farmer willingness to grow sweet sorghum for sale of stalks only	32	8	44	16
View on farmers' awareness on the existence of such varieties	32	36	0	32
Availability of the capacity to produce ethanol from sweet sorghum	28	24	24	24
Availability of the capacity to produce sugar from sweet sorghum	32	32	18	18
Willingness to have small mill on farm (farmer stakeholders)	64	0	24	12
Willingness to promote/market sweet	28	0	56	16
Challenges on the use of sweet sorghum				
Similarity of infrastructure for sweet sorghum as for sugarcane	8	20	20	52
Use of sweet sorghum for ethanol requiring adjustment to sugarcane machinery	28	8	0	64
Use of sweet sorghum for sugar requiring adjustment to sugarcane machinery	6	6	16	72
Possibility of deploying mobile crashers on-farm	36	8	20	36
View on whether producing ethanol from sweet sorghum is more expensive than using sugarcane	12	20	20	48
View on whether producing ethanol from sweet sorghum is more expensive than using sugarcane	28	6	20	46

The study also indicated that stakeholders are generally aware of the use of sorghum for bioethanol production and would help in promoting their production and adoption if suitable sorghum varieties were to be developed (Table 3.4-2). However, infrastructural challenges in bio-ethanol production were identified. Only 7% of the stakeholders were of the opinion that the infrastructure for processing sweet sorghum is the same as for sugarcane processing, thus the crops would complement each other in the mills (Table 3.4-2). The sugarcane processing plants are already established in Zimbabwe and South Africa, and Zimbabwe has experience in using ethanol from sugarcane to blend with fossil petrol. The sugarcane agronomists suggested that sweet sorghum could be a good complementary fallow crop for sugarcane. A third of the stakeholders suggested that some adjustments are needed to the sugarcane equipment to process sweet sorghum (Table 3.4-2). A significant number (63%) suggested that a centralised small mill could be used to serve the community for juice extraction. On-farm mobile crushers could also be used to process the sweet sorghums to reduce transport and storage costs for small-scale farmers. There was also a perception among stakeholders (47%) that bio-fuel could be cheaper than fossil-based fuels. This result was consistent with findings from an economic study at Triangle in Zimbabwe's lowveld, which indicated that bio-ethanol would cost US$0.19 compared with the then global ethanol price of US$0.30 – US$0.35 (Woods, 2000). In addition to the environmental friendliness of bio-ethanol, stakeholders were of the views that the use of sorghum bio-ethanol can be used to create local employment and to enhance rural development in the region. This was consistent with previous reports of the potential benefits of bio-ethanol (Woods, 2000; Prasad *et al*., 2007; Wheater, 2007; Yamba *et al*., 2007).

3.4.3 Current sorghum production and potential competing crops

Total sorghum production, consumption and trading varied between the three areas with the highest production in Chipinge South (Figure 3.4-1a). Regardless of the fact that the farmers planted more landrace varieties and very few improved cultivars, yield was highest in Chipinge South (Figure 3.4-1b). This could be attributed to the fact that farmers in Chipinge South the highest quantities of inorganic fertiliser as basal and top dressing to the sorghum crop compared to the other areas (Figure 3.4-1c). In addition, the soils in Chipinge South are generally fertile alluvial soils along the Save river valleys. Therefore, fertiliser should be made accessible to small-scale farmers to enhance sorghum yield. Grain sale depended on surplus production and was high in Chivi South. Uses of grain sorghum ranged from animal feed, thatching, and manure while sweet sorghum stalks were mainly used as snacks in the household and sold for household income.

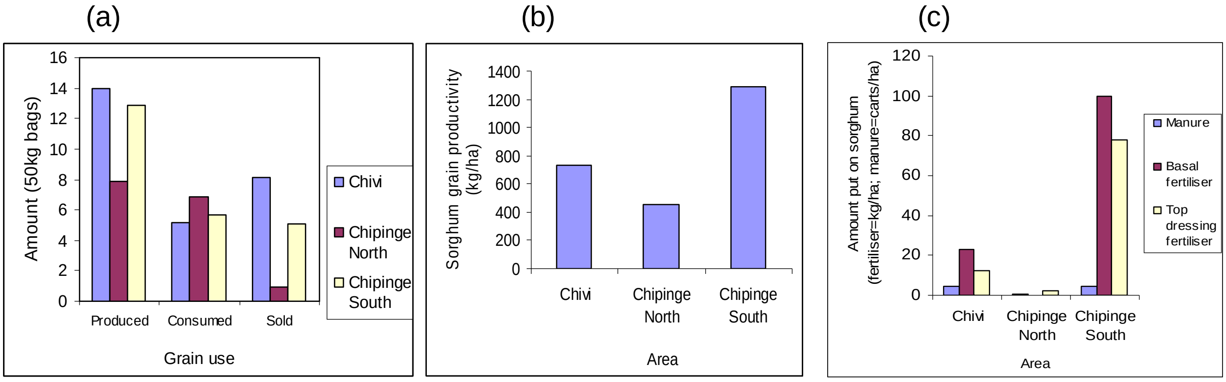

Figure 3.4-1: Sorghum (a) total production per household (b) yield (kg ha^{-1}), and (c) organic fertiliser (kg ha^{-1}) and manure (carts ha^{-1}) in the study area

There was a great diversity in sorghum cultivars grown by farmers, but landraces were predominant in all districts. Five improved varieties and one landrace were grown in Chivi, while five improved varieties and 12 landraces were grown in Chipinge North and 11 landraces and three improved varieties were reported in Chipinge South. Predominance of landrace varieties was also reported by Mekbib (2006) in Ethiopia. Mekbib (2006) reported that landraces were preferred by farmers because they were superior to the improved varieties with respect to height, high biomass, seed weight, and grain yield. While the observation that Chipinge South was dominated by landraces but achieved higher grain yield compared to Chivi where mostly improved cultivars were grown (Figure 3.4-1c) also suggests superiority of landraces in Zimbabwe, the use of more inorganic fertiliser on those landraces in Chipinge South is the main reason of yield superiority in that area. Heterogeneity of landrace varieties is more likely to confer grain yield stability due to population buffering in the variable production environments in marginal areas (Almekinders and Elings, 2001). It is therefore important to breed for high sugar content in the adapted landraces with high biomass and seed yield to develop superior dual-purpose sorghum varieties.

The crops that can possibly compete with sweet stem sorghum production at a commercial level are maize for food and cotton for household income. Results showed that household land holding hardly exceeded 2.0ha but differed significantly between the three areas (Table 3.4-3. More than 50% of the land was allocated to cotton with maize in second place (Table 3.4-3). There is, therefore, the need to provide incentives for farmers to grow sweet stem sorghums. This can be achieved through the development of superior varieties such as hybrids and providing improved seed to make sorghum competitive in the area. There were no significant differences within districts between years because and holdings are usually fixed over a longer period of time and might only change when parents partition it to allocate to children starting their own families

Table 3.4-3: Five-year production area planted to the three major crops per household and P-values for each year across the three areas studied in Zimbabwe

Crop	Year	Mean area planted (ha) per household			Mean(se)	P-Value
		Chivi	Chipinge North	Chipinge South		
Sorghum	2006	1.0	0.8	0.6	0.8 (0.06)	0.02
	2005	0.9	0.9	0.5	0.8 (0.06)	0.02
	2004	0.8	0.9	0.5	0.8 (0.06)	0.04
	2003	1.1	0.9	0.5	0.8 (0.07)	0.00
	2002	0.9	0.9	0.5	0.7 (0.08)	0.02
	Mean over five years	0.9	0.9	0.5		
Maize	2006	1.6	0.2	0.8	0.9 (0.09)	0.00
	2005	1.4	0.2	0.8	0.8 (0.08)	0.00
	2004	1.4	0.2	0.7	0.8 (0.09)	0.00
	2003	1.7	0.2	0.8	0.9 (0.11)	0.00
	2002	1.7	0.2	0.9	0.9 (0.12)	0.00
	Mean over five years	1.7	0.2	0.8		
Cotton	2006	2.3	1.0	1.0	1.4 (0.20)	0.01
	2005	1.8	0.8	0.8	1.1 (0.16)	0.02
	2004	1.8	0.7	0.7	1.1 (0.17)	0.04
	2003	-	0.8	0.8	0.8 (0.11)	0.12
	2002	-	0.8	0.8	0.8 (0.11)	0.13
	Mean over five years	2.0	0.8	0.8		
Total land allocated to the three crops (ha) per household		4.6	1.9	2.1		

3.4.4 Ideal traits in sorghum cultivars for farmers

Farmers suggested the trait they desired in new sorghum cultivars (Table 3.4-4). The majority of the farmers desired high yielding, early to medium maturity cultivars with large white grains. Early maturity was preferred in Chivi and Chipinge North whereas in Chipinge South medium maturing varieties which can escape late season drought were preferred (Table 3.4-4). Early maturing makes the maximum use of the little rain and are therefore drought tolerant. In Chipinge South, medium to large red grain sorghums were preferred (Table 3.4-4). Sweet grains were preferred by farmers in Chipinge North and Chipinge South whereas farmers in Chivi preferred the non-sweet grain sorghum cultivars (Table 3.4-4). The farmers have small land holdings hence they can only improve production through enhanced yield. Therefore the varieties with large and compact to semi-compact heads which are associated with high yields were the most preferred. Sweet and non-sweet grains were desired by farmers because they are suitable for making porridge and the non-alcoholic beverages which are brewed from red grain sorghums. Therefore a third of the Chipinge South farmers preferred red grains (Table 3.4-4).

Table 3.4-4: Percentage of farmers preferring certain traits in sorghum in the three case study areas

Trait	Level	Chivi	Chipinge North	Chipinge South
Grain yield	1. Low	2	3	0
	2. Medium	2	3	10
	3. High	96	94	90
Grain Size	1. Small	0	0	13
	2. Medium	18	6	47
	3. Large	82	94	40
Grain taste	1. Sweet	16	54	97
	2. Non-sweet	80	38	3
	3. Bitter	4	8	0
Grain colour	1. White	64	65	63
	2. Tan	7	14	0
	3. Brown	11	9	3
	4. Red	18	12	34
Head size	1. Small	0	0	13
	2. Medium	23	3	57
	3. Large	77	97	30
Head Shape	1. Compact	48	75	30
	2. Semi-compact	34	13	57
	3. Loose	18	12	13
Maturity	1. Early	68	97	47
	2. Medium	30	3	50
	3. Late	2	0	3
Plant height	1. Short	64	82	47
	2. Medium	36	12	50
	3. Tall	0	6	3
Stem diameter	1. Thin	9	6	3
	2. Medium	65	9	90
	3. Thick	26	84	7
Stem taste	1. Sweet	93	87	100
	2. Non-sweet	7	13	0
Leaf number	1. Few	21	37	17
	2. Medium	74	47	76
	3. Many	5	16	7
Drought tolerance	1. Low	29	3	0
	2. Medium	57	9	3
	3. High	14	88	97
Disease/pest resistance	1. Low	57	6	0
	2. Medium	29	3	3
	3. High	14	91	97

All farmers preferred short-to-medium maturity cultivars with sweet stems of medium leafiness and thick stalks; because they are convenient for harvesting and more resistant to lodging than tall and thin varieties. In the areas surveyed, harvesting is generally done by hand, hence plant height should be considered as an important trait during cultivar development. In general, farmers associated the medium to thick stems with high lodging resistance, and they provided better building and thatching materials and are also used in building grain-drying structures. Thus thick stems are associated with strength for thatching materials. Farmers in Chipinge North and Chipinge South pointed lack of access to pesticides as a limitation and therefore prefer cultivars with pest resistance. It was not clear why farmers in Chivi preferred low pest and disease resistance, but the observed low disease and pest pressure compared to the threats from baboons and birds in this area could be the reason.

The most important traits selected for in sorghum by breeders were (i) high grain yield potential, (ii) tolerance to pests (especially stalk borers, birds, and weevils) and diseases, (iii) drought tolerance, (iv) end user traits (traits required and requested for by the users of the crop, for example high malting quality for beer sorghums), (v) quality traits, (vi) high harvest index, (vii) dwarf cultivars, and (viii) stay green trait. The traits that were cited by breeders for grain sorghum were generally in agreement with those cited by farmers (Table 3.4-4) but very few improved varieties were grown by small-scale farmers. Currently, sorghum breeders in Zimbabwe and South Africa breed for short, strong stemmed and high yield through a large head size in grain cultivars. These traits have been emphasised in widely grown varieties *Macia, SV1, SV2*, and the brewing commercial hybrids which are not suitable for food. Overall, there was a general agreement between the farmers and breeders on what traits to prioritise in cultivar development. Currently there are no breeding programmes that emphasise development of specialised sweet stem and dual-purpose sorghums in southern Africa; hence there is need to set the right priorities for dual-purpose and sweet sorghum development.

The foreseeable challenges and opportunities in breeding sweet stem and dual-purpose sorghum varieties and deploying dual-purpose sorghums in Zimbabwe and South Africa are summarised in Figure 3.4-3.

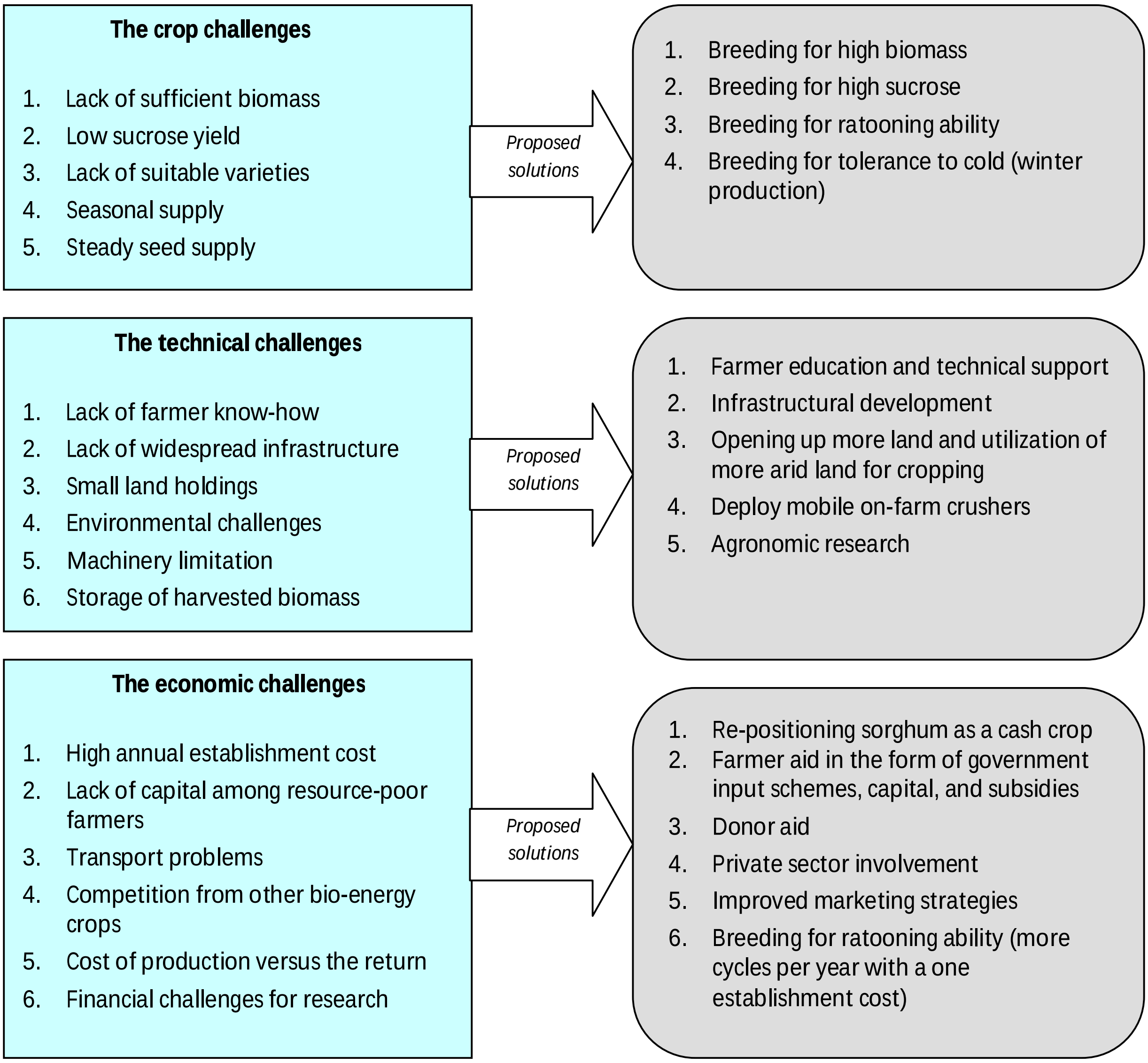

Figure 3.4-3: Challenges and possible solutions to the use of sweet sorghum as a bio-energy crop in southern Africa

3.5 Conclusion

The farmers and the non-farmer stakeholders concurred in their view that development of dual-purpose sorghum would be a viable option that could alleviate poverty, enhance food security, create rural employment and boost rural development. Despite the fact that small-scale farmers had limited knowledge of dual-purpose sorghums and bio-energy production, they were willing to adopt the varieties if made available. The farmers' "ideal" variety was identified and would be considered in setting priorities for the dual-purpose sorghum breeding program. Generally stakeholders were optimistic of the technology and opportunities to overcome the infrastructural, economic and technical challenges were identified.

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CHAPTER 4

[2]Variability for grain yield components and stem sugar traits for the development of dual-purpose sorghum cultivars for grain and bioenergy

4.1 Abstract

Traditionally, sorghum is grown for grain and fodder purposes. Little has been done to develop dual-purpose sorghums that combine high grain yield and stem sugar in the region. The aim of the study was to determine the levels of genotypic variation for the grain yield and stem sugar content using 80 sorghum varieties evaluated under dryland conditions in South Africa. Highly significant ($P \leq 0.01$) differences among genotypes were observed for mean brix data and associated traits. Mean brix ranged between 6.48 to 20.68°brix at maturity, and 7.24 to 18.48°brix at anthesis; while stem biomass ranged from 3.8 to 40.9t ha^{-1}. Twenty three cultivars had positive standard heterosis for stem sugar and out-performed the standard variety ZLR1 by 10 to 30%. Seed yield ranged from 0.5 to 5.5t ha^{-1} indicating the potential for developing dual-purpose cultivars for both grain and stem sugar production. Ten varieties had brix values greater than 16.0, which is above those reported for prominent sweet stem varieties like "Wray", while values for biomass and grain yield were within the range reported in other studies. There was a strong, positive and significant correlation between the brix data at anthesis and at maturity. However, cultivars that did not follow this trend and exhibited less sugar at anthesis and more at maturity (and vice versa) were also observed. The negative and highly significant correlation between grain yield and stem biomass indicated that a compromise might have to be reached for seed production purposes if cultivars for stem sugar production are to be sustained in commerce. However, the correlation between grain yield and stem sugar at anthesis and at maturity were both positive but only significant for the former, suggesting that high grain yielding varieties had more sugar than low grain yielders at anthesis, but at maturity, grain yield was generally independent of stem sugar content. Genotypes that combined high brix at maturity, better seed and biomass yield were identified as a breeding source germplasm. Path analysis revealed that direct selection for stem brix at maturity was more important than indirect selection in developing cultivars with improved stem sugar content; therefore, stem sugar content at anthesis is a major selection criterion.

Key words: Genotypic variability, sorghum varieties, grain yield, stem biomass, stem brix

[2] Submitted to the Proceedings of the 9th African Crop Science Society Conference 28 September – 1 October 2009, Cape Town, South Africa

4.2 Introduction

The global call for alternative fuel sources has resulted in research and development worldwide in replacing at least a portion of motor vehicle fossil fuel based consumption with biomass-based fuels (Kammen, 2006). There are predictions that the world will run short of fossil fuel within the next two decades. For example, Kangama and Rumei (2005) reported that China alone will need 99 million barrels of fuel per day by 2031 if its consumption rate is the same as that of the US at present. Currently, world production is about 79 million barrels per day and there are slim chances of any significant increases. Fuel will thus become limiting and expensive, only affordable to a few rich nations. In that view and to reduce heavy reliance on finite fossil-based fuels, countries like China, USA, Italy, Spain, and Brazil among others have set up programmes to generate bio-ethanol from crops such as wheat, maize, sugar beet, sugarcane, algae and sweet stem sorghums. However, use of maize for fuel production is a non-viable option for Africa due to its perpetual cereal deficits. Therefore, biomass-based sources, which present no competition to food security, are ideal for this purpose. Sweet stem sorghum, having been demonstrated to produce bioethanol yields of between 3000 and 8000l ha^{-1}, presents one of the best suited crops for this purpose (Roman *et al*., 1998; Woods, 2001; FAO, 2002; Dolciotti *et al*., 1998). Stem sugar from sweet sorghum can be extracted by pressing, fermentation and distillation to produce bio-ethanol (FAO, 2002) that can be used for domestic lighting or in combustion engines in the industry.

Sweet sorghum has a number of advantages in Africa as a biofuel crop. Woods (2001) demonstrated that sweet sorghums could be successfully incorporated into the sugarcane processing system, and therefore countries in southern Africa can exploit this option because they have viable sugar industries based on sugarcane. Zimbabwe and South Africa, for example, have well developed sugar mills with experience in the production of bio-ethanol. Sweet sorghum is also widely adapted, has rapid growth, can have high grain yield potential, and has the potential to accumulate high biomass apart from stem sugar (Reddy and Sanjana, 2003). Cultivar development programmes have focused on developing specialized cultivars for grain, fodder, or stem sugar. Limited efforts have been put in combining these traits into one cultivar. Combining grain yield and stem sugar can be beneficial to the small-scale and resource-poor farmer subsisting on small, marginally-dry and sandy land holdings used for both food production and income generation. Therefore, dual-purpose sorghums that provide both high grain yield and high stem sugar are desirable as they satisfy dietary energy and home income requirements from grain and the sale of sweet stalks for sugar extraction, respectively. According to Woods (2001) the dual-purpose sorghum varieties can lead to sustainable rural development, enhanced renewable energy production, higher health standards through cleaner fuels, and improved food security in Africa. Farmers in the semi-arid areas of southern Africa already grow sorghum and are now allocating more land to sorghum than before. For example, in Musikavanhu, a lowland dry communal farming area in Zimbabwe, Chivasa *et al*. (2001) reported that sorghum was grown by 94% of the farmers and was allocated to 82% of the land. Derera *et al*. (2006), working in the same area reported similar findings. On the food security aspect, many world bodies are expressing reservations on the potential of bio-energy crop to compete for land with food crops, thereby pushing food prices beyond the reach of many (Guiying *et al.,* 2000). This creates the niche for dual-purpose sorghum where farmers can harvest the grain for food and sell the stalks for sugar extraction. FAO reported dual-purpose sorghums as giving a yearly gross margin of US$1,300 ha^{-1} compared to only US$27 ha^{-1} for maize grain (Gnansounou *et al.*, 2005). Development of these cultivars with adaptation to the marginal and dry tropical lowlands in southern Africa is therefore an important activity with possible multiplier effects on the socio-economic conditions of the small-scale farmers.

Cultivar development is, however, based on the exploitation of genetic variability for the traits of interest. Therefore, an estimation of the genotypic variability available for stem sugar accumulation and the associated traits in the current sorghum collection is important in determining the feasibility of developing specialised sweet stem as well as dual-purpose sorghum varieties. Further, the relationships between the traits are also important in determining selection procedures, that is, either to employ direct, or if the traits are correlated to implement an indirect selection strategy. These relationships have been studied in different crops using correlation coefficients, which measure the linear relationships between traits, and path coefficients that measure the remaining non-linear relationships (Makanda *et al.*, 2009; Bidgoli *et al.*, 2006; Ofori, 1996).

The objective of this study was to investigate the variability for stem sugar accumulation and associated traits in 80 sorghum varieties in the germplasm collection at the African Centre for Crop Improvement of the University of KwaZulu-Natal, South Africa. These materials were collected from farmers in southern Africa, from African national breeding programmes and introduced entries from outside Africa including the International Crops research Institute for the Semi-Arid Tropics (ICRISAT) in India. The collection has never been characterised under southern African conditions, especially for seed yield and their suitability for the production of stem sugar. A study of the relationships between the traits using correlation and path coefficients is also reported. The information helps to formulate a breeding strategy for development of new sweet stem and dual purpose sorghum varieties for deployment in Africa. Such information is lacking and currently there are not many breeding programmes that emphasise stem sugar content especially in sorghum cultivars.

4.3 Materials and Methods

4.3.1 Experimental design and management

A preliminary evaluation of 80 experimental varieties was conducted at Ukulinga Research Farm at the University of KwaZulu-Natal, in South Africa (29°37′S 30°22′; 596 m.a.s.l.), during the 2006/2007 summer season. Sources of the materials included South Africa, Zimbabwe, Mozambique, Botswana, Kenya, USA, and Mexico. The sweet stem sorghum variety ZLR1, which is widely grown by resource-poor farmers in marginal and dry areas of southern African, was included as the standard check.

The experiment was laid out as a 16 × 5 row-column alpha design with three replications. Each entry was planted in five-row plots of 4.0m length at 0.7m and 0.2m, inter-row and intra-row spacing, respectively. There were 100 plants per plot. The trial site received 800mm moisture through rainfall and supplementary irrigation. A basal fertiliser, (2:3:4, N:P:K) was applied at a rate of 250kg ha^{-1} while Lime Ammonium Nitrate (28% N) was top-dressed at a rate of 200kg ha^{-1}. The fields were kept weed-free by hand weeding. Stalkborer granules were used to control stalkborer damage and the heads were covered using fine mesh bags at anthesis to prevent predation of the developing grain by birds.

4.3.2 Data collection

Stem sugar content, expressed in °brix, was measured at both anthesis and seed harvestable maturity using a refractometer by dividing the stem into three equal parts and taking three measurements from the middle internode of each section. The final measurement was an average of the three. Stem diameter was measured using a veneer calliper on the three mid-internode sections. Grain yield was measured and adjusted to 12.5% moisture content two weeks after sampling for stem sugar content at maturity measurement. Stem biomass was measured by removing leaves and heads, then cutting at ground level and weighing the stems at the hard dough stage of each due to differences in maturity times. Plant height and number of days to 50% flowering were also measured.

4.3.3 Data analyses

Data was analysed as a fixed effects model in REML using GenStat (11th edition) computer package (Payne *et al*., 2007). Data analysis showed that rows, columns and their interaction were not significant (P>0.05) for all the traits and the trial was, therefore, analysed as a complete randomised design with three replications. Histograms were also plotted using raw data in GenStat (Payne *et al*., 2007) to show the variability of genotypes for the traits. Percent relative stem sugar accumulation and percent standard heterosis for stem sugar accumulation were computed according to Kaushik *et al.* (2004) and Virmani (1994) as follows:

Relative stem sugar (%) = $[(X_E)/\mu]*100\%$, where: X_E = Observed mean entry value; μ = Trial mean

Standard heterosis (%) = $[(X_E)/X_{SC}]*100\%$, where: X_E = Observed mean entry value; X_{SC} = Mean of standard check

Pearson's phenotypic correlation coefficients between the traits measured were computed using GenStat (Payne *et al*., 2007). Path coefficients analysis was conducted between the response variable, stem sugar at maturity and the other traits including stem brix at anthesis, grain yield, days to anthesis, stem biomass, plant height and stem diameter as independent variables using the regression method based on the work of Wright (1921, 1960), Dewey and Lu (1959) and Cramer *et al.* (1999).

4.4 Results and Discussion

4.4.1 Mean stem sugar content and associated traits

Analysis of variance showed that the 80 genotypes were significantly different (P≤0.05) for stem sugar at both anthesis and maturity. The differences among the genotypes for the remaining traits were highly significant (P≤0.01) (Table 4.4-1). These results suggested that there is considerable variation among the genotypes for use in new cultivar development for both grain and stem sugar production.

Table 4.4-1: Mean squares for sorghum traits measured in 80 genotypes at Ukulinga farm, during 2006/2007 season

Source	df	Brix at anthesis	Brix at maturity	Grain Weight ha^{-1}	Days to anthesis	Biomass weight ha^{-1}	Plant height	Stem diameter
Cultivar	79	130.11*	155.50*	287.84**	622.59**	801.16**	933.52**	245.68**
Block	2	0.14	1.45	4.48*	0.01	9.27**	2.57	1.18
Error	158	6.73	10.98	1.11	66.92	12.65	556.6	0.67
Total	239							

*, ** = significant at P≤0.05 and P≤0.01 respectively

Mean stem sugar content ranged from 2.5 to 18.6°brix at anthesis and 3.5 to 19.3°brix maturity (Table 4.4-2), and showed a normal distribution peaking at about 11°brix at anthesis and 9°brix at maturity of the grain (Figures 4.4-1a and b). The highest observed mean stem sugar values were 18.6°brix for cultivar MN4361 at anthesis and 19.3°brix for cultivar P9528 at maturity. These values fall on the upper half of those reported in the literature for sorghum and are comparable to those reported for sugarcane, a specialised sugar crop. For example, Woods (2001) reported a range of between 11.0 and 18.5°brix at maturity for sorghum and 16.8°brix for sugarcane, in the southern lowveld in Zimbabwe, while Tsuchihashi and Goto (2005) reported values of 15.6°brix under rain-fed and 13.4°brix under dry season conditions for the popular sweet sorghum cultivar “Wray” in Indonesia. In the current study, 23 cultivars were above 13°brix at anthesis and the number increased to 36 at physiological maturity, suggesting that some cultivars accumulated more stalk sugar between anthesis and physiological maturity of the grain. For example, Kari Mtama-1 had 11.7°brix at anthesis which rose to 18.4 at maturity (Table 4.4-2). This trend was also shown by P9528, RTX436, MN1557 (short), MN2500 and some cultivars in Table 4.4-2. This implied that some cultivars were able to accumulate sugar in the stem at the same time feeding the developing grain from the same photo-assimilates. The other cultivars showed a decrease in stem sugar from anthesis to grain maturity. For example, IS 8193Xaf 28 decreased from 16.8°brix at anthesis to 6.1°brix at maturity (Table 4.4-2). Cultivars ICSV 574, SDSH 90162 and MN 4322 showed similar trends (Table 4.4-2), suggesting photo-assimilates translocation to the developing grain from the stems. However, ICSV 700, MRL15, MN 4361, IRAT-204, ICSB 323, PIRIRA 1, ICSB 731, ZLR1, ICSVP 3046 did not change in stem sugar concentration from anthesis to grain maturity, an observation that suggest that grain yield was generally independent of stem sugar accumulation and that there was negligible to none stem sugar remobilisation from stem to the grain.

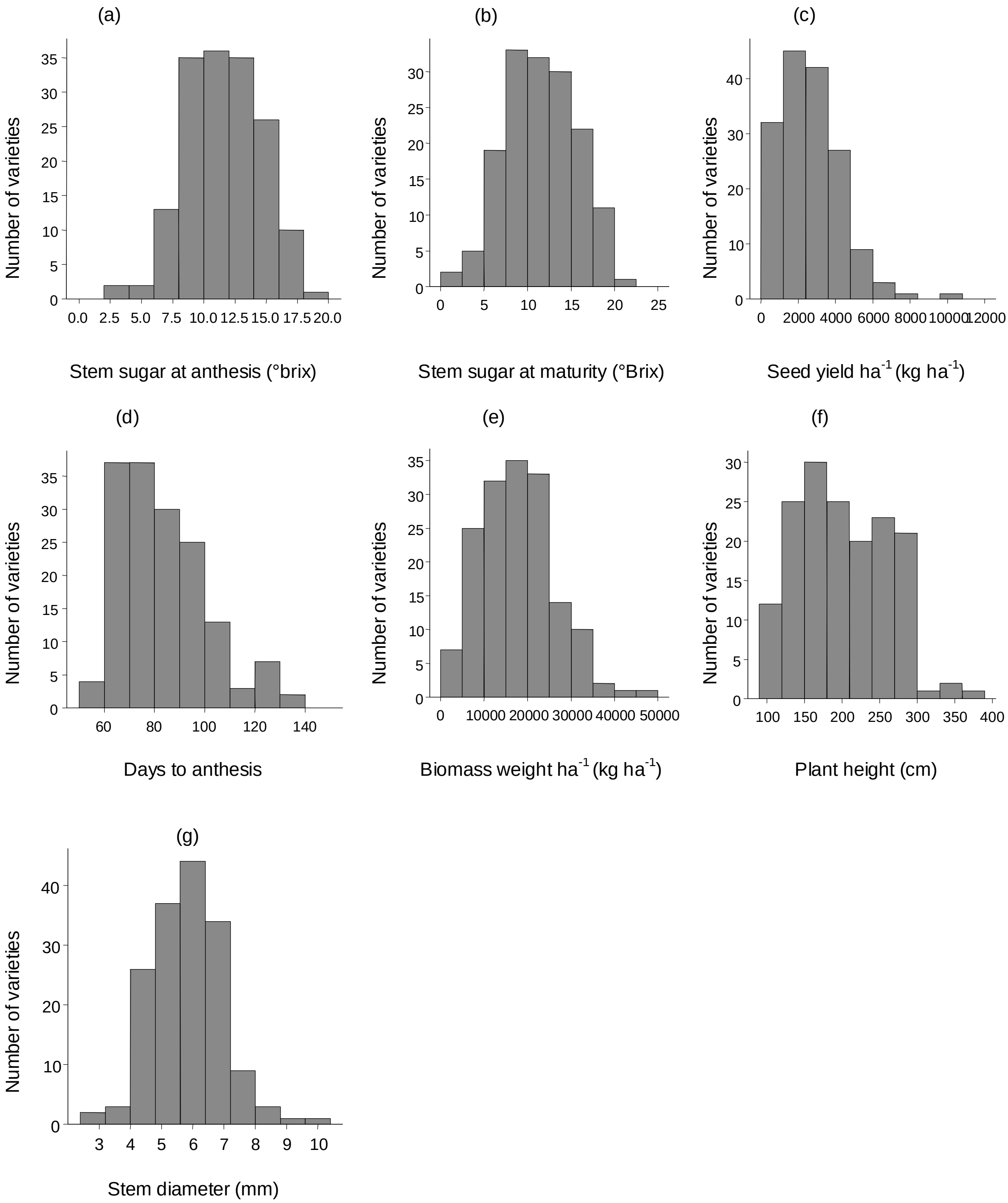
Table 4.4-2: Means of traits measured for the top 30 and bottom five stem brix performers at maturity (data sorted by stalk sugar performance at maturity)

Name	Brix at anthesis	Brix at maturity	Grain yield (kg ha^{-1})	Days to anthesis	Biomass weight (t ha^{-1})	Plant height (cm)	Stem diameter (mm)	R brix (%)	Std brix H (%)
Top 30 stem sugar performers at anthesis									
P9528	14.3	19.3	2605	69.1	3.65	124.1	5.5	160.8	130.4
RTX 436	13.1	19.0	1917	68.3	3.82	105.3	4.7	158.3	128.4
KARI Mtama-1	11.7	18.4	2389	82.5	15.05	196.9	5.3	153.3	124.3
IRAT-204	16.5	18.4	2739	85.1	11.05	138.9	3.4	153.3	124.3
MN 4361	18.6	17.9	1948	58.9	7.98	201.5	4.9	149.2	120.9
MN1557(Short)	6.9	17.3	3120	96.8	44.75	265.4	7.1	144.2	116.9
MN 2500	7.4	17.0	639	115.1	27.22	281.8	8.1	141.7	114.9
MRL15	17.2	16.9	5064	85.3	16.54	180.0	6.5	140.8	114.2
P9521	10.1	16.6	4535	71.3	5.69	149.4	5.2	138.3	112.2
ZSV 3	11.3	16.5	5703	80.6	12.95	188.3	6.6	137.5	111.5
ICSV 700	16.7	16.5	2244	82.8	24.64	231.2	5.7	137.5	111.5
ICSB 323	17.6	16.1	5186	75.2	11.04	111.5	3.8	134.2	108.8
GV 3020	12.9	15.9	4869	64.2	15.58	125.1	6.4	132.5	107.4
MN 1435	9.9	15.8	1291	121.7	28.91	309.6	5.4	131.7	106.8
PIRIRA 1	15.8	15.8	2559	58.9	14.87	167.1	5.7	131.7	106.8
MN 4002(Tall)	10.7	15.7	-	87.8	33.10	180.2	5.9	130.8	106.1
MN 4320(Short)	11.0	15.7	401	68.2	22.11	251.1	6.2	130.8	106.1
THAR	13.9	15.7	3180	67.5	10.17	177.1	6.1	130.8	106.1
SERENA	11.7	15.5	3821	93.5	14.59	176.8	6.9	129.2	104.7
ICSB 731	15.9	15.5	4043	74.5	9.55	171.8	5.1	129.2	104.7
MN 4132	8.8	15.4	-	102.3	21.96	254.6	5.9	128.3	104.1
SDS 342	11.8	15.0	2801	76.7	24.72	176.0	4.9	125.0	101.4
Sefofo	8.1	15.0	459	90.2	32.99	268.3	6.9	125.0	101.4
ZLR1*	13.8	14.8	2550	72.1	16.53	227.1	5.5	123.3	100.0
ICSB 5	7.8	14.8	618	69.1	6.66	118.1	5.7	123.3	100.0
ICSVP 3046	14.6	14.8	1858	85.6	25.37	224.4	5.3	123.3	100.0
GADAM EL HAMAM	11.6	14.4	3598	83.6	26.40	191.1	5.9	120.0	97.3
MN 4320(Tall)	12.1	14.1	2078	75.0	29.52	289.8	6.8	117.5	95.3
ICSB 478	12.7	13.9	1939	82.5	23.50	182.9	6.3	115.8	93.9
SDSL 89569	8.7	13.8	1217	84.3	14.28	181.9	7.5	115.0	93.2
Bottom 5 stem sugar performers									
ICSV 574	11.7	7.2	2460	101.8	28.42	226.4	7.4	60.0	48.6
IS 8193xAF 28	16.8	6.1	1591	98.8	13.37	258.8	6.2	50.8	41.2
P9513B	8.7	5.8	1274	94.0	29.85	219.3	4.6	48.3	39.2
SDSH 90162	10.5	5.6	2082	78.7	9.50	170.2	5.7	46.7	37.8
MN 4322	7.8	3.5	39	53.7	8.94	152.1	2.3	4.2	3.4
Mean	11.8	12.0	2832.8	84.6	17.80	204.0	5.8		
P. value	0.05	0.02	<0.001	<0.001	<0.001	<0.001	<0.001		
SED	3.7	5.0	1512.0	12.0	5.1	33.9	1.2		

***** = standard check; SED = standard error of difference; R brix (%) = relative stem brix (%) at maturity; Std brix H (%) = standard stem brix heterosis (%) at maturity

Stem biomass ranged between 3,0 and 50,0t ha^{-1} and was also negatively skewed (Figure 4.4-1e); an observation that could be attributed to the fact that the cultivars were developed primarily for grain yield and not for stem sugar that may have resulted in breeding for higher biomass levels. In this study, the highest yielding entry with respect to stem biomass yield produced 44.754 ha^{-1} which is not comparable to the highest of 63.9 ha^{-1} reported under irrigation conditions in Zimbabwe by Woods (2001). A total of five cultivars averaged above 30.0t ha^{-1} stem biomass yields (Table 4.4-2), which is comparable to some of the entries reported by Woods (2001). These yields are, however, less than 50.0 to 140.0t ha^{-1} that have been reported for specialised sweet sorghum cultivars developed specifically for stem sugar production in Europe (Claassen *et al.*, 2004). Further, the experiments were also conducted in different mega environments, that is, temperate Europe versus subtropical African conditions in South Africa. Due to the differences in environmental conditions such as daylength, European cultivars are not adapted to African tropical conditions. However, the highest observed biomass yield in the current study was 44.7t ha^{-1} for cultivar MN1557 with intermediate maturity date (Table 4.4-2) under rain-fed conditions indicates a clear potential for improvement gains from the current germplasm base. The components of biomass yield, that is, plant height and stem diameter, also followed similar trends (Table 4.4-2), with negative skeweness with plant height ranging between 100 to 400cm (Figure 4.4-1f) while average plant stem diameter ranged between 3 to 10mm (Figure 4.4-1g).

Twenty three cultivars had grain yields above 3.0t ha^{-1}. Of these, 11 were between 4.0 and 6.0t ha^{-1}, one yielded 7.0 and one 8.4 t ha^{-1} .Mean grain yield ranged from as low as 0.4t ha^{-1} to as high as 8.4t ha^{-1} and was negatively skewed with most varieties yielding between 1.0 and 3.0t ha^{-1} (Figure 4.4-1c). This potential for grain production, together with that of stem sugar accumulation demonstrates the opportunity available for developing dual-purpose sorghum cultivars, apart from specialised sweet stem cultivars alone. Further, adaptation to variable season lengths were demonstrated by the variability observed in these varieties with days to anthesis varying between 60 and 140 days. However the majority of the cultivars took less than 90 days to anthesis of which 25 took less than 75 days, giving a negatively skewed distribution (Figure 4.4-1d). Overall, 51 cultivars recorded stem brix above 11°brix, 62 cultivars recorded yield above 1.5 t ha^{-1}, while only 10 cultivars recorded stem biomass above 30 t ha^{-1}. These findings demonstrated that it was possible to develop improved dual-purpose sorghum cultivars for grain yield and stem sugar. Cultivars that showed high performance for stem sugar at grain maturity, and stem biomass were identified. These were ICSV 700, MN1557 (short), Kari Mtama-1, MRL15, GV 3020, ZLR1, ICSVP 3046, AND GADAM EL HAMAM (Table 4.4-2). There is adequate variability for grain yield and stem sugar but not so much for stem biomass. This could be attributed to emphasis on reduced plant height and improved harvest index selected for in most grain sorghums.



(a)
Number of varieties
0
5
10
15
20
25
30
35
0.0 2.5 5.0 7.5 10.0 12.5 15.0 17.5 20.0
Stem sugar at anthesis (°brix)
(b)
Number of varieties
0
5
10
15
20
25
30
0 5 10 15 20 25
Stem sugar at maturity (°Brix)
(c)
Number of varieties
0
10
20
30
40
0 2000 4000 6000 8000 10000 12000
Seed yield ha-1 (kg ha-1)
(d)
Number of varieties
0
5
10
15
20
25
30
35
60 80 100 120 140
Days to anthesis
(e)
Number of varieties
0
5
10
15
20
25
30
35
0 10000 20000 30000 40000 50000
Biomass weight ha-1 (kg ha-1)
(f)
Number of varieties
0
5
10
15
20
25
30
100 150 200 250 300 350 400
Plant height (cm)
(g)
Number of varieties
0
10
20
30
40
3 4 5 6 7 8 9 10
Stem diameter (mm)

Figure 4.4-1: Histogram showing variation of the traits among 80 sorghum germplasm evaluated at the University of KwaZulu-Natal (South Africa) in the 2006/2007 rainy season: (a) stem brix at anthesis, (b) stem brix at maturity, (c) seed yield, (d) days to anthesis, (e) stem biomass, (f) plant height, (g) stem diameter

4.4.2 Correlation and path coefficient analysis

A correlation study revealed that there could be some challenges in developing new sweet sorghum varieties. There was a negative and highly significant (P≤0.01) phenotypic correlation observed between grain yield and stem biomass at maturity (Table 4.4-3), suggesting the presence of a yield penalty as biomass is improved thereby impacting negatively on seed production. However, path analysis showed that both stem biomass and grain yield had positive but very low effects on stem sugar content at maturity as both their direct effects were low and only significant (P≤0.05) for stem biomass and the indirect effects were also low (Table 4.4-4). This is supported by their non-significant correlation coefficients to stem sugar at maturity (Table 4.4-3). However, more trials over many sites are required to ascertain these relationships. Grain yield was negatively and highly significantly (P≤0.01) correlated to days to anthesis, suggesting that early flowering cultivars were generally low seed yielding compared to late cultivars. This can be attributed to the fact that these materials were mainly bred for grain yield and earliness. Further, late sorghum cultivars are usually high biomass types and the negative correlation could have resulted from the usage of most of the photo-assimilates for biomass growth rather than for grain yield. However, both the direct and indirect effects of days to anthesis to stem sugar at maturity were negligible and the total correlation to the latter was also not significant (P≥0.05) (Table 4.4-4). The correlation coefficients between grain yield and brix at both anthesis and maturity were positive, low, and only significant (P≤0.05) between grain yield and °brix at anthesis (Table 4.4-3). This implied that high grain yielding varieties had more stem sugar than low grain yielders at anthesis, but at maturity, grain yield was generally independent of stem sugar content. In a similar study, Guiying *et al.* (2000) reported a negative correlation of -0.472 between stem sugar and 1000-seed weight at maturity. Arguably, 1000-seed weight on its own is not reflective of grain yield; because it does not indicate the yield per head. However, even if there is a negative association between stem sugar content and yield, it was found in a parallel study that a significant number of farmers were willing to compromise grain yield in adopting dual- purpose varieties with high stem sugar content provided a premium price was paid for the stem sugar (unpublished data).

Table 4.4-3: Correlation coefficients between sorghum traits measured in 80 varieties at Ukulinga farm, during 2006/2007 season

	Brix at anthesis	**Brix at maturity**	**Grain yield (kg ha^{-1})**	**Days to anthesis**	**Biomass weight (t ha^{-1})**	**Plant height (cm)**
Brix at maturity	0.2349*					
Grain yield (kg ha^{-1})	0.2472**	-0.0342				
Days to anthesis	-0.2562**	-0.0795	-0.2953**			
Biomass weight (t ha^{-1})	-0.0838	-0.0523	-0.3603**	0.516**		
Plant height (cm)	-0.1876*	-0.0815**	-0.3482**	0.6709**	0.6414**	
Stem diameter (mm)	-0.1586*	-0.0869	-0.225**	0.4234**	0.4872**	0.3222**

*, ** = significant at P≤0.05 and P≤0.01, respectively.

Table 4.4-4: Path coeffi cient analysis table showing the direct and indirect effects of the sorghum trait to stem sugar at maturity

Trait	**Direct path coefficients on brix at maturity**	**Indirect path values via**						**Total correlation**
		Brix at anthesis	**Grain yield (kg ha^{-1})**	**Days to anthesis**	**Biomass weight (t ha^{-1})**	**Plant height (cm)**	**Stem diameter (mm)**	
Brix at anthesis	0.2060*		<0.0000	-0.0025	<0.0000	0.0128	0.0186	0.2349*
Grain yield (kg ha^{-1})	<0.0000	-0.0509		-0.0048	<0.0000	0.0099	0.0117	-0.0342
Days to anthesis	0.0164	-0.0528	<0.0000		<0.0000	-0.0121	-0.0220	-0.0705
Biomass weight (t ha^{-1})	0.0001*	-0.0173	<0.0000	0.0085		-0.0183	-0.0253	-0.0523
Plant height (cm)	-0.0285**	-0.0386	<0.0000	0.0110	<0.0000		-0.0253	-0.0815**
Stem diameter (mm)	-0.0520	-0.0327	<0.0000	0.0069	<0.0000	-0.0092		-0.0869

*, ** = significant at P≥0.05 and P≥0.01, respectively.

The correlation between stem sugar at anthesis and stem sugar at maturity was positive and significant (P≤0.05) (Table 4.4-3), and the direct effect of stem sugar at anthesis to the later was positive, high and significant (P≤0.05) although the indirect effects were generally low (Table 4.4-4). These results suggest that stem brix at anthesis can be used as an indicator for stem brix at maturity. Although this observation was true for a number of genotypes, it was earlier observed in section 4.4.1 that several genotypes exhibited considerable changes in their stem sugar content between the two stages (Table 4.4-2). A positive and highly significant (P≤0.01) correlation was also observed between days to anthesis and both plant height and stem biomass (Table 4.4-3), suggesting that stem biomass increased as the growth cycle became longer. Marginally-dry tropical lowlands require shorter growth cycle varieties that can maximise yields with limited moisture that is available during the short rain season. This, based on the correlation, will compromise biomass yield. Hybrids, which can accumulate high biomass over a short time, may be needed for those environments. Alternatively a compromise can be reached between earliness and biomass yield. Although the negative and highly significant (P≤0.01) correlation coefficient and the direct effect of plant height to stem sugar at maturity (Table 4.4-3 and 4.4-4) seem to suggest that taller plants had lower stem sugar concentrations at maturity, the total sugar per unit area has been shown to increase as the biomass increases (Woods, 2001; Kangama and Rumei, 2005). This can be due to the fact that, although lower concentration per each cross sectional stems area, taller plants have more sugar because of their greater length compared to shorter ones, thereby yielding more sugar per unit area. High tillering might also result in high stem sugar yields per unit area if the tillers are fully developed to almost the size of the main tiller.

Stem diameter was positively and highly significantly (P≤0.01) correlated to days to anthesis, biomass and plant height, while it was negatively and highly significantly (P≤0.01) correlated to grain yield. Stem diameter is an associated trait of biomass and its association pattern was expected to follow those of other biomass traits, that is, plant height, days to anthesis, and biomass yield. However the negative and significant (P≤0.05) correlation between stem diameter and stem sugar at anthesis and its non-significant association with stem sugar at maturity seems to suggest that thinner stems have more sugar concentration at anthesis, but at maturity the stem diameter did not affect sugar accumulation. The direct effect of stem diameter on stem sugar at maturity was negative but low and the indirect effects through other traits were also negligibly low (Table 4.4-4). This implied that thicker stems had lower stem sugar concentrations compared to their thin counterparts. This phenomenon requires further investigation because biomass yields are improved though plant height and stem thickness. More trials across many sites might be needed to confirm this finding because the screening was conducted in one site.

4.5 Conclusions

Overall, the preliminary study demonstrated that there is high genetic variability for the development of sweet and dual-purpose sorghum varieties in the current germplasm collection. Varieties KARI Mtama-1, MRL15, ICSV700, GV3020, SDS342, ZLR1, ICSVP3046, MN4320 (tall), ICSB478, MN1557 (short), and GADAM EL HAMAM with high brix values, high grain yield, short maturity time and appreciable stem biomass levels were selected for use as source germplasm for the dual-purpose sorghum breeding programme. Some cultivars maintained stem brix levels from anthesis to flowering while others exhibited lower stem brix at maturity compared to their anthesis values. This suggested remobilisation of assimilates in some genotypes and none in others. Therefore, breeding dual-purpose sorghums will depend on the identification of those that maintained high stem brix until maturity over those that showed evidence of remobilisation of stem sugars to the grain. The observed independence of stem brix and grain yield at maturity suggested that the two traits could be bred into one cultivar without compromising the other in most genotypes. Further, path analysis revealed that direct selection for stem sugar at maturity was more important than indirect selection during cultivar development because in all cases, the direct effects were more important than the indirect effects. Therefore, individual traits can be used in selection without serious complications from correlated responses.

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CHAPTER 5

[3]Heterosis, combining ability and cultivar superiority of sorghum germplasm for stem-sugar traits across six environments

5.1 Abstract

There is limited information on the genetics, heterosis and stability of stem sugar traits in sweet sorghum, especially in southern Africa. Suitable cultivars are currently not available and commercial production is largely based on landraces yet hybrid cultivars have been demonstrated to be more productive than pure-line varieties. Therefore a study was conducted to determine heterosis of experimental hybrids, the combining ability of the inbred lines, and the cultivar superiority of both hybrids and pure lines for stem sugar traits across six environments. Eight cytoplasmic male-sterile lines, designated females, were crossed to 10 male lines in accordance with a North Carolina Design II mating scheme. The 80 hybrids, parents and check varieties were evaluated in Mozambique, South Africa and Zimbabwe during 2008-09 in replicated row-column α-lattice designs. There was significant variation among genotypes for stem sugar, stem biomass and the associated traits. Hybrids were predominant in the top 20 for stem brix and stem biomass demonstrating their superiority to pure line varieties. Standard heterosis of up to 25% and 100% was observed for stem brix and stem biomass, respectively, indicating huge gains that can be realised by developing hybrids. Twenty-seven hybrids displayed positive better-parent heterosis for stem brix and 25 for stem biomass. General and specific combining ability effects were significant for all traits implying that both additive and non-additive gene action, respectively, were important for controlling the traits. Therefore, a breeding programme that exploits both additive and non-additive variance in developing hybrid sorghum cultivars is recommended.

Keywords: cultivar superiority index, general combining ability, heterosis, sorghum hybrids, specific combining ability, stem sugar traits

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5.2 Introduction

Sweet sorghum (*Sorghum bicolour* L. Moench) has the potential to improve livelihoods of rural communities in southern Africa due to its potential industrial use for bioethanol production. Stem sugars accumulated by the varieties can be extracted and fermented to provide liquid fuels such as bioethanol. However, sweet sorghum's potential to stimulate rural growth due to its high biomass potential has not received enough attention (Leistritz and Hodur, 2008) especially in tropical Africa. Small-scale and resource-poor farmers in southern Africa reside in marginal and dry tropical lowland environments where sorghum plays an important role due to its drought tolerance compared to other grain cereals (Tsuchihashi and Goto, 2008). Sweet sorghum has a clear comparative advantage over the leading crop, sugarcane (*Saccharum officinarum* L), in bio-fuel production. It can grow under dryland conditions where sugarcane cannot grow (Tsuchihashi and Goto, 2008). Thus sorghum would require less irrigation water than sugarcane in tropical lowlands and dry mid-altitude environments which accounts for about 16% and 19%, respectively, of the cereal mega-environments in southern Africa (Vivek *et al.*, 2005). These areas are characterised by low, erratic and uni-modal annual rainfall during November to March with a high probability of a mid-season dry spell, mid-season drought or a full-season drought. However, the tropical lowland environments are warm enough to produce sorghum throughout the year provided irrigation is applied during off-season.

Literature on the production of sweet sorghums has been scarcely reported, but all year round production has been demonstrated in Indonesia (Tsuchihashi and Goto, 2008). Woods (2000) demonstrated that it was possible to grow sweet sorghum for both bioethanol and bagasse for electricity generation in the tropical lowlands of Zimbabwe, but only in the summer (in-season), November to April. There is therefore need to generate research information on the potential to produce the crop in the tropical lowland environments, both in-season and off-season, and in the dry mid-altitude environments where sorghum plays an important role. Although only about 5% of the land in Africa is under irrigation, some small-scale farmers in the tropical lowlands in southern Africa have access to irrigation facilities. This area includes Chokwe, Makhathini, and Muzarabani in Mozambique, South Africa, and Zimbabwe, respectively. Farmers have traditionally grown sweet stem landraces for chewing as snacks, but only on a small scale. This necessitates the inclusion of the tropical lowland off-season during the evaluation of experimental entries. The challenge is to make available appropriate sweet sorghum cultivars for this purpose. This demonstrates the need to develop productive sweet sorghum hybrids for production at a commercial level. With sweet sorghum, industrial use might economically justify the high costs associated with irrigation during the off-season and in-season should the need to supplement arise.

Research has demonstrated stem sugar concentrations of between 14.0 and 18.5°brix in specialized sweet sorghum cultivars (Guiying *et al*., 2000; Woods, 2000; Tsuchihashi and Goto, 2004), but similar work on dual-purpose cultivars is lacking. Tsuchihashi and Goto (2004) reported stem brix values of about 13 under dryland production in Indonesia. Part the current study reported low stem brix values during the off-season in the tropical lowland environments (Makanda *et al*., 2009). This suggests that stem sugar concentration can be depressed under both dryland and off-season conditions. However, the varieties used in the former study might not be adaptable to the tropical conditions in southern Africa; especially the off-season production and those in the latter have not been evaluated during in-season. This necessitates the need to evaluate experimental hybrids across environments to determine performance stability as well as specific adaptations to the different regions. Lin and Binns (1988) devised a measure of performance stability, the cultivar superiority index (P*i*), across environments. The P*i* is the distance mean square between the response observed in a cultivar in a particular environment and the maximum response observed for the same environments. Therefore, a cultivar with a low P*i* is superior in performance across environments and selected over another with a high P*i* because it shows consistency in performance across environments (Lin and Binns, 1988). Selection is based on a single value, which simplifies the process. The index does not require check varieties in all the environments unlike the previously proposed indices (Lin and Binns 1985; Lin *et al*., 1985), which reduces the trial size and cost. The index has been successfully used in screening barley cultivars by Lin and Binns (1988).

Development of a viable breeding programme for sweet sorghum requires a clear breeding strategy. This depends on the understanding of gene action for the traits of interest. Schlehuber (1945) reported that genes with partial dominance action controlled sucrose content in hybrids. Baocheng *et al*. (1986) reported that genes with additive and dominance effects influenced stem sugar accumulation. Guiying *et al*. (2000) reported that recessive genes exhibiting additive effects controlled stem sugar accumulation in sorghum. Following a QTL analysis, Natoli *et al*. (2002) reported no significant segregation for genes with major effects on stem sugar percentage. However, studies by Ritter *et al*. (2008) suggested involvement of major genes in addition to genes with minor effects for stem brix. Moderate to high h^2 estimates, ranging between 40% and 96% (Baocheng *et al*., 1986; Guiying *et al*., 2000), and the predominance of genes with additive effects suggest that brix could be improved through selection.

Knowledge of the combining ability of the parents, especially for hybrid cultivar development is important for the optimization of a breeding strategy. Reports on the combining ability of sorghum lines for stem brix are scarce in the literature. However, there are reports of significant GCA and SCA effects for the associated traits, but their level of importance was dependent on the germplasm that was evaluated. Kenga *et al*. (2004) reported that SCA effects were predominant over GCA for grain yield and days to anthesis, while Haussmann *et al*. (1999) reported that GCA effects were more important than SCA effects. Nevertheless, results obtained elsewhere may not necessarily give an indication of the behaviour of the genes in a different environment. Falconer and Mackay (1996) reported that combining ability and heritability information is pertinent to the set of genotypes and the environment where it has been tested.

Sorghum hybrid cultivars have been shown to be more productive than pure-lines (Kenga *et al*., 2004; Li and Li, 1998). However, the cost of producing hybrids is only justified when their performance surpasses those of their parents and current varieties. A survey of the literature showed extensive reports on heterosis for grain yield but little information is available on stem sugar heterosis in sorghum. Corn (2008) reported better parent heterosis values ranging between -24% and 7% for stem brix, and -27% to 43% for stem biomass. Therefore there is potential to exploit heterosis in new sweet sorghum cultivar development.

Given the foregoing, this study aimed at studying (i) the combining ability effects, (ii) heterosis and (iii) cultivars superiority of experimental entries for stem brix and associated traits across six environments representing the target recommendation domain in southern Africa. The following hypotheses were tested:

i. cultivars that are superior to those on the market can be developed from the current germplasm,
ii. there are high levels of heterosis for stem brix and associated traits that can be exploited in cultivar development from the current germplasm

iii. genes with additive effects control stem brix, stem biomass and associated traits in sorghum, and

iv. genes with non-additive effects control stem brix, stem biomass and associated traits in sorghum.

5.3 Materials and Methods

5.3.1 Germplasm

Eighteen sorghum lines were divided into two groups based on the status of their cytoplasms. Eight cytoplasmic male-sterile (CMS) A-lines, designated as females, were crossed to 10 cytoplasmic male-fertile lines in accordance with a North Carolina Design II mating scheme to generate 80 hybrids. The males were made up of introduced (improved lines) and southern African (adapted materials) germplasm. Female parents were obtained from the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) in India (Table 5.3-1). During hybridisation, two heads of each of the CMS female lines used covered with a pollination bag and no pollinations were done on them to ensure that the CMS system had not broken. The 80 experimental hybrids, 18 parents and two check varieties were evaluated in trials as described in Section 5.3.2. Iso-cytoplasmic B-lines were grown in lieu of their respective CMS A-lines during the evaluation.

Table 5.3-1: Name, origin and pedigree of parental sorghum lines used in the study

Line No.	Name	Fertility status	Origin	Pedigree	Role in crosses
1	ZLR1 †	CMF	Zimbabwe	Landrace	Male
2	MRL15	CMF	-	Unknown	Male
3	ICSV700	CMF	ICRISAT India	(IS 1082 x SC 108-3)-1-1-1-1-1	Male
4	ICSVP3046	CMF	ICRISAT India	(ICSV 700 x ICSV 708)-9-1-3-1-1-1	Male
5	S35	CMF	ICRISAT India	-	Male
6	Macia	CMF	Mozambique	SDS 3220	Male
7	ZLR2	CMF	Zimbabwe	Landrace	Male
8	ICSR165	CMF	ICRISAT India	SPV 422	Male
9	ICSR57	CMF	ICRISAT India	(SC 108-3 x 148)-12-5-3	Male
10	Thar	CMF	-	-	Male
11	ICSA731	CMS	ICRISAT India	ICSV 1171BF	Female
12	ICSA479	CMS	ICRISAT India	[9ICSB 70 x ICSV 700) x PS 19349B]-5-4-1-2-2	Female
13	ICSA4	CMS	ICRISAT India	[(BTx 622 × UChV2)B lines bulk]-10-1-1	Female
14	ICSA724	CMS	ICRISAT India	ICSP 1B/R MFR-S 7-303-2-1	Female
15	ICSA307	CMS	ICRISAT India	[(ICSB 26 × PM 1861)×(ICSB 22 × ICSB 45) × (ICSB 52 × ICSB 51)]1-3-12-3-1	Female
16	ICSA474	CMS	ICRISAT India	(IS 18432 x ICSB 6)11-1-1-2-2	Female
17	ICSA26	CMS	ICRISAT India	[(296B x BTx 624)B lines bulk]-2-1-1-3	Female
18	ICSA623	CMS	ICRISAT India	(ICSB 11 x PM 17467B)5-1-2-1	Female
Introduced checks					
Saccaline		CMF	USDA	-	
Grassl		CMF	USDA	-	

† = local check; CMF = cytoplasmic male fertile; CMS = cytoplasmic male sterile; - = unknown pedigrees

5.3.2 Experimental sites

The experiment was conducted at Chokwe Research Station (CRS) (24° 31′ S; 33° 0′ E, 40m.a.s.l) in Mozambique and at Makhathini Research Station (MRS) (27º 24'S; 32º 11' 48" E, 72m.a.s.l.) in South Africa during off-season (May to September 2008) and in-season (November 2008 to April 2009). Further in-season trials were conducted at Rattray-Arnold Research Station (RARS) (17º 40' S; 31º 14' E, 1308m.a.s.l.) in Zimbabwe and at Ukulinga Research Farm (URF) (30º 24' E; 29º 24' E, 781m.a.s.l.) in South Africa during November 2008 to April 2009. Both CRS and MRS represent the tropical lowland environments in southern Africa where there is potential for sorghum production both in-season and off-season without adverse effects of low temperatures. The two sites have annual long term mean rainfall of about 600mm and maximum temperatures of about 25-30^{0}C (Figure 5.3-1). RARS and URF represent the mid-altitude environments with annual rainfall of about 800mm and maximum temperatures of 20-30^{0}C (Figure 5.3-1). Although the rainfall is seasonal at all sites, the temperatures and availability of irrigation facilities at CRS and MRS make them ideal for sorghum production throughout the year, unlike URF and RARS where low winter temperatures make it impossible to grow cold sensitive crops like sorghum during May to September. Both CRS and MRS are surrounded by small-scale irrigation schemes with perennial water sources.

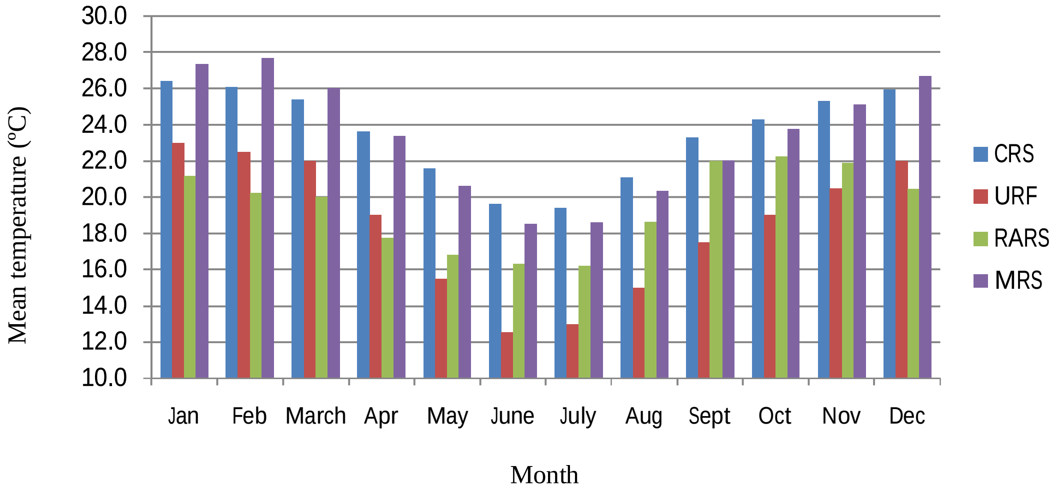

Figure 5.3-1: Long term mean (five-year) temperatures for CRS, URF, RARS and MRS [Data source: Agricultural Research Council-ISCW AgroMet Potchefstroom (2009); Seed Co. Zimbabwe Ltd (2009); Gaisma (2007)]

5.3.3 Experimental design and management

The experiments were laid out as replicated row-column α-designs at each site during May of 2008. Seeds of each entry were planted by hand in two-row plots of 3.0m length at 0.75m inter-row and 0.20m intra-row spacing resulting in a population density of about 66 667 plants ha^{-1}. At MRS and URF, the experiment was laid as a 10 rows × 10 columns and at CRS and RARS, it was a 5 rows × 20 columns. The trials were supplied with 800mm moisture through irrigation during off-season and by supplementary irrigation during in-season. The trials were supplied with 250kg ha^{-1} basal fertiliser (2:3:4, N:P:K) and 200kg ha^{-1} top dressing fertiliser (Lime Ammonium Nitrate with 28% N). The fields were kept weed free by hand weeding. At planting, Curaterr 5G (carbofuran), a systemic insecticide, was applied to prevent damage of the emerging seedlings by mice and cutworm. Stalkborer granules (dimethyl-(2,2,2-trichloro-1-hydroxyethyl) phosphonate) were used to control stalkborer damage and the sorghum heads were covered using fine mesh bags at anthesis to prevent bird predation on the developing grain.

Stem sugar concentration was measured in brix, using an Atago PAL-1 digital hand-held pocket refractometer (with automatic temperature compensation ranging from 0 to 50°C) at the hard dough stage. Due to differences in maturity, each entry was harvested separately when it reached the hard dough stage. The stems were divided into three equal parts, top, middle and bottom sections, and three brix measurements were taken using the middle internode of each section. Stalk juice was squeezed from the cut internode section into the sample stage of the refractometer using a pair of pliers. Both the pliers and the refractometer sample stage were rinsed with clean water and dried with tissue paper before the next sample was measured to contamination with stalk juice from previous samples. Stem diameter and stem juiciness score were also measured from the three mid internode sections using a veneer calliper and a rating scale of 1 (juicy) to 9 (dry) depending on the ease of pressing and resultant juice pressed, respectively. The final values for stem brix, diameter and juice score were an average of the three measurements. Juiciness was scored because of the absence of juice extractors that would assist in the quantification of total amounts of juice per stalk weight. In the absence of juice extractors, breeders risk discarding good materials if selection is based on the refractometer reading alone. To address this problem, an index, the 'stem °brix-juice index' was calculated as follows:

$$\text{Stem brix-juice index} = \text{brix} \div \log[\text{juice score} + 1]$$

Given the same brix reading, this calculation results in an upward adjustment of juicy cultivars over dry ones because at equal brix readings, juicier cultivars have more sugar compared to drier ones. With this index, total sugar becomes a function of stem biomass per unit area. At a given biomass yield, cultivars with high indices are selected over those with lower indices.

Stem biomass was measured at the hard dough stage by stripping plants of all leaves and heads, then cutting at ground level and weighing the stems. Plant height was measured using a 3.0m ruler. Number of days to 50% flowering (time in days taken for half of the plants in a plot to reach anthesis) and days to 95% physiological maturity (time in days to the stage when about 95% of the plants have reached the hard dough stage) were also measured by visual inspection.

5.3.4 Data analyses

Data were analysed using REML procedure in GenStat® (Payne *et al.*, 2007) following a fixed effects model:

$$Y_{ijkl} = \mu + s_i + r_j(s_i) + b(r_j{*}s_i) + m_k + f_l + mf_{kl} + s_i{*}m_{ik} + s_i{*}f_{ij} + s{*}mf_{ikl} + e_{ijkl}$$

Where: Y_{ijk} = observed hybrid response; μ = overall population mean; s_i = effect of the i^{th} environment; $r_j(s_i)$ = effects of the j^{th} replication in the i^{th} environment; $b(r_j{*}s_i)$ = effects of the blocks in the j^{th} replication in the i^{th} environments; m_k = effect of the k^{th} male parent; f_l = effect of the l^{th} female parent; mf_{kl} = interaction effect of the k^{th} male and the l^{th} female parents; $s_i{*}mf_{kl}$ = interaction effect of the i^{th} environments and the interaction effects between the k^{th} male and the l^{th} female parents; and e_{ijkl} is the experimental error.

The hybrid variation was partitioned into male and female parent main effects giving two independent estimates of GCA effects, while the male × female interaction estimates the SCA effects (Hallauer and Miranda, 1988; Kearsey and Pooni, 1996). The GCA effects for the parents were calculated according to Kearsey and Pooni (1996) as follows:

$GCA_f = X_f – \mu$ and $GCA_m = X_m – \mu$, Where: GCA_f and GCA_m = GCA of female and male parents, respectively; X_f and X_m= mean of the female and male parents, respectively; μ = overall mean of all crosses.

The standard error (SE) and standard error of a difference (SED) for male and female GCA effects were calculated according to Dabholkar (1992) separately because the numbers of males and females were not balanced as follows:

$SE_{male} = \sqrt{(MSE/s{*}r{*}f)}$, $SE_{female} = \sqrt{(MSE/s{*}r{*}m)}$ and $SED_{male} = \sqrt{(2MSE/s{*}r{*}f)}$, $SED_{female} = \sqrt{(2MSE/s{*}r{*}m)}$, Where: MSE = mean square error; r = number of replications; f and m = number of female and male parents, respectively.

The SCA effects of the crosses were computed according to Kearsy and Pooni (1996) as follows:

$SCA_X = X_X - E(X_X) = X_X – [GCA_f + GCA_m + \mu]$, Where: SCA_X = SCA effects of the two parents in the cross; X_X = observed mean value of the cross; $E(X_X)$ = expected value of the cross basing on the GCA effects of the two parents; GCA_f and GCA_m = GCA of female and male parents, respectively.

The standard error (SE) and standard error of the difference (SED) for the SCA effects were calculated according to Dabholkar (1992) as follows:

SE = √(MSE/r) and SED = √(2MSE/r), Where: MSE = mean square error; r = number of replications.

Better parent heterosis (%) was computed according Alam *et al*. (2004) as follows:

Better parent heterosis (%) = $[(X_x – X_{BP})/X_{BP}]*100\%$, Where: X_X = observed mean value of the cross; X_{BP} = mean of the better parent.

Standard heterosis was computed according to Kaushik *et al*. (2004) as follows:

Standard heterosis (%) = $[(X_E)/X_{SC}]*100\%$, Where: X_E = observed mean value of the entry; X_{SC} = mean of standard check.

Stability of the entries across the environments was measured by the cultivars general superiority index (P*i*) calculated in excel in accordance with Lin and Binns (1988) as follows:

$$Pi = \sum_{j=1}^{n} \left(Y_{ij} - M_j\right)^2 / (2n)$$

Where: n = number of locations; Y_{ij} = the yield of the i^{th} cultivars in the j^{th} environment; M_j = the maximum yield recorded in the j^{th} environment

The P*i* were computed both *per se* and *inter se* for the sorghum parents to determine their stability as pure lines and in hybrid combinations, respectively. The entries that were not represented in all the environments had their P*i* computed across those environments in which they were grown. A further parameter, P(*is* – *ps*), was devised and computed as the difference between the parental performances *inter se* minus its performance *per se* to compare their performance in hybrid crosses against their performance as pure lines. Therefore, positive P(*is* – *ps*) indicate that a genotype was superior in cross combinations than as pure lines and vice versa.

5.4 Results

5.4.1 Mean performance and standard heterosis

Environments, entries, and environments × entry interaction were significant (P≤0.01) for all traits (Table 5.4-1). Site × entry interaction tables are presented for the major traits, stem brix and stem biomass only because, for all the traits, the Spearman's Rank Correlations of entries across environments were significant (r = 0.593; P≤0.05). This meant that the environments ranked the entries similarly and therefore only overall means were presented for the rest of the traits.

Table 5.4-1: Mean squares for stem brix and associated traits of sorghum hybrids across six environments

Source	df	Stem brix	Stem juice score	Stem brix -juice index	Stem biomass (t ha^{-1})	Plant height (cm)	Stem diameter (mm)	Days to 50% flowering
Evt	5	247.25**	320.40**	106.00**	124.34**	1351.81**	1980.58**	758.11**
Rep(Evt)	8	23.63	20.43	21.45	21.08	16.96	40.35	12.40
Block(Rep)(Evt)	142	151,55	134.33	109.39	114.96	140.72	287.27	153.46
General analysis of all entries including checks								
Genotypes	99	342.92**	189.31**	267.51**	734.29**	3636.14**	315.25**	946.85**
Evt*Genotype	495	831.41**	420.64**	477.09**	691.07**	1583.42**	773.62**	934.64**
Error	371	6.36	2.61	105.90	201.03	479.10	4.65	34.35
Combining ability analysis								
Hybrids	79	289.37**	115.50**	221.01**	317.37**	2165.97**	227.59**	489.34**
GCA_m	9	70.02**	27.57**	60.09**	124.52**	1262.45**	96.14**	225.28**
GCA_f	7	57.47**	16.75*	30.58**	42.94**	411.15**	21.26*	66.06**
SCA	63	161.88**	71.17	130.35**	149.91**	492.37**	110.19**	198.00**
Evt*Hybrids	395	681.58**	262.91	385.65**	428.34**	1306.22**	628.14**	723.55**
Evt*GCA_m	45	132.12**	46.61	66.84**	145.96**	575.12**	223.87**	442.27**
Evt*GCA_f	35	143.21**	51.27	62.01**	40.00	171.49**	75.12**	67.80**
Evt*SCA	315	406.25**	165.03	256.81**	242.38	559.61**	329.15**	213.48*
Error	491	5.90	2.90	104.4	242.90	369.30	3.84	32.43

Evt = environments; **, * significant at P≤0.01 and P≤0.05, respectively

Site means for stem brix ranged from 8.32 to 13.07°brix, being lowest at Makhathini Research Station during both the winter and summer periods (Table 5.4-2). Sixteen of the top 20 genotypes ranked high in stem brix performance across environments were hybrids, three were parents and one was an introduced stem brix check, Saccaline (Table 5.4-2). The local stem brix check, ZLR1, had a mean rank of 38 across environments while the introduced stem brix check was ranked 15. Stem brix values of the top 20 brix performers were above 10°brix during the summer seasons in the mid-altitude environments and at CRS (Table 5.4-2). The values were lower during winter at both CRS and MRS and during summer at MRS (Table 5.4-2). The bottom five performers at each site were generally poorly ranked across the environments (Table 5.4-2).

Table 5.4-2: Stem brix of selected sorghum hybrids and parents over six environments (genotype by environment mean matrix SED = 0.95)

Entry	Site						Overall mean	Mean rank	Standard heterosis	P*i*
	Tropical lowland				Mid-altitude					
	CRS-S	CRS-W	MRS-S	MRS-W	RARS	URF				
Top 20 stem brix performers										
ICSVP3046×ICSA4	14.50	16.23	11.55	9.23	15.15	14.53	13.53	11.30	125.05	1.86
ICSV700×ICSA731	13.77	14.30	12.35	9.97	15.45	13.40	13.21	12.50	122.09	2.72
ICSR165×ICSA307	14.32	13.90	10.95	9.93	14.70	13.07	12.81	14.83	118.39	3.37
ZLR1×ICSA26	13.78	9.77	12.57	10.17	14.03	13.82	12.36	16.67	114.23	5.82
ZLR1×ICSA307	14.75	12.12	9.50	7.27	15.18	14.82	12.27	21.33	113.40	4.82
MRL15×ICSA26	15.38	12.07	12.43	9.25	13.68	10.10	12.15	19.17	112.29	7.45
ICSB479*	12.57	8.77	10.25	11.45	13.90	15.72	12.11	21.17	111.92	8.53
Saccaline ‡	-	-	9.22	-	12.02	14.88	12.04	15.33	111.28	6.85
ICSR165×ICSA724	12.65	13.00	9.75	7.55	15.47	13.57	12.00	24.50	110.91	5.59
MRL15×ICSA4	11.38	9.53	12.38	8.50	13.90	15.38	11.85	24.00	109.52	7.37
ICSR165×ICSA4	15.88	11.30	12.90	5.42	10.35	15.20	11.84	28.17	109.43	10.28
ICSV700×ICSA307	15.80	8.55	11.75	8.38	10.15	16.10	11.79	27.67	108.96	9.15
ICSR165*	16.27	10.18	10.53	7.95	12.68	12.72	11.72	48.33	108.32	9.29
ICSR165×ICSA479	11.00	10.95	-	8.85	16.00	-	11.70	24.00	108.13	7.67
ICSR165×ICSA26	13.25	10.68	10.75	7.28	14.70	13.20	11.64	26.83	107.58	7.09
S35×ICSA4	12.50	-	10.60	-	9.47	13.57	11.54	37.25	106.65	10.64
ICSV700*	13.12	9.98	7.85	-	10.55	15.77	11.45	32.60	105.82	11.11
Macia×ICSA307	15.52	11.90	10.60	9.10	13.15	8.28	11.43	25.67	105.64	10.92
ICSVP3046×ICSA731	13.12	10.23	10.70	10.05	11.18	12.30	11.26	28.50	104.07	9.08
ICSV700×ICSA4	14.57	9.30	9.90	7.07	13.40	13.15	11.23	31.83	103.79	9.03
Bottom 5 stem brix performers										
MRL15×ICSA724	3.73	8.82	4.97	6.20	11.22	9.48	7.40	63.83	68.39	33.11
ZLR2×ICSA724	1.88	9.52	6.58	5.95	6.75	12.35	7.17	63.83	66.27	36.94
Msinga	-	-	6.03	8.23	4.90	9.30	7.12	64.75	65.80	32.72
ICSV700×ICSA474	8.55	5.08	4.08	8.90	8.22	6.42	6.88	67.00	63.59	17.94
Robbocane 11/59	9.10	-	4.65	5.65	5.10	9.62	6.82	75.20	63.03	34.74
ZLR2×ICSA307	2.65	-	-	8.52	6.12	-	5.76	72.50	53.23	49.79
Parents										
ICSV3046	12.75	10.75	5.72	7.47	11.06	17.85	10.93	37.00	101.02	13.66
ICSB307	13.05	7.42	7.55	9.15	11.22	16.82	10.87	33.83	100.46	12.28
ZLR1 †	13.05	13.55	8.57	7.92	9.82	12.02	10.82	38.17	100.00	10.40
ICSB4	-	8.72	-	-	12.23	-	10.48	74.60	96.86	17.93
Thar	10.28	-	7.58	-	-	13.05	10.30	27.13	95.19	14.54
ICSB724	13.85	8.25	4.70	10.07	8.32	16.23	10.24	39.83	94.64	17.00
ICSB731	15.05	10.07	4.82	7.33	11.40	12.38	10.18	41.83	94.09	14.57
ICSB623	10.10	9.95	12.10	9.15	4.90	14.22	10.07	38.67	93.07	18.86
Macia	13.65	9.27	7.62	5.90	8.16	15.40	10.00	44.67	92.42	15.46
MRL15	12.57	12.23	7.55	6.82	8.25	12.52	9.99	45.50	92.33	14.41
S35	11.28	-	5.75	-	5.58	16.65	9.82	46.17	90.76	24.18
ICSB26	9.93	8.53	4.33	11.45	9.90	13.50	9.61	48.50	88.82	19.31
ICSR57	11.00	7.65	8.10	9.73	8.93	10.68	9.35	48.33	86.41	19.33
ZLR2	10.78	11.15	5.75	7.00	3.33	11.15	8.19	57.17	75.69	28.35
ICSB474	8.85	8.35	5.47	7.20	9.25	9.70	8.14	63.50	75.23	25.46
Site mean	11.85	10.39	8.61	8.32	10.70	13.07	10.48			
	9.79				11.89					

†, ‡ = regional and introduced stem brix checks, respectively; * = parents in the top 20 and bottom 5; CRS-S = Chokwe Research Station Summer/in-season: CRS-W = Chokwe Research Station Winter/off-season; MRS-S = Makhathini Research Station Summer/in-season; MRS-W = Makhathini Research Station Winter/off-season trial; RARS = Rattray Arnold Research Station Summer/in-season; URF = Ukulinga Research Farm Summer/in-season; – = data not available and P*i* values for the cultivars computed across the environments they were represented

Stem biomass showed similar trends. Makhathini Research Station winter trial recorded significantly lower stem biomass than the rest of the environments (Table 5.4-3). An introduced stem brix entry, Grassl, topped the list of 20 highly-ranked performers which was also constituted by 17 hybrids and two parent varieties (Table 5.4-3). There were a few entries that deviated from the general rank in some environments. For example, hybrid ZLR1×ICSA479 recorded significantly lower yields at CRS in summer and MRS in winter but had high yields in the rest of the environments (Table 5.4-3). ICSB31 also showed high performance at URF in summer but very poor performance at the rest of the environments. Such entries could largely be responsible for the significant interaction between entries and environments. However, most of the entries were consistently ranked across environments as confirmed by the Spearman's Rank correlations.

Stem brix-juice index values ranged from 9.7 (hybrid ZLR1×ICSA623) to 35.7 (hybrid ICSR165×ICSA307) and three hybrids and one parent had more than 100% standard heterosis for the index (Table 5.4-4). Juice scores ranged from juicy cultivars with close to 1.0 scores to dry cultivars averaging a score of 6.0 (Table 5.4-4). Most juice scores were between 2.0 and 3.0, showing that the entries were generally juicy. Stem diameter ranged from 12mm to 20mm with most entries between 14mm and 16mm (Table 5.4-4). Plant height and days to 50% flowering ranged from 108cm (parent ICSB623) to 315cm (hybrid S35×ICSA26) and 62 days (hybrid Thar×ICSA479) to 105 days for the introduced stem biomass check variety Grassl, respectively.

Table 5.4-3: Stem biomass (kg ha^{-1}) performance of selected sorghum hybrids and parents over six environments (genotype by environment mean matrix SED = 5890)

Entry	Site						Overall Mean	Mean rank	Standard heterosis	P*i*
	Tropical lowland				Mid-Altitude					
	CRS-S	CRS-W	MRS-S	MRS-W	RARS	URF				
Top 20 biomass performers										
Grassl ‡	63114	-	69904	32159	82381	95089	68529	2.67	201.23	2.80
ICSR165×ICSA26	48643	45900	49291	26781	94143	68549	55551	10.50	163.12	4.74
ICSR165×ICSA474	46429	55189	53764	24904	85714	55022	53504	11.17	157.11	4.34
MRL15×ICSA474	33200	47089	107557	38517	38857	47768	52165	16.83	153.18	6.34
ICSR165×ICSA307	57557	55422	42125	43506	49667	53616	50316	11.83	147.75	8.02
ICSR165*	55971	30278	72827	14683	50571	64732	48177	23.00	141.47	4.74
ICSVP3046*	33243	24889	53296	25983	48190	92232	46306	20.50	135.97	6.15
S35×ICSA4	45643	-	68854	-	33429	35525	45863	15.83	134.67	11.30
S35×ICSA307	46693	-	56798	-	53000	25558	45512	14.67	133.64	11.72
ZLR1×ICSA479	27343	53322	60018	31956	52571	44643	44976	18.00	132.07	6.64
ICSR165×ICSA4	47164	33478	58664	21278	51762	47121	43245	20.50	126.99	6.54
ICSVP3046×ICSA26	39657	54900	48211	12844	65190	36607	42902	24.17	125.98	7.74
ICSV700×ICSA731	43021	44844	32112	32815	57905	45089	42631	18.17	125.18	8.50
ICSVP3046×ICSA731	50914	49822	35564	20200	51000	39576	41179	23.00	120.92	9.07
ICSVP3046×ICSA307	54929	43989	43380	20041	51667	32701	41118	23.17	120.74	8.86
MRL15×ICSA4	34857	13278	71196	23070	60000	42411	40802	26.17	119.81	7.08
ICSV700×ICSA474	30357	56289	29150	33089	55714	33973	39762	23.33	116.76	10.45
Thar×ICSA4	41029	-	46836	-	33190	37054	39527	19.00	116.07	14.07
ZLR1×ICSA474	28136	49044	26450	31517	70286	30089	39254	26.33	115.27	10.69
ICSV700×ICSA307	28414	34589	51143	23558	54048	42411	39027	26.50	114.60	8.11
Bottom 5 biomass performers										
Macia*	17505	6778	22012	13389	15238	17031	15326	69.00	45.00	21.99
ICSB724*	14836	6500	15284	9283	15000	27991	14816	69.50	43.51	21.22
ICSB731*	17550	11200	6736	14158	6667	30513	14471	67.67	42.49	22.61
ICSB26*	14807	18600	8807	12674	16143	15558	14432	72.33	42.38	22.51
Robbocane 11/59	6600	-	12693	15287	20667	12768	13603	60.67	39.94	25.17
ICSB623*	9543	24744	3196	6489	12000	6161	10356	77.17	30.41	25.76
Parents										
ZLR1 †	23143	28117	27941	35931	57500	31696	34055	34.00	100.00	11.89
ICSV700	16821	34483	36968	-	25714	55737	33945	34.67	99.68	13.92
Thar	31629	-	38395	-	-	12768	27597	23.67	81.04	20.92
ICSB474	17493	19444	22468	20722	49286	24554	25661	51.83	75.35	15.28
MRL125	39957	20544	29168	13544	27333	22857	25567	50.00	75.08	15.57
S35	32271	-	35773	-	10429	12455	22732	39.50	66.75	24.93
ICSB479	2910	22967	457	25758	24952	35714	18793	56.00	55.18	20.81
ICSR57	29729	14833	16971	8137	15571	27232	18746	61.50	55.05	19.36
ICSB307	26914	16044	5814	13350	11429	26741	16715	65.00	49.08	21.55
ZLR2	20764	23167	8014	9772	17286	15000	15667	70.00	46.00	21.99
ICSB4	-	8322	-	-	3333	-	5828	27.00	17.11	26.84
Mean	29911	33519	33235	20950	37708	30200	30702			
	29404				33954					

†, ‡ = regional and introduced stem brix checks, respectively; * = parents in the top 20 and bottom 5; CRS-S = Chokwe Research Station Summer/in-season: CRS-W = Chokwe Research Station Winter/off-season; MRS-S = Makhathini Research Station Summer/in-season; MRS-W = Makhathini Research Station Winter/off-season trial; RARS = Rattray Arnold Research Station Summer/in-season; URF = Ukulinga Research Farm Summer/in-season; – = data not available and P*i* values for the cultivars computed for across the environments they were represented; P*i* = cultivar superiority index, the values were divided by 100,000,000 because of their big sizes

Table 5.4-4: Stem juice-brix index and other stem sugar traits of selected sorghum hybrids and parents across six environments

Entry	Stem brix-juice index		[a]Stem juice score	Stem diameter (mm)	Plant height (cm)	Days to 50% flowering
	Values	Standard heterosis (%)				
Top 20 stem brix-juice index performers						
ICSR165×ICSA307	35.7	112.8	2.4	14.9	236.7	87.5
ZLR1×ICSA474	32.5	102.5	2.3	14.0	246.1	81.8
IOCSV700×ICSA731	32.1	101.3	2.3	14.6	246.0	87.9
ICSVP3046 *	32.0	101.0	2.7	14.7	224.8	86.0
ZLR1 †*	31.7	100.0	1.4	14.9	223.8	86.8
ICSR165×ICSA724	31.3	98.8	2.0	16.6	203.8	91.3
ICSV700×ICSA724	31.3	98.8	1.5	14.9	246.9	88.2
ICSV700×ICSA479	30.5	96.3	1.8	13.9	226.0	89.5
MRL15×ICSA479	30.2	95.3	2.2	17.2	223.8	87.1
MRL15×ICSA26	30.2	95.1	2.5	14.7	204.9	88.1
ZLR1×ICSA307	30.1	94.9	2.1	14.8	224.8	85.5
Macia×ICSA307	30.0	94.6	2.4	15.7	159.5	83.9
ICSV700×ICSA307	29.5	93.2	2.0	15.4	244.8	96.8
ICSR165 *	29.5	92.9	2.8	17.8	219.0	99.5
ZLR1×ICSA479	29.1	91.8	2.0	13.9	230.6	79.8
ZLR1×ICSA26	28.5	90.0	2.8	14.1	230.5	83.2
ZLR1×ICSA731	28.0	88.4	1.8	13.7	227.8	80.3
MRL15×ICSA474	27.6	87.1	3.4	16.7	230.8	83.0
ICSVP3046×ICSA731	27.3	86.0	3.0	14.7	240.4	90.0
Macia×ICSA4	26.8	84.6	2.8	16.1	218.1	93.8
Saccaline ‡	25.7	81.1	2.5	13.8	192.8	74.8
Bottom 5 stem brix-juice index performers						
Msinga	12.0	37.8	5.4	14.1	-	82.8
S35×ICSA479	11.6	36.5	6.0	20.8	295.0	88.0
ZLR2×ICSA724	11.5	36.3	4.2	15.4	165.6	83.5
ZLR1×ICSA307	11.2	35.3	4.2	14.9	131.7	85.8
ZLR1×ICSA623	9.7	30.7	4.4	15.8	135.0	79.9
Parents						
ICSV700	26.3	83.0	2.0	14.9	262.8	89.0
ICSVP3046	24.3	76.6	2.5	15.8	224.5	97.3
ICSB307	24.0	75.7	2.0	15.8	143.9	92.9
ICSB731	23.9	75.3	2.2	14.3	179.0	91.2
MRL15	23.7	74.7	2.9	15.6	181.4	86.5
ICSB724	23.7	74.7	1.8	15.2	128.7	86.5
ICSB479	23.5	74.0	3.4	14.1	183.7	92.6
ICSB26	21.3	67.1	2.6	13.7	120.2	83.8
Macia	20.8	65.6	2.8	13.4	152.5	80.6
S35	19.6	61.8	3.0	16.5	183.2	80.0
ICSB4	18.4	58.0	4.5	14.1	115.2	87.7
ICSR57	18.2	57.5	3.8	14.4	131.6	87.5
ZLR2	16.6	52.4	4.0	12.7	124.3	77.0
Thar	16.6	52.2	3.5	16.1	239.1	105.0
ICSB623	15.9	50.2	3.6	12.1	108.4	83.7
Mean	21.8		3.0	15.1	206.8	85.8
P-value	<0.001		<0.001	<0.001	<0.001	<0.001
SE	3.08		0.52	0.54	5.13	1.58
SED	4.36		0.73	0.77	7.26	2.23

†, ‡ = regional and introduced stem brix checks, respectively; * = parents in the top 20 and bottom 5; a stem juice was scored using the scale 1 = juicy and 9 = dry.

5.4.2 Cultivar superiority

Hybrid cultivars ICSVP3046×ICSA4, ISCV700×ICSA731, ICSR165×ICSA307, ZLR1×ICSA26, and ZLR1×ICSA307 were the top five with less than 6.0 P*i* indices (Table 5.4-2). The top 20 stem brix performing cultivars generally had lower P*i* indices compared to the bottom five performers. Male parents ZLR1, ICSV700, ICSVP 3046, ICSR165 and female parents ICSA479, ICSA307 with low *per se* P*i* values showed high stability for stem brix across environments (Table 5.4-5). Male parents ICSR165 and ZLR1 and female parents ICSA479 and ICSA4 (with low P*i* values *inter se*) further showed high cultivar superiority for stem brix in single cross hybrid combinations (Table 5.4-5). Most parents with positive P*i*(*is* – *ps*) values showed better performance in crosses than as pure lines for stem brix (Table 5.4-5). Those with negative P*i*(*is* – *ps*) values were more stable as pure lines.

Cultivar superiority indices for stem biomass followed a similar trend. Conversely, most parents exhibited better performance as pure lines than in hybrid combinations for stem biomass. Cultivars with high stem biomass means across all environments displayed low P*i* values compared to those with low stem biomass means (Table 5.4-3). For example, the introduced biomass check (Grassl) and the rest of the top 20 entries had P*i* values less than 15.00, while the bottom five were above 21.00 (Table 5.4-3). The P*i* values were consistent with the mean rank of the entries across environments. Entries with low *Pi* values were generally ranked high across the environments. Male parents ICSVP3046 and ICSR165 were most stable for stem biomass. However, all parents, except ICSVP3046 and ICSR165, exhibited better stem biomass stability as individual entries than in crosses hence the negative *inter se* minus *per se* P*i* values (Table 5.4-5).

Table 5.4-5: *Per se* and *inter se* cultivar superiority indices (P*i*) of 18 sorghum parents for stem brix and stem biomass across six environments

	Stem brix P*i*			[a]Stem biomass P*i*		
	inter se	per se	P*i*(*is* – *ps*)	inter se	per se	P*i*(*is* – *ps*)
Male parents						
ZLR1	13.22	10.4	2.82	11.83	11.89	-0.06
MRL15	16.67	14.41	2.26	11.46	15.57	-4.10
ICSV700	15.59	11.11	4.48	10.74	13.92	-3.19
ICSVP3046	15.19	13.66	1.53	9.95	6.14	3.81
Macia	16.71	15.46	1.25	14.86	21.06	-6.20
ZLR2	27.16	28.35	-1.19	13.41	21.99	-8.59
ICSR165	9.40	9.29	0.11	8.38	4.74	3.64
ICSR57	13.43	19.33	-5.90	17.80	19.36	-1.56
S35	24.25	24.18	0.07	16.59	24.93	-8.34
Thar	26.72	14.54	12.18	16.22	20.92	-4.70
Female parents						
ICSA731	18.94	14.56	4.378	13.20	22.61	-9.42
ICSA479	14.92	8.53	6.39	13.37	20.81	-7.43
ICSA4	13.00	17.93	-4.93	12.80	26.84	-14.05
ICSA724	25.00	17.00	8.00	16.01	21.22	-5.21
ICSA307	19.01	12.28	6.73	12.15	21.55	-9.40
ICSA474	21.35	25.46	-4.11	9.02	15.28	-6.26
ICSA26	15.09	19.31	-4.22	11.53	22.51	-10.98
ICSA623	20.04	18.86	1.18	17.09	25.76	-8.66

[a] = P*i* score divided by 100,000,000

5.4.3 Better parent heterosis

Heterosis values are presented for stem brix and stem biomass because stem brix was significantly correlated to stem brix-juice index (r = 0.575; P<0.001), stem biomass strongly correlated with both plant height (r = 0.603; P<0.001) and stem diameter (r = 0.423; P<0.001), and juice score with stem brix-juice index (r = 0.643; P<0.001). For days to 50% flowering, all the entries showed adaptation to the season, implying that they were adapted. Therefore, only the two major traits will be presented and the associated traits assumed to follow similar trends. Twenty-seven hybrids displayed positive better parent heterosis of up to 24% for stem brix (Figure 5.4-1). Nine hybrids were above 10% and 12 of the 27 hybrids involved locally adapted parents ZLR1, Macia, MRL15 and Thar (Figure 5.4-1). Twenty-five hybrids displayed better parent heterosis for stem biomass of up to 79% (Figure 5.4-2). Ten of these were hybrids involving local parents ZLR2, ZLR1, Thar, MRL15, and Macia and 16 hybrids displayed better parent heterosis above 10% (Figure 5.4-2). The tall introduced male parents ICSV700 and ICSVP3046 were predominant in crosses displaying positive better parent heterosis (Figure 5.4-2). Ten hybrids ICSV700×ICSA731, ZLR1×ICSA26, ICSR165×ICSA307, IMDP97×ICSA26, S35×ICSA4, ICSVP3046×ICSA731, ICSV700×ICSA307, MRL15×ICSA474, MRL15×ICSA4, and ICSR165×ICSA26 displayed positive and significant better parent heterosis for both stem brix and stem biomass (Figures 5.4-1 and 5.4-2).

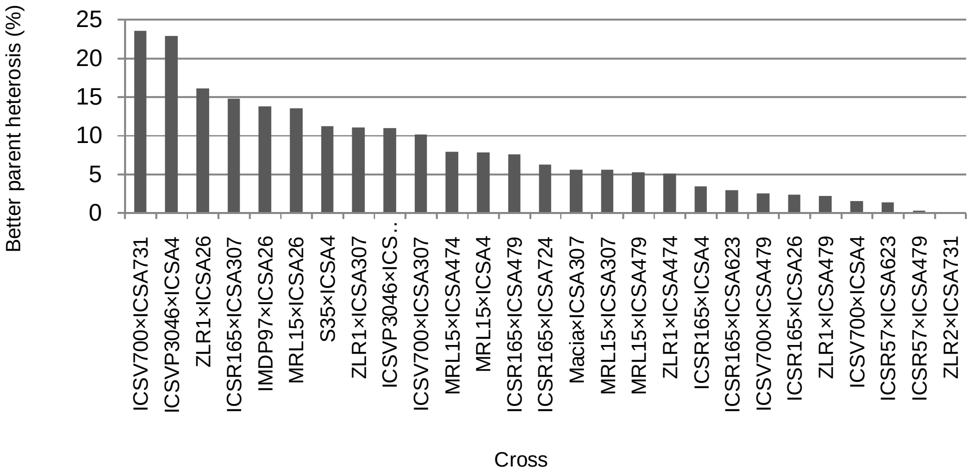

Figure 5.4-1: Twenty-seven sorghum hybrids exhibiting positive better-parent heterosis for mean stem brix across six environments

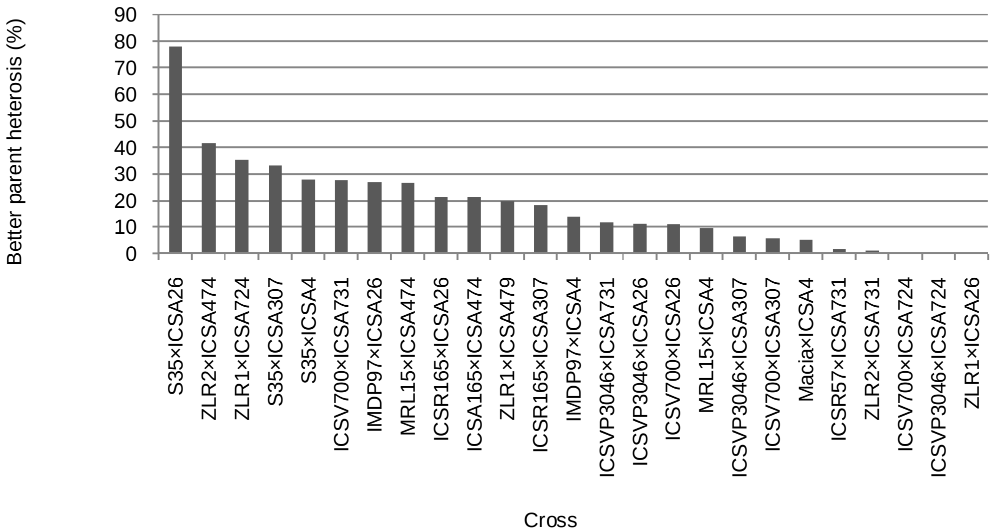

Figure 5.4-2: Twenty-five sorghum hybrids displaying positive better-parent heterosis for stem biomass across six environments

5.4.4 Combining ability effects

The male and female GCA effects and SCA effects were significant (P≤0.05) for all the traits, except male GCA effects for juice score (Table 5.4-1). The interaction of GCA effects and site was also significant (P≤0.05) for the traits except female GCA effects for stem biomass (Table 5.4-1). The interaction between SCA effects and environments was significant (P≤0.05) for all traits except for juice score and stem biomass (Table 5.4-1).

Table 5.4-6: GCA effects for the male and female sorghum parents for stem brix and associated traits across six environments

		Stem °brix	Stem juice score	Stem brix-juice index	Plant height (cm)	Stem diameter (mm)	Stem biomass (kg ha^{-1})	Days to 50% flowering
Male parents								
ZLR1		0.5*	-0.4**	4.4**	14.2**	-1.1**	5098*	-3.4**
MRL15		0.1	0.0	1.3	-9.2**	0.2	-686	-0.9
ICSV700		0.5*	-0.5**	4.1*	25.5**	-0.4*	3575	4.3**
ICSVP3046		0.2	0.0	0.4	22.8**	0.2	4433*	3.9**
Macia		-0.2	-0.3	0.5	-24.8**	-0.8*	-6185**	-2.4**
ZLR2		-1.5**	1.1	-7.5**	-37.6**	-1.0**	-6646**	-3.3**
ICSR165		1.0	0.2	1.4	15.4**	0.2	9455**	3.6**
ICSR57		-0.3	-0.3	-0.7	-37.2**	-0.9**	-9120**	-0.5
S35		0.2	0.6**	-2.0	27.3**	2.6**	1167	0.5
Thar		-0.6*	0.5**	-4.6**	22.6**	2.3**	-262	-2.0*
	SE	0.23	0.18	1.09	1.82	0.19	1472.7	0.56
	SED	0.33	0.26	1.54	2.57	0.27	2082.7	0.79
Female parents								
ICSA731		-0.1	0.1	-0.7	4.6*	0.0	37	0.6
ICSA479		0.6*	0.0	1.9*	9.8*	-0.3	-76	-0.7
ICSA4		0.8*	0.2	1.1	2.6	-0.2	1306	-0.3
ICSA724		-1.0**	0.2	-1.2	-12.5**	0.2	-2419	0.3
ICSA307		0.7**	-0.6**	4.9**	-1.7	0.4**	764	4.5**
ICSA474		-0.5**	-0.1	-0.6	23.6**	-0.1	7921**	-2.3*
ICSA26		0.5**	-0.2	1.6	1.1	-0.7**	1687	1.4*
ICSA623		-0.9**	0.4**	-4.6**	-42.3**	-0.4**	-9886**	-3.2*
	SE	0.22	0.17	0.98	1.71	0.18	1388.4	0.52
	SED	0.32	0.24	1.39	2.42	0.26	1963.6	0.74

**,* = significant at P≤0.01 and P≤0.05, respectively

Male parents ZLR1, ICSV700 and female parents ICSA479, ICSA4 and ICSA26 significantly (P≤0.05) increased stem brix by up to 0.8°brix in their hybrids (Table 5.4-6). The male parents ICSVP3046, Thar, ICSR165, ZLR2 and MRL15 displayed significant (P≤0.05) SCA effects of up to 2.6ºbrix in single cross hybrid combinations with female parents ICSA731, ICSA4, ICSA724, ICSA26, ICSA474 and ICSA623 (Figure 5.4-3a). Stem juiciness was significantly (P≤0.05) increased by ZLR1, ICSV700, ICSA307 and ICSA623 (Table 5.4-6). Entries that showed significant SCA effects for stem juiciness were also observed (Figure 5.4-3b). The stem brix-juice index was also significantly (P≤0.05) improved by cultivars that increased stem brix (Table 5.4-6). Stem biomass was significantly (P≤0.05) increased by male parents ZLR1, ICSVP3046, ICSR165 and female parent ICSA47 (Table 5.4-6). These male parents together with ICSV700, Thar, ICSR165, ZLR2 and MRL15 displayed significant (P≤0.05) SCA effects in crosses ranging from 373kg ha^{-1} for the cross MRL15×ICSA307 to 26kg ha^{-1} for S35×ICSA26 (Figure 5.4-4). The majority of the male parents significantly (P≤0.05) increased plant height by up to 25cm, except for MRL15, Macia, ZLR2 and ICSR578 which significantly (P≤0.05) reduced it (Table 5.4-6). The female parents displayed similar trends with ICSA731, ICSA479 and ICSA474 significantly (P≤0.05) increasing plant height while ICSA724 and ICSA623 significantly (P≤0.05) reduced it (Table 5.4-6). Parents increasing and reducing days to flowering were also observed (Table 5.4-6).

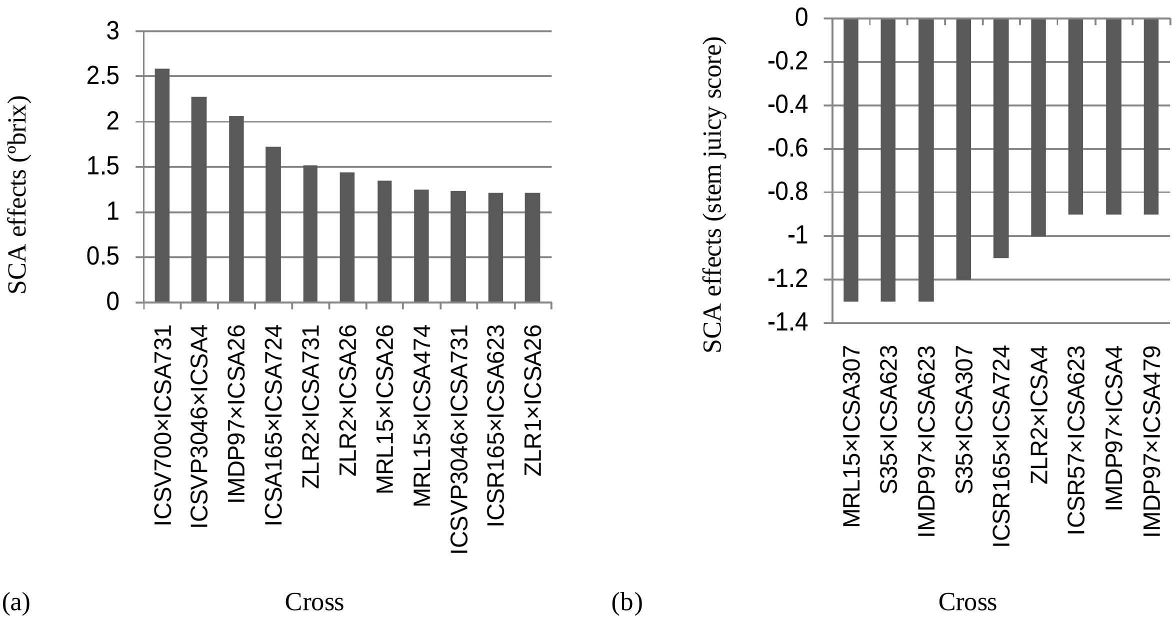

Figure 5.4-3: Sorghum crosses showing positive and significant SCA effects for (a) stem brix across six environments (SE = 0.65; SED = 0.92) and (b) stem juice score (SE = 0.46; SED = 0.64)

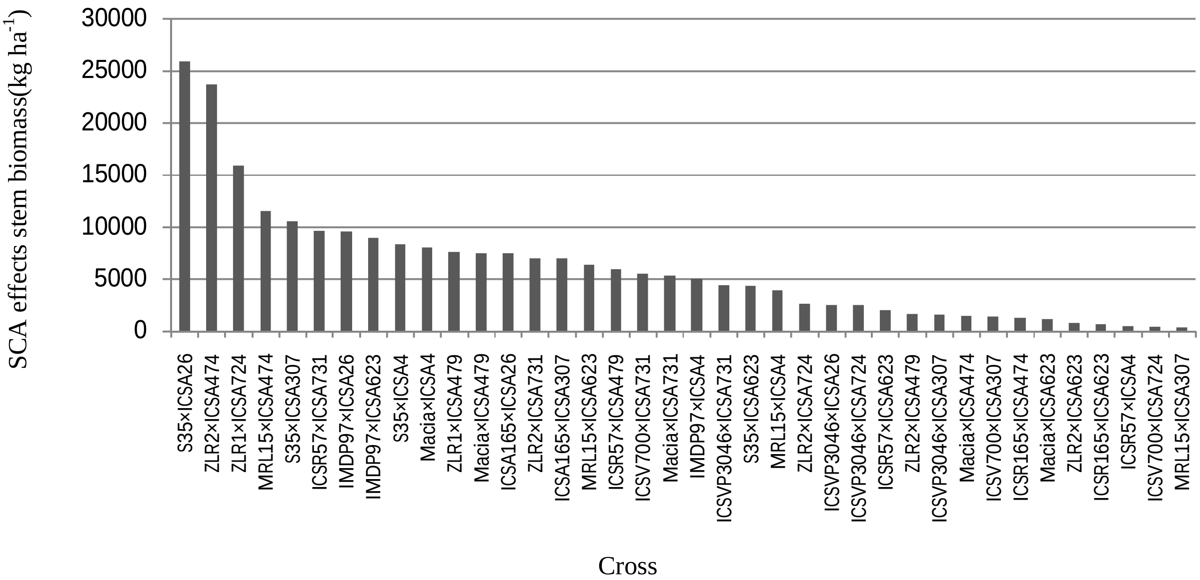

Figure 5.4-4: Thirty-eight sorghum crosses showing positive and significant SCA effects for stem biomass weight across six environments (SE = 162.4; SED = 229.7)

5.5 Discussion

5.5.1 Mean performance and standard heterosis

High overall means observed at CRS during both summer and winter and at URF and RARS during summer for stem brix and stem biomass can be attributed to differences in temperature. Temperatures between 25 - 30ºC obtained at CRS, RARS and URF are generally ideal for sorghum production. At MRS, summer maximum temperatures are generally too high (30 to 35ºC), which could have impacted negatively on stem biomass and stem brix. Further, during winter, MRS usually has lower temperatures compared to CRS (Figure 5.3-1), which could have resulted in reduced growth and depressed stem brix values as reported by Makanda *et al*. (2009). The observation that the top performing entries for both stem brix and stem biomass was constituted mainly by hybrids can be attributed to heterosis. Corn (2008) reported similar results and provided the same conclusions. This suggests that hybrid cultivars are superior to pure line varieties for both traits. However, the presence in the top 20 performers of pure line cultivars ICSB479, Saccaline, ICSR57 and ICSV700 for stem brix and Grassl, ICSR165, and ICSVP3046 for stem biomass demonstrates that pure line cultivars still have a role to play in the region. The observations that hybrids constituted the top five stem brix performers with above 10% standard heterosis for the trait, demonstrated the high potential of the current experimental hybrids.

Stem brix and stem biomass values observed in this study are comparable to those reported in literature. For example, Guiying *et al*. (2000), Woods (2000) and Tsuchihashi and Goto (2004) reported values between 13.4 and 18.5ºbrix and Woods (2000), Tsuchihashi and Goto (2004), Claassen *et al*. (2004) and Corn (2008) reported stem biomass yields of between 39.5t ha^{-1} and 140t ha^{-1} in Indonesia, Europe, and the USA. Plant height, a determinant of stem biomass followed similar trends. Overall, this demonstrates the high levels of heterosis for both traits in the current germplasm. Further, standard heterosis of up to 201% for stem biomass and 25% for stem brix indicated the presence of many entries that can potentially become cultivars for the region because they outperformed the regional standard check variety, ZLR1. The heterosis observed for stem biomass could be attributed to the dominance and epistatic gene effects as reported in literature (Sleper and Poehlman, 2006; Rooney and Aydin, 1999). The same inferences can be made for plant height and stem diameter because both traits are the chief determinant of stem biomass, and were positively and significantly correlated to it. The observation that some cultivars were juicer than others suggests that further gains in stem sugar yields can be achieved through selection of juicy cultivars among the high stem brix and stem biomass performers.

The variable times to 50% flowering among the current experimental hybrids indicates the possibility for selection for different season lengths in the tropical lowland and dry mid-altitude environments in the region. For example, 15.9% of southern Africa is tropical lowland characterised by relatively short rainy seasons while 19% is dry mid-altitude characterised by longer seasons but with more or less the same amount of precipitation (Vivek *et al*., 2005). Given the variability for flowering times in the current germplasm, short season varieties can be developed for both in-season and off-season production in the tropical lowland environments. Alternatively, long season high biomass cultivars can be developed for the mid-altitude environments such as RARS and URF to take advantage of more moisture available to maximise sugar yields.

5.5.2 Performance stability and better parent heterosis

The presence of many entries with low P*i* values for stem brix and stem biomass suggested the presence of entries with general stability across environments. These could be deployed to the generality of the region in southern Africa. Most of these entries were hybrids, suggesting that hybrids were more robust to site effects compared to pure line cultivars. The top 20 performers for stem brix and stem biomass were generally more stable as indicated by their low P*i* values for the traits compared to the bottom five (Tables 5.4-2 and 5.4-3). There seemed to be a cumulative effect of genes from male and female parents on stem brix stability. For example, the male parent ICSV700 had a stem brix P*i* value of 11.11 and in hybrid combination with ICSA731 (P*i* = 14.56) and ICSB4 (P*i* = 17.93) resulted in hybrids with P*i* values of 2.72 and 9.03, respectively (Table 5.4-2). The same trend was observed for male parent ZLR1 with female parents ICSA26 and ICSA307. In all cases, hybrids displayed better stability than that of either parent. Alternatively, hybrids could have higher buffering capacities to variable environments than pure line varieties. Generally, heterozygosity of cultivar or heterogeneity of populations improves stability compared to homozygosity or homogeneity (Léon, 1991; Hill *et al*. 1998; Helland and Holland, 2001). Therefore, breeding for stem brix, general adaptation could be enhanced by developing hybrid cultivars. However, stem biomass exhibited a different phenomenon for stability. In this case, the male parent seemed to be contributing a preponderance of genes for stability. For example, ICSR165 had a P*i* index of 4.74 and in hybrid combination with ICSA26 (P*i* = 22.51) and ICSA474 (P*i* = 15.28) resulted in a hybrid with P*i* values of 4.74 and 4.34, respectively (Table 5.4-3). The same trend was observed for ICSVP3046 and ISCA26. In all the cases, the stability of the hybrid was equal to that of one parent. The observation that the stem brix *inter se* stability of the parents was higher than the *per se* for most parents (Table 5.4-5) suggests that most of the parents produced hybrids with superior stability for the trait. These can be used to breed for stable hybrids. However, the opposite was true for stem biomass where parents developed less stable hybrids, except for ICSVP3046 and ICSR165. In this case parents were generally more stable as stem biomass cultivars than their hybrids.

The levels of better parent heterosis for stem brix and stem biomass observed in this study were high and surpassed those reported from other studies, although different sets of germplasm and environments were used. For example, Corn (2008) reported maximum stem brix and stem biomass heterosis of 7% and 43%, respectively, in Texas, USA. The high heterosis for both traits in this study is likely to have resulted from a higher diversity in the germplasm. The study used both local and introduced parents for hybrid production. The observation that 12 of the 27 crosses (Figure 5.4-1) and 10 of the 25 crosses (Figure 5.4-2) with high better parent heterosis for stem brix and stem biomass, respectively, were constituted from crosses involving local parents support this argument. In a similar study on stem biomass, Schlehuber (1945) found F_1 hybrids to be better performing than either parent, further providing evidence of heterosis for the trait. The regional parents could have been more adapted to the region, which could also have resulted in better performance in hybrid combination. This is supported by the observation that three of the regional parents ZLR1, MRL15 and Macia involved in crosses with high better parent heterosis had low P*i* values, demonstrating general adaptation to the region. Further, the identification of 10 parents showing positive and significant better parent heterosis for both stem brix and stem sugar shows that it is possible to exploit heterosis for both traits in one cultivar.

5.5.3 Combining ability effects

The significance of GCA effects due to both male and female parents for all traits implied that genes with additive effects were important for the traits and breeding progress could be achieved through selection of good parents. The significance of SCA effects for all traits, except stem juice score, suggested that further gains can be achieved through hybridisation capitalising on non-additive gene effects. The parents with positive and significant GCA effects for stem brix, stem brix-juice score, stem biomass, plant height and stem diameter (Table 5.4-6) could be used in sweet sorghum hybrid production to improve stem sugar and biomass production. Non-additive gene action was shown to be important by the presence of crosses with significant SCA effects, 11 for stem brix, nine for stem juiciness and 38 for stem biomass. This demonstrated that further gains in sugar performance could be realised through hybridisation. These results on combining ability could imply that both stem brix and stem biomass are quantitatively inherited and genes with dominant and epistatic effects controlled the traits as previously reported (Baocheng *et al*., 1986; Rooney and Aydin, 1999; Guiying *et al*., 2000). The same inferences can be made for plant height and stem diameter because they closely followed the trends of stem biomass due to the significant correlation to the latter.

However, for stem juiciness, only genes with additive effects were predominant as previously reported by Schlehuber (1945). The observation that crosses between parents differing in juice score could result in either intermediate or juicer hybrids suggested than genes with partial dominance or overdominance effects controlled the trait. For example, ZLR1 had an average juice score of 1.4 and ICSA731 averaged 2.2 but their hybrid, ZLR1×ICSA731, had a juice score of 1.8 (Table 5.4-4). This is an example of genes with equal effects, suggesting co-dominance. The same was observed for the cross ZLR1×ICSA731. In another cross, ZLR2 and ICSA724 averaged a score of 4.0 and 1.8 respectively, but their hybrid ZLR2×ICSA724 had a score of 4.2, drier than either parent. This suggested negative overdominance for the dry stem trait. In contrast, ICSV700 (score 2.0) and ICSA724 (score 1.8) produced a juicer hybrid ICSV700×ICSA724 with a score of 1.5, better than either parents. This suggested positive overdominance. Therefore, apart from genes with additive effects, genes show partial dominance and positive and negative overdominance also controlled the trait. Juicer parents are more desirable over their drier counterparts. Given the same stem brix reading, juicer cultivars have higher sugar yields than drier cultivars. Further, it also seems logical that juicer cultivars may allow for the accumulation of more sugar without putting pressure on the osmotic potential of the plant. The stem brix-juice index catered for these differences such that juicier parents with lower stem brix reading are adjusted upwards and drier parents with high stem brix are adjusted downwards to achieve a better comparison of the extremes. In this regard, parents with positive GCA effects for the index are desired as they are considered better stem sugar combiners.

The observation that both male and female GCA effects and SCA effects significantly interacted with the environments for all traits except stem juice scores implied that the environment played an important role in influencing the expression of both the additive and non-additive gene effects. The observation is consistent with reports of significant genotype × environment interaction in sorghum (Chapman *et al*., 2000; Haussmann *et al*., 2000; Kenga *et al*., 2004). This has a bearing on breeding for the different micro environments within the region. It entails testing of the parents for both GCA and SCA across environments before the parents are selected. This also gives scope for selecting parents with general adaptation versus those with specific adaptation. However, in the current study, analyses showed that genotypes were generally consistent across environments, suggesting that the interaction was largely a result of changes in magnitude of performance rather than major reversal of ranks.

5.6 Conclusions

The study demonstrated that it is possible to develop and produce superior sweet sorghum cultivars in southern Africa. Production could be enhanced by breeding hybrid cultivars. Both additive and non-additive gene effects were shown to be important in controlling stem brix, stem biomass and the associated traits in sorghum. Parental lines ZLR1 and ICSR165, which showed positive and significant GCA effects and in combination displayed positive and significant SCA effects for stem brix and stem biomass, were identified as potential parents for inclusion in the sweet sorghum hybrids development programme. Parents ICSV700, ICSVP3046, ICSA4, ICSA307, and ICSA26, which showed significant GCA effects on at least one of the two traits and a positive value on the other, and featured prominently among crosses with significant and positive SCA effects, were also included among the potential parents.

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CHAPTER 6

[4]Combining ability, heterosis and cultivar superiority of sorghum germplasm for grain yield traits across tropical low and mid altitude environments

6.1 Abstract

Sorghum grain production in sub-Saharan Africa is constrained by limited availability of varieties. Hybrid cultivars have been shown to be more productive for grain than pure line and landraces hence their development can enhance productivity and food security. This study was, therefore, conducted to determine combining ability of 18 sorghum lines, the level of heterosis and cultivar superiority of experimental hybrids in tropical lowland and mid-altitude environments. Eight cytoplasmic male-sterile lines were crossed with 10 male fertile lines in accordance with the North Carolina II mating scheme to generate 80 experimental hybrids. The hybrids, parents and two standard check varieties were evaluated in replicated row-column α-designs across six environments in Mozambique, South Africa and Zimbabwe. Cultivar superiority was assessed using the cultivar superiority index (P*i*). Results indicated significant ($P \leq 0.05$) differences among genotypes for both grain yield potential and secondary traits. Hybrids were predominant in the top 20 ranking for grain yield, and displayed up to 285% standard heterosis. Overall hybrid mean yield was significantly higher than that of parents and standard check varieties, which was attributed to high levels of average heterosis and standard heterosis, respectively. Grain yield data was positively and significantly correlated with head length and number of leaves per plant, suggesting an improvement in grain yield potential as the number of leaves and head size increase. General combining ability (GCA) and specific combining ability (SCA) effects were significant ($P \leq 0.05$) for all traits, implying that both additive and non-additive gene effects were important. Both GCA and SCA effects significantly interacted with site effects demonstrating the need for multilocation testing of potential cultivars. However, the top grain yielders were generally stable across environments. Parents ICSV700, ICSR165, S35, IMDP97, ICSA4, ICSA724, and ICSA26 with positive and significant GCA effects, which also revealed significant SCA effects in crosses for grain yield were identified as potential materials for inclusion in the hybrid breeding programme.

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Keywords: cultivar superiority index, general combining ability, heterosis, sorghum hybrids, specific combining ability

6.2 Introduction

Agricultural research in southern Africa focuses on sustainable development and sorghum presents a valuable and strategic food security crop that is highly adaptable to a broad range of environments. Currently there is a huge gap between production and consumption of the staple cereals in Africa because production of both sorghum and other cereals is not adequate to meet the cereal needs of the population. Sorghum production can be enhanced by developing highly productive cultivars and possibly extending production to include the off-season in warm tropical lowland environments (≤800m above sea level, m.a.s.l.). This can be done in places where irrigation is economically feasible. These places include Chokwe in Mozambique, Muzarabani, Save Valley and Chiredzi in Zimbabwe, the Zambezi Valley areas covering parts of Zambia, Zimbabwe, Malawi and Mozambique, and the Makhathini Flats in South Africa. More than 70% of Mozambique is lowland with many water sources that can be harnessed to irrigate the crop to boost crop production. However, in-season production remains the mainstay of cereal production in the region and supplying high yielding cultivars will boost regional food security.

Grain yields of up to 6.2t ha^{-1} have been reported for in-season production (Borrell *et al*., 2000; Guiying *et al.*, 2000) while off-season production in Ethiopia and India yielded of up to 1.6t ha^{-1} (Food Security Unit 1998; Patil 2007). The potential exist to improve off-season production to the levels attainable in-season through plant breeding. Further, hybrid cultivars have been demonstrated to be more productive than pure line varieties (LI and Li, 1998; Kenga *et al*., 2004; Kamau, 2007). New hybrid cultivars need to be tested against successful varieties on the market and their pure line parents. The comparison is achieved by investigating the levels of heterosis in potential hybrid cultivars (Falconer and Mackay, 1996). Heterosis can be computed from the performance of the hybrid over that of the better parent (BP heterosis) or the average (mid-parent) performance of the parents (MP heterosis) or the mean performance of the entry over that of the standard check variety or varieties (standard heterosis) (Alam *et al*., 2004; Kaushik *et al*., 2004; Virmani, 1994). Standard and BP heterosis are commonly used by breeders whose aim is to produce hybrids that are superior to their parents and cultivars on the market. New cultivar release is based on performance of the experimental cultivar relative to the current varieties. Grain yield heterosis of 13 – 88% (Haussmann *et al*., 2000), 23.9 – 39.6% (Blum *et al.*, 1990) and relative hybrid superiority of 47.1% (Haussmann *et al*., 1999) have been reported in sorghum, demonstrating the advantages of hybrid cultivars over both parental and pure line varieties. Identification of highly productive hybrids can revolutionise sorghum production in the sub-Saharan African region, replicating the sorghum success stories of China (Li and Li, 1998) and India (Kenga *et al*., 2004) with further improvement on food security and rural development. Further, the use of landraces in hybrid development has been demonstrated to improve heterosis due to the genetic diversity with improved male-sterile (A) female lines. In China, 38% of the restorer (R) lines are landraces and 43% of all hybrids on the market were generated in crosses involving those restorer lines (Li and Li, 1998). The authors cited examples of the most widely grown high yielding hybrids, *Jinza 5* and *Yuanza 12*, that were constituted from crosses involving local landrace male parents. In this regard, it might be prudent to include locally adapted cultivars and landraces in hybrid cultivar development.

In hybrid oriented breeding programmes, the knowledge of combining ability of the parents and the inheritance of the trait is important. This information helps in optimising the breeding strategy, either selection when general combining ability (GCA) effects are important or inbreeding followed by cross breeding when specific combining ability (SCA) effects are predominant. If both are important, then selection followed by hybridisation is the way forward. Significant GCA effects are attributed to preponderance of genes with additive effects and SCA indicates predominance of genes with non-additive effects (Kenga *et al*., 2004; Mutengwa *et al.,* 1999; Sharma, 1994). Studies have shown both GCA and SCA effects to be important in many sorghum traits including grain yield (Haussmann *et al*., 1999; Tadesse *et al*., 2008; Kenga *et al*., 2004; Yu and Tuinstra, 2001). Further, heritability in the narrow sense (h^2) of between 10 - 86% for grain yield and 91-99% for days to flowering have been reported (Warkad *et al*., 2008; Bello *et al*., 2007; Biswas *et al*., 2001; Lothrop *et al*., 1985; Haussmann *et al*., 1999). The significant GCA and SCA effects and the medium to high h^2 estimates suggests that grain yield is quantitatively inheritance and can be improved through selection and hybridisation. However, both combining ability and heritability information is dependent on the germplasm set evaluated and the specific environments sampled hence it cannot be generally applied (Falconer and Mackay, 1996).

Significant genotype × environment interaction effects which can cause challenges in breeding new cultivars have been reported in sorghum (Chapman *et al*., 2000). This implies that before a potential cultivar is released, detailed multi-location evaluations must be conducted to determine its adaptation and stability of performance. Many methods of quantifying genotype × environment interaction are available but the cultivar superiority index (P*i*) proposed by Linn and Binns (1988) is both simple and effective. The P*i* is defined as the distance mean square between a cultivar's observed value and the maximum value observed in a given environment. It follows that cultivars displaying high P*i* values are specifically adapted to certain environments whereas those with low P*i* values show general adaptation. The latter are considered stable across environments. This method has the advantage that, unlike the initially proposed indices (Lin and Binns, 1985; Lin *et al*., 1985), the requirement of the check variety in all environments is removed because the index is not dependent on it. The index uses the maximum observed value in each environment as the reference (potential) for that environment from which the distance mean squares are computed. These computations are done for each environment and the values summed to give the index of each genotype across environments.

The objectives of this study were to evaluating experimental hybrids across environments for heterosis, combining ability effects of the parental lines, and assess cultivar superiority for grain yield traits. The following hypotheses were tested:

i. sorghum hybrid cultivars that are superior to those on the market can be developed from the current germplasm;
ii. there are high levels of heterosis for grain yield and associated traits that can be exploited in hybrid cultivar development from the current germplasm; and
iii. genes with additive effects control grain yield and associated traits in sorghum, and
iv. genes with non-additive effects control grain yield and associated traits in sorghum.

6.3 Materials and Methods

6.3.1 Germplasm and experimental sites

Eighteen sorghum lines were divided into two groups based on the status of their cytoplasms. Eight cytoplasmic male-sterile (CMS) A-lines were designated as females and crossed to 10 cytoplasmic male-fertile lines in accordance with a North Carolina Design II mating scheme to generate 80 hybrids. The males were constituted from introduced (improved lines) and southern African (adapted materials) germplasm, while female parents were obtained from the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) in India (Table 6.3-1). During hybridisation, the two heads of each CMS female lines was self pollinated to ensure that there was no breakdown of the CMS system. The hybrids, 18 parents and two check varieties were evaluated in trials. During the evaluation, the iso-cytoplasmic B-lines were grown in lieu of their respective CMS A-lines.

In-season and off-season trials were conducted at Chokwe Research Station (CRS) (24° 31′ S; 33° 0′ E, 40m.a.s.l) in Mozambique and at Makhathini Research Station (MRS) (27º 24'S; 32º 11' 48" E, 72m.a.s.l.) in South Africa during May to September 2008 and November 2008 to April 2009. Further in-season trials were conducted Rattray-Arnold Research Station (RARS) (17º 40' S; 31º 14' E, 1308m.a.s.l.) in Zimbabwe and at Ukulinga Research Farm (URF) (30º 24' E; 29º 24' E, 781m.a.s.l.) in South Africa during November 2008 to April 2009. Both CRS and MRS represent the tropical lowland environments in southern Africa where there is potential for sorghum production both in-season and off-season without adverse effects of low temperatures. The two sites have annual long term mean rainfall of about 600mm and maximum temperatures of about 25-30^{0}C (Figure 6.3-1). RARS and URF represent the mid-altitude environments with annual rainfall of about 800mm and maximum temperatures of 20-30^{0}C (Figure 6.3-1). Although the rainfall is seasonal at all sites, the temperatures and availability of irrigation facilities at CRS and MRS make them ideal for sorghum production throughout the year, unlike URF and RARS where low winter temperatures make it impossible to grow cold sensitive crops like sorghum during May to September. Both CRS and MRS are surrounded by small-scale irrigation schemes with perennial water sources from dams.

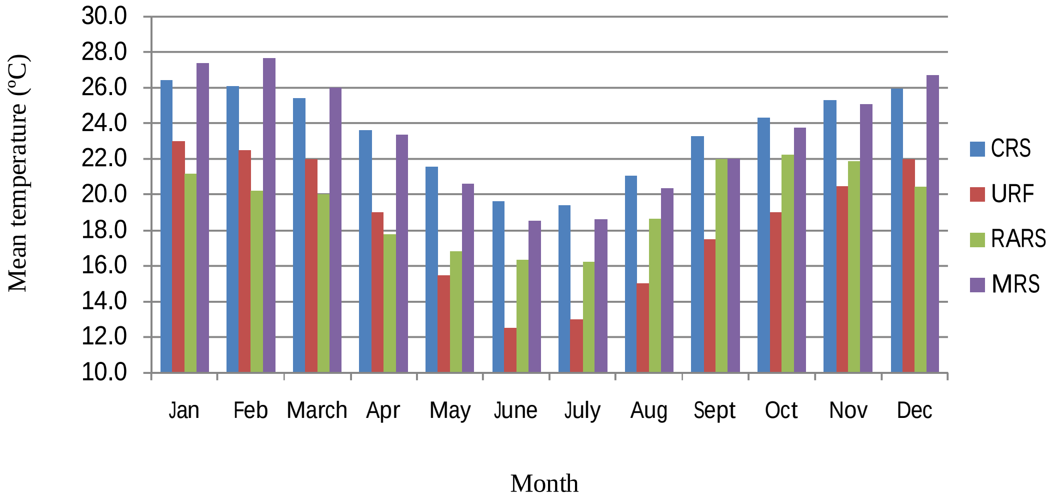


Figure 6.3-1: Long term (five year) mean temperatures for the sites [Data source: Agricultural Research Council-ISCW AgroMet Potchefstroom (2009); Seed Co. Zimbabwe Ltd (2009); Gaisma (2007)]

Table 6.3-1: Name, origin and pedigree of parental sorghum lines used in the study

Line No.	Name	Fertility status	Origin	Pedigree	Role in crosses
1	ZLR1	CMF	Zimbabwe	Landrace	Male
2	MRL15	CMF	-	Unknown	Male
3	ICSV700	CMF	ICRISAT India	(IS 1082 x SC 108-3)-1-1-1-1-1	Male
4	ICSVP3046	CMF	ICRISAT India	(ICSV 700 x ICSV 708)-9-1-3-1-1-1	Male
5	S35	CMF	ICRISAT India		Male
6	Macia †	CMF	Mozambique	SDS 3220	Male
7	ZLR2	CMF	Zimbabwe	Landrace	Male
8	ICSR165	CMF	ICRISAT India	SPV 422	Male
9	ICSR57	CMF	ICRISAT India	(SC 108-3 x 148)-12-5-3	Male
10	IMDP97	CMF	-	Unknown	Male
11	ICSA731	CMS	ICRISAT India	ICSV 1171BF	Female
12	ICSA479	CMS	ICRISAT India	[9ICSB 70 x ICSV 700) x PS 19349B]-5-4-1-2-2	Female
13	ICSA4	CMS	ICRISAT India	[(BTx 622 × UChV2)B lines bulk]-10-1-1	Female
14	ICSA724	CMS	ICRISAT India	ICSP 1B/R MFR-S 7-303-2-1	Female
15	ICSA307	CMS	ICRISAT India	[(ICSB 26 × PM 1861)×(ICSB 22 × ICSB 45) × (ICSB 52 × ICSB 51)]1-3-12-3-1	Female
16	ICSA474	CMS	ICRISAT India	(IS 18432 x ICSB 6)11-1-1-2-2	Female
17	ICSA26	CMS	ICRISAT India	[(296B x BTx 624)B lines bulk]-2-1-1-3	Female
18	ICSA623	CMS	ICRISAT India	(ICSB 11 x PM 17467B)5-1-2-1	Female

† = regional check; CMF = cytoplasmic male fertile; CMS = cytoplasmic male sterile

6.3.2 Experimental design and management

The experiments were laid out as replicated row-column α-designs at each site during May of 2008. Seeds of each entry were planted by hand in two-row plots of 3.0m length at 0.75m inter-row and 0.20m intra-row spacing with a resultant theoretical population density of about 66 000 plants ha^{-1}. At MRS and URF, the experiment was laid as a 10 rows × 10 columns and at CRS and RARS, it was a 5 rows × 20 columns. Some hybrids did not yield sufficient seed for evaluation in all the environments. The trials were supplied with 800 mm moisture through irrigation during off-season and by supplementary irrigation during in-season. The trials were supplied with 250kg ha^{-1} basal fertiliser (2:3:4, N:P:K) and 200kg ha^{-1} top dressing fertiliser (Lime Ammonium Nitrate with 28% N). The fields were kept weed free by hand weeding. At planting, Curaterr 5G (carbofuran), a systemic insecticide, was applied to prevent damage of the emerging seedlings by mice and cutworm. Stalkborer granules (dimethyl-(2,2,2-trichloro-1-hydroxyethyl) phosphonate) were used to control stalkborer damage and the sorghum heads were covered with 2.0kg fine mesh bags at anthesis to prevent bird predation on the developing grain.

Harvesting was done by hand after the hard dough stage and grain yield was measured per plot and converted to per hectare (kg ha^{-1}) after adjusting to 12.5% grain moisture content. Grain moisture was measured using a DICKEY-John mini GAG® Plus moisture meter. Numbers of days to 50% flowering (number of days taken for half of the plot to reach anthesis), number of days to 95% maturity (number of days taken for about 95% of the plants to reach the hard dough stage), number of tillers per plant (tillers that were taller than half of the main plant), head length (measured with a 30cm ruler), number of leavers per plant (measured by counting the nodes on the stem), and weight of 1000 seeds were also measured.

6.3.3 Data analyses

Data were analysed using REML procedure in GenStat® (Payne *et al.*, 2007) following a fixed effects model:

$$Y_{ijkl} = \mu + s_i + r_j(s_i) + b(r_j{*}s_i) + m_k + f_l + mf_{kl} + s_i{*}m_{ik} + s_i{*}f_{ij} + s{*}mf_{ikl} + e_{ijkl}$$

Where: Y_{ijk} = observed hybrid response; μ = overall population mean; s_i = effect of the i^{th} environment; $r_j(s_i)$ = effects of the j^{th} replication in the i^{th} environment; $b(r_j{*}s_i)$ = effects of the blocks in the j^{th} replication in the i^{th} environments; m_k = effect of the k^{th} male parent; f_l = effect of the l^{th} female parent; mf_{kl} = interaction effect of the k^{th} male and the l^{th} female parents; $s_i{*}mf_{kl}$

= interaction effect of the i^{th} environments and the interaction effects between the k^{th} male and the l^{th} female parents; and e_{ijkl} is the experimental error.

Data were also analysed according to season, that is, the in-season versus the off-season experiments using entries that were common in both seasons. This excluded male parents IMDP97 and S35 and their hybrids which were not evaluated during the off-season period. The hybrid variation was partitioned into male and female parent main effects giving two independent estimates of GCA effects, while the male × female interaction estimates the SCA effects (Hallauer and Miranda, 1988; Kearsey and Pooni, 1996). The GCA effects for the parents and SCA were calculated according to Kearsey and Pooni (1996). The standard error (SE) and standard error of a difference (SED) for male and female GCA effects were calculated according to Dabholkar (1992) separately because the numbers of males and females were not balanced. Better parent heterosis (%) was computed according to Alam *et al*. (2004) and standard heterosis was computed according to Kaushik *et al*. (2004). Stability of the entries across the environments was measured by the cultivars general superiority index (P*i*) calculated according to Lin and Binns (1988). The entries that were not represented in all the environments had their P*i* computed across those environments in which they were grown.

6.4 Results

6.4.1 Mean performance and cultivar superiority

Sites and entries main effects and site × entries interaction effects were significant ($P \leq 0.01$) for all traits measured (Table 6.4-1). The contrast hybrids vs. parents vs. check varieties was not significant for grain yield, days to 95% maturity and number of tillers per plant, but was significant for head length, days to 50% flowering and number of leaves per plant. However, the interaction between entry type and site were not significant for the traits.

Grain yield was highest at Chokwe Research Station during summer, the in-season period (CRS-S) which, together with Chokwe Research Station during winter, the off-season period (CRS-W) and RARS, significantly out-yielded Makhathini Research Station during summer ,(MRS-S), Makhathini Research Station during winter (MRS-W) and URF (Table 6.4-2). Hybrids had the highest grain yield (2128kg ha^{-1}) followed by parents (2008kg ha^{-1}) and then the check variety (1527kg ha^{-1}) which yielded the lowest. However, the check variety for grain had significantly (P≤0.01) longer heads (23.3cm) than the parents (21.1cm) and hybrids (22.7cm). Hybrids (2.83g) and parents (2.63g) had significantly (P≤0.05) higher 1000 seed weight compared to the grain check varieties (1.94g). Hybrids (86 and 137 days) and parents (87 and 136 days) took significantly (P≤0.01) longer to achieve both 50% flowering and 95% physiological maturity than the check varieties (77 and 128 days), but the grain yield check variety had significantly (P≤0.01) more leaves per plant (10.5) than both the parents (9.5) and hybrids (9.9). Spearman's Rank Correlation coefficients of varieties between sites were significant (r = 0.438; P≤0.05) showing that the sites ranked the entries in a similar way. Therefore, the site by entry interaction table was presented for the major traits, grain yield, and the overall means were presented for the rest of the traits.

Table 6.4-1: Mean squares for grain yield and associated traits of sorghum hybrids across six environments

Source	df	Grain yield (kg ha^{-1})	Head length (cm)	Number of tillers plant^{-1}	Number of leaves plant^{-1}	Days to 50% flowering	[a]Days to 95% maturity	[b]1000 seed weight (g)
Evt	5	558.5**	837.4**	1320.9**	2907.7**	758.1**	99.2**	-
Rep(Evt)	8	24.5	8.97	54.7	11.4	12.4	2.9	0.9
Block(Rep)(Evt)	143	241.6	194.1	217.9	167.4	153.5	27.2	10.0
General analysis of all entries including parents and checks								
Entries	99	763.7**	962.5**	249.3**	546.9**	946.9**	171.5**	534.2
Evt *Entries	389	977.5**	354.7**	553.4**	477.1**	934.6**	123.4**	-
Error	476	944872.0	6.1	0.8	1.8	34.4	48.5	0.1
Combining ability analysis								
Hybrids	79	487.7**	527.2**	139.6**	345.4**	489.3**	135.1**	-
GCA_m	9	95.2**	256.1**	29.6**	207.1**	225.3**	30.1**	-
GCA_f	7	60.7**	160.8**	23.4**	11.8	66.1**	16.0*	-
SCA	63	331.8**	110.4**	86.6*	126.4**	198.0**	89.1*	-
Evt*Hybrids	395	648.7**	255.5**	459.7**	379.1**	723.6**	81.5	-
Evt*GCA_m	45	181.2**	60.6**	65.0*	196.1**	442.3**	13.7	-
Evt*GCA_f	35	56.2**	39.7*	45.3	42.5**	67.8**	9.3	-
Evt*SCA	315	411.3**	155.2	349.4**	140.5*	213.5*	58.5	-
Error	491	899746.0	5.8	0.8	1.6	32.4	51.6	-

Evt = environments; **, * significant at P≤0.01 and P≤0.05, respectively; df = degrees of freedom; [a] = data only available for two sites; [b] = data only available for one site hence Combining ability analysis was not performed

Grain yield ranged from 131kg ha^{-1} recorded for hybrid ICSVP3046×ICSA474 at URF to as high as 6997kg ha^{-1} for hybrid S35×ICSA4 recorded at CRS-S (Table 6.4-2). The top 20 grain yield performers were composed of 15 hybrids and five parents with the top eight being hybrids (Table 6.4-2). The top 20 entries displayed standard heterosis ranging from 146 to 285%. The top entry S35×ICSA4 yielded twice as much as the number 20 entry ZLR1×ICSA731 and 76 times the lowest yielding entry ICSVP3046×ICSA474 (Table 6.4-2). Although the Spearman's Rank Correlation analysis suggested that the entries were consistently ranked across environments, entries that deviated from this and displayed major rank reversal were also observed. For example parental line MRL15 displayed a very low mean (863kg ha^{-1} at MRS-W while the rest of the sites recorded yields above 2000kg ha^{-1} (Table 6.4-2). ICRS165 and hybrid cultivars ICSV700×ICSA731 and, IMDP97×ICSA731 displayed a similar trend. The top ranked entries were more stable across environment hence the low cultivar superiority indices (P*i*) compared to the poorly ranked entries with high indices (Table 6.4-2). Noteworthy were hybrids S35×ICSA4, IMDP97×ICSA4, ICSR165×ICSA4, and ZLR1×ICSA724 and parental line MRL15 which had P*i* vales of less than 5.0 compared to the less stable entries with P*i* values reaching as high as 17.5 (Table 6.4-2). The trend shown by the P*i* was also consistent with the mean rank of the entries across environments, with stable cultivars being well ranked and less stable ones being poorly ranked (Table 6.4-2).

Table 6.4-2: Grain yield (kg ha^{-1}) of selected sorghum hybrids and parents across six environments (genotype by environment mean matrix SED = 396.8)

Entry	Environment						Entry mean	Mean rank	Standard heterosis (%)	Pi
	Tropical lowland				Mid-altitude					
	CRS-S	CRS-W	MRS-S	MRS-W	RARS-S	URF				
Top 20 grain yield performers										
IMDP97×ICSA4	6304	-	2027	-	6635	6871	5459	7.3	275.0	1.05
S35×ICSA4	6997	-	1490	-	5500	4343	4583	13.8	284.7	1.84
ICSV700×ICSA307	5623	3748	2652	4422	3622	1569	3606	13.3	221.2	9.55
ICSR165×ICSA4	6664	2517	2268	3379	5151	2767	3791	9.5	220.3	2.98
Macia×ICSA731	5395	2217	2188	2520	6609	326	3209	22.3	208.7	6.32
IMDP97×ICSA724	2333	-	1891	-	6829	1810	3216	26.0	203.1	9.94
ZLR1×ICSA724	5902	2782	2818	2998	3745	2362	3435	12.2	201.1	4.24
Macia×ICSA4	3145	4533	2192	4001	3223	2205	3217	18.7	188.4	6.57
IMDP97 *	5231	-	1323	-	-	2757	3104	25.7	180.6	6.46
S35 *	5849	-	1462	-	2506	1548	2841	33.8	180.4	8.79
ICSR165×ICSA479	6799	1861	-	1262	3071	-	3248	31.5	179.0	5.18
ICSR165×ICSA26	4286	2072	1530	2318	5949	1143	2883	24.7	178.1	6.58
ICSR165 *	5152	2774	907	2689	4584	1074	2863	24.7	177.6	6.28
MRL15×ICSA4	1908	2262	2388	2433	6875	2581	3075	19.8	174.9	7.23
IMDP97×ICSA731	5731	-	903	-	2854	1386	2719	37.3	174.3	9.09
ZLR2×ICSA731	2338	1870	3482	1021	6732	869	2719	31.0	170.2	9.28
S35×ICSA623	3906	-	1367	-	3969	-	3081	32.0	169.8	6.82
ICSV700×ICSA724	6650	1988	2859	1791	1903	510	2617	31.3	167.5	8.24
MRL15 *	5652	2369	863	2147	3756	3229	3003	23.8	163.0	4.79
ICSV700×ICSA731	6993	2587	1760	1782	1056	205	2397	37.7	156.3	9.43
MRL15×ICSA623	3634	2107	1925	2311	4158	2586	2787	21.0	155.8	6.23
ZLR1 *	2046	1976	2818	3924	3269	2505	2756	25.0	154.7	8.10
ICSR57×ICSA474	5746	1574	1632	1780	3112	2800	2774	27.2	152.6	5.75
ZLR1×ICSA731	1900	2347	2334	2430	4299	1350	2443	25.5	146.7	9.08
Bottom five grain yield performers										
ICSB623 *	595	1537	425	544	1515	752	895	67.8	50.9	16.21
ICSB4 *	-	742	-	863	807	-	804	72.7	44.3	12.77
MRL15×ICSA479	1331	1374	533	109	622	-	794	74.4	43.8	15.34
ICSB479 *	200	1478		599	1322	1221	964	67.8	40.5	16.73
ICSVP3046×ICSA474	1222	793	618	348	675	131	631	77.5	40.3	17.57
Parents										
ICSB307	4017	3067	626	1808	2153	2452	2354	34.5	128.7	7.91
ICSB474	1749	1653	798	2196	4763	1048	2035	40.7	123.0	10.45
ICSVP3046	2414	2574	1293	2106	2473	529	1898	40.3	119.7	11.07
ICSV700	2379	3424	830	-	1638	712	1797	48.6	114.0	13.34
ICSR57	4068	1602	914	1516	1567	2881	2091	40.8	106.6	8.74
ICSB724	2544	2022	221	2370	2032	3024	2036	40.3	101.3	9.50
Macia ‡	1807	1174	1599	1911	2580	1479	1758	44.0	100.0	11.35
ZLR2	2766	541	-	365	3211	1248	1626	53.0	94.9	13.25
ICSB26	2290	2336	787	1401	1785	1202	1634	50.2	94.8	11.79
ICSB731	2974	1140	630	1562	1103	2848	1710	51.0	81.7	10.79
Mean	3163	1899	1476	1520	2969	1341	2085			
	2015				2155					

‡ = regional check variety; - = data not available; SED = standard error of difference; * = parents in the top 20 or bottom five performers; CRS-S = Chokwe Research Station Summer/in-season: CRS-W = Chokwe Research Station Winter/off-season; MRS-S = Makhathini Research Station Summer/in-season; MRS-W = Makhathini Research Station Winter/off-season trial; RARS = Rattray Arnold Research Station Summer/in-season; URF = Ukulinga Research Farm Summer/in-season

Most of the males parents displayed high P*i* values *per se* than *inter se* as shown by the positive values of P*i*(*is* – *ps*) (Table 6.4-3).The majority of the female parents showed better stability *inter se* than *per se* hence the negative P*i*(*is* – *ps*) values (Table 6.4-3). Regional parents ZLR1, MRL15 and IMDP97 and introduced ICRISAT India lines ICSR57 and S35 showed high stability *per s*e for grain yield than *inter se* (Table 6.4-3). Female lines ICSA307 and ICSA474 also displayed better stability *per se* (Table 6.4-3). However the same trend was not replicated *inter se* where both regional and introduced lines displayed both high and low stability (Table 6.4-3). The remainder of the parents, both male and female were superior in stability *inter se* than *per se*.

Table 6.4-3: *Per se* and *inter se* cultivar superiority indices (P*i*) of 18 sorghum parents for grain yield across six environments

Male parent	Grain yield P*i*			**Female parent**	Grain yield P*i*		
	inter se	*per se*	P*i*(*is* – *ps*)		*inter se*	*per se*	P*i*(*is* – *ps*)
ZLR1	10.76	8.10	2.66	ICSA731	9.38	10.79	-1.41
MRL15	11.98	4.79	7.19	ICSA479	12.31	16.73	-4.42
ICSV700	9.09	13.34	-4.25	ICSA4	7.94	12.77	-4.83
ICSVP3046	13.23	11.07	2.16	ICSA724	10.03	9.50	0.53
Macia	9.57	11.35	-1.78	ICSA307	13.61	7.91	5.70
ZLR2	9.53	13.25	-3.72	ICSA474	13.78	10.45	3.33
ICSR165	7.61	6.28	1.33	ICSA26	9.26	11.79	-2.53
ICSR57	10.68	8.74	1.94	ICSA623	8.08	16.21	-8.13
S35	8.90	8.79	0.11				
IMDP97	14.39	6.46	7.93				

Head length varied from 15 to 27cm and entries in the top 20 had longer heads than those in the bottom five (Table 6.4-4). The weight of 1000 seeds also differed with the top grain yield performers having heavier grain than the bottom performers and heterosis for the traits was as high as 156% (Table 6.4-4). Standard heterosis for the traits ranged from 62 to 109% (Table 5). Number of tillers varied from 1.2 to 4.2 but the modal observation was between 2 and 3 tillers per plant (Table 6.4-4). Number of leaves per plant ranged from 7 to 16.5 although most entries were between 9.0 and 12.0 leaves per plant (Table 6.4-4). Days to 50% flowering also varied with earliest entries flowering in 77 days and late ones in 99 days. Days to 95% physiological maturity followed similar trends (Table 6.4-4).

Table 6.4-4: Means of traits associated with grain yield for selected sorghum hybrids and parents across six environments

Entry	Trait						Standard heterosis for 1000 seed weight (g)
	Head length (cm)	Number of tillers plant^{-1}	Number of leaves plant^{-1}	[a] Days to 95% maturity	Days to 50% flowering	[b] 1000 seed weight (g)	
Top 20 grain yield performers							
S35×ICSA4	27.1	1.9	11.7	134.0	88.1	3.6	156.5
IMDP97×ICSA4	25.0	2.4	11.8	131.0	81.8	2.9	126.1
ICSV700×ICSA307	22.1	2.1	12.4	133.8	96.8	3.4	147.8
ICSR165×ICSA4	24.4	2.3	9.6	139.9	91.6	2.8	121.7
Macia×ICSA731	23.4	2.3	9.1	134.9	81.3	3.3	143.5
IMDP97×ICSA724	24.4	2.9	11.8	126.0	83.5	2.9	126.1
ZLR1×ICSA724	25.9	2.8	9.8	130.0	80.2	2.5	108.7
Macia×ICSA4	24.6	1.9	10.2	134.9	93.8	2.5	108.7
IMDP97*	23.3	4.2	9.3	-	105.0	-	-
S35*	21.0	1.6	9.3	125.0	80.0	-	-
ICSR165×ICSA479	15.3	2.3	10.2	135.4	89.2	3.1	134.8
ICSR165×ICSA26	22.7	1.2	7.0	135.0	91.2	3.1	134.8
ICSR165*	18.3	1.8	12.1	137.0	99.5	2.6	113.0
MRL15×ICSA4	23.9	2.2	11.1	133.3	81.5	2.6	113.0
IMDP97×ICSA731	25.1	1.8	10.8	132.5	92.0	2.8	121.7
ZLR2×ICSA731	22.2	2.7	10.5	133.3	81.5	3.1	134.8
S35×ICSA623	23.4	1.8	16.5	131.5	88.0	2.6	113.0
ICSV700×ICSA724	21.5	1.6	11.3	135.5	88.2	3.2	139.1
MRL15*	21.1	1.9	10.7	134.9	86.5	2.8	121.7
ICSV700×ICSA731	19.6	2.6	11.9	139.9	87.9	3.1	134.8
MRL15×ICSA623	21.1	2.1	10.1	136.8	83.5	2.2	95.7
ZLR1*	24.1	2.4	9.6	139.1	86.8	1.8	78.3
ICSR57×ICSA474	21.7	2.7	9.3	137.8	82.8	3.8	165.2
ZLR1×ICSA731	24.3	2.2	8.2	137.7	80.3	2.4	104.3
Bottom five grain yield performers							
ICSB623*	19.5	1.6	8.4	136.4	83.7	2.6	113.0
ICSB4*	16.9	1.7	6.0	138.4	87.7	2.0	87.0
MRL15×ICSA479	19.4	1.9	13.2	141.5	87.1	2.7	117.4
ICSB479*	15.4	1.2	9.6	135.8	92.6	2.6	113.0
ICSVP3046×ICSA474	20.0	1.7	11.3	149.4	84.7	3.7	160.9
Parents							
ICSB307	26.2	1.4	9.3	137.5	92.9	2.5	108.7
ICSB474	18.0	2.1	8.7	131.4	80.9	3.4	147.8
ICSVP3046	18.3	1.4	11.5	139.4	97.3	2.9	126.1
ICSV700	16.9	2.4	14.3	137.9	89.0	2.9	126.1
ICSR57	21.8	1.9	8.3	135.3	87.5	3.4	147.8
ICSB724	21.3	1.2	10.0	141.0	86.5	2.2	95.7
†Macia	24.7	2.7	9.1	134.0	80.6	2.3	100.0
ZLR2	23.2	2.3	10.7	139.9	77.0	2.2	95.7
ICSB26	26.6	2.2	8.0	131.7	83.8	2.1	91.3
ICSB731	20.8	2.1	9.8	135.9	91.2	2.8	121.7
Mean	22.6	2.1	10.4	135.9	85.8	2.7	
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	
SED	1.1	0.3	0.6	4.5	2.5	0.35	

[a, b] = data available for two and one sites, respectively; - = data not available; SED = standard error of difference; * = parents in the top 20 or bottom five performers; † = regional check

6.4.2 In-season versus off-season performance

Analysis by season showed significant differences (P≤0.01) for grain yield between in-season and off-season environments. The top 20 performers for the two environments are presented in Table 6.4-5.

Table 6.4-5: Off-season and in-season grain yield performance of selected hybrids and parents

Off- season			In-Season		
Entry	**Mean yield (kg ha^{-1})**	**Standard heterosis (%)**	**Entry**	**Mean yield (kg ha^{-1})**	**Standard heterosis (%)**
Top 20 yielders			**Top 20 yielders**		
Macia×ICSA4	4267	276.5	ICSR165×ICSA479	4314	223.5
ICSV700×ICSA307	4018	260.4	ICSR165×ICSA4	4212	218.2
ICSV700 [a]	3424	221.9	ZLR2×ICSA474	4202	217.7
ICSR165×ICSA4	2948	191.1	ZLR2×ICSA479	4100	212.4
ZLR1×ICSA724	2890	187.3	Macia×ICSA731	4005	207.5
ZLR1 [a]	2756	178.6	ZLR1×ICSA724	3707	192.1
ICSR165 [a]	2740	177.6	ZLR1×ICSA623	3700	191.7
ICSR165×ICSA724	2573	166.8	MRL15 [a]	3698	191.6
ICSB307 [a]	2563	166.1	ICSR165×ICSA623	3548	183.8
ZLR1×ICSA731	2388	154.8	MRL15×ICSA4	3438	178.1
Macia×ICSA731	2368	153.5	Macia×ICSA474	3403	176.3
Macia×ICSA26	2365	153.3	ICSV700×ICSA307	3366	174.4
ZLR1×ICSA4	2362	153.1	ZLR2×ICSA731	3355	173.8
ICSVP34046 [a]	2340	151.7	ICSV700×ICSA724	3333	172.7
ICSV700×ICSA474	2321	150.4	ICSR57×ICSA474	3323	172.2
Macia×ICSA724	2275	147.4	ICSR165×ICSA26	3227	167.2
ICSVP3046×ICSA307	2272	147.2	ZLR2×ICSA26	3170	164.2
MRL15 [a]	2258	146.3	MRL15×ICSA623	3076	159.4
ICSB724 [a]	2231	144.6	ZLR1 [a]	2863	148.3
ICSV700×ICSA731	2184	141.5	MRL15×ICSA26	2810	145.6
Parents			**Parents**		
ICSB474	1870	121.2	ICSR165	2612	135.3
ICSB26	1868	121.1	ZLR2	2609	135.2
ICSR57	1559	101.0	ICSR57	2358	122.2
Macia	1543	100.0	ICSB307	2312	119.8
ICSB731	1393	90.3	ICSB474	2089	108.2
ICSB623	1140	73.9	ICSB724	1955	101.3
ICSB479	1127	73.0	Macia	1930	100.0
ICSB4	791	51.3	ICSB731	1889	97.9
ZLR2	453	29.4	ICSVP3046	1772	91.8
			ICSB26	1516	78.5
			ICSV700	1390	72.0
			ICSB623	822	42.6
			ICSB4	807	41.8
			ICSB479	735	38.1
Season mean	1677			2321	
SED (overall)	0.449				
SED (overall)	0.635				

[a] = parents in the top 20 grain yield performers

In-season trials had significantly higher mean yield (2321kg ha^{-1}) than the off-season trials (1677ka ha^{-1}). The Spearman's rank correlation coefficient between the in-season and the off-season environments was positive and significant (r = 0.282; P = 0.013). The top 20 grain genotypes with respect to yield ranking were largely different between the off-season and the in-season environments. Five entries, ICSR165×ICSA4, ZLR1×ICSA724 and Macia×ICSA731 and parents ZLR1 and MRL15, were ranked in the top 20 in both environments (Table 6.4-5).

6.4.3 Relationships among traits

Grain yield was positively and significantly (P≤0.05) correlated to head length, number of leaves per plant and days to 50% flowering (Table 6.4-6). Number of leaves was also positively and significantly (P≤0.05) correlated to days to 50% flowering (Table 6.4-6). However, head length was negatively and significantly (P≤0.05) correlated to days to 50% flowering (Table 6.4-6). The weight of 1000 seeds was negative and significantly (P≤0.05) correlated to head length but positive and significantly (P≤0.05) correlated to days to 50% flowering (Table 6.4-6).

Table 6.4-6: Correlation coefficients between grain yield and its components for sorghum hybrids and parents across six environments

	Grain yield (kg ha^{-1})	1000 seed weight (g)	Head length	Number of leaves plant $^{-1}$	Number of tillers plant^{-1}
Grain yield (kg ha^{-1})	1.00				
1000 seed weight (g)	-0.02	1.00			
Head length (cm)	0.22**	-0.21*	1.00		
Number of leaves plant^{-1}	0.29**	0.26	-0.03	1.00	
Number of tillers plant^{-1}	0.07	-0.12	0.09	0.04	1.00
Days to 50% flowering	0.15*	0.44**	-0.21*	0.39**	-0.10

**, * significant at P≤0.01 and P≤0.05, respectively

6.4.4 Better-parent heterosis

Better-parent heterosis is presented for grain yield and its strongly associated trait, head length. Twenty-seven crosses displayed positive better parent heterosis of up to 95% for grain yield (Figure 6.4-1). For head length, 36 crosses displayed positive better parent heterosis of up to 31% (Figure 6.4-2). Parents with a regional origin and adaptation (regional parents ZLR1, MRL15, ZLR2, Macia and IMDP97) featured in 15 of the crosses with positive better parent heterosis for grain yield and in 20 of the 36 crosses with positive better parent heterosis for head length.

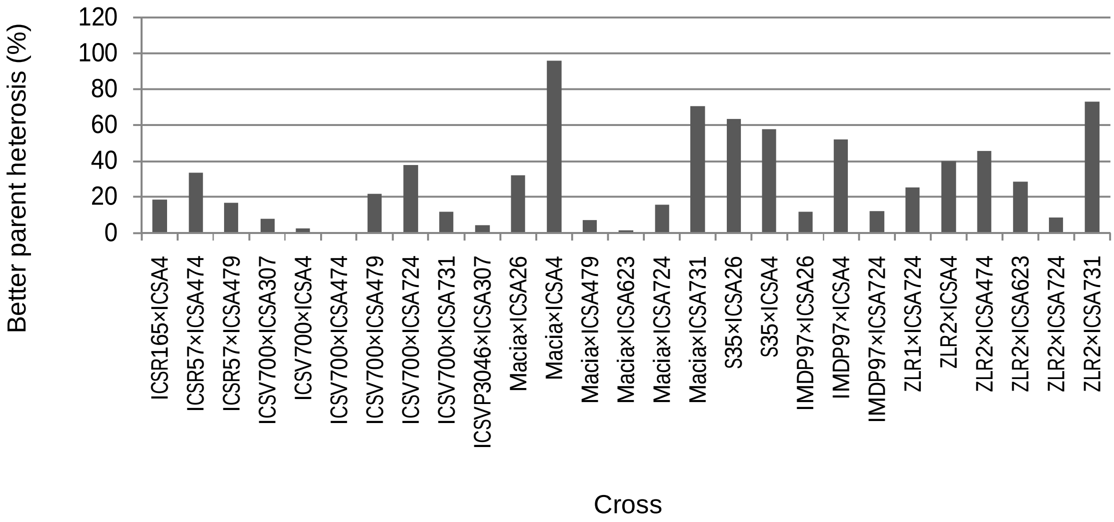


Figure 6.4-1: Twenty-seven sorghum hybrids showing positive better-parent heterosis for mean grain yield

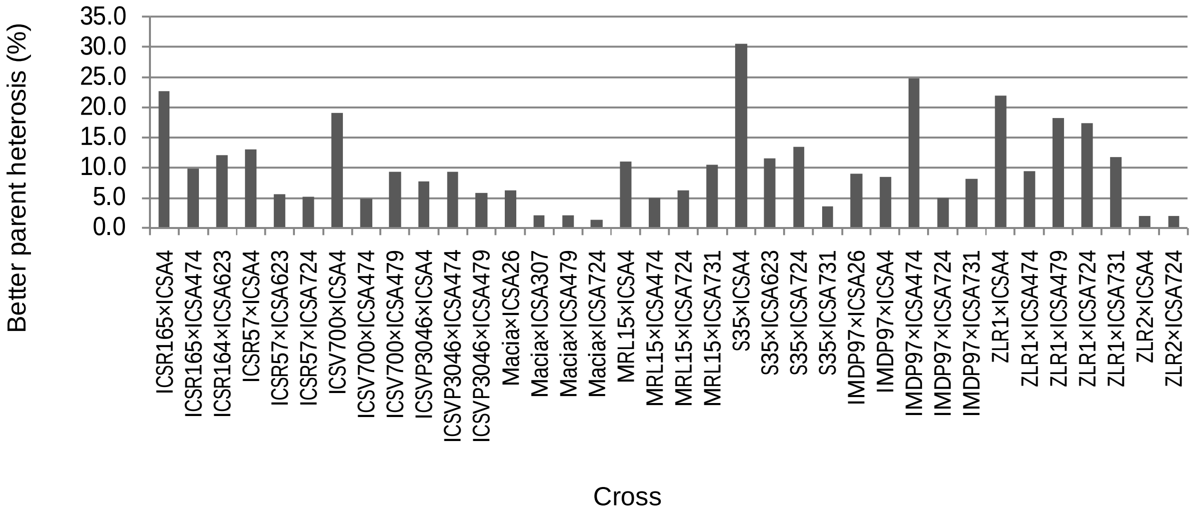
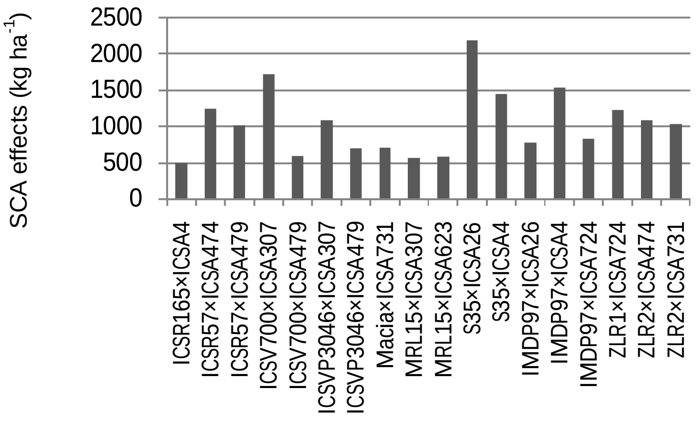


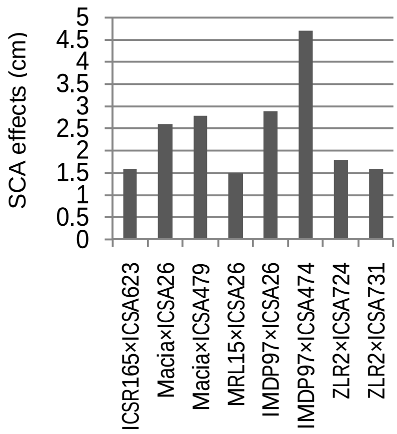
Figure 6.4-2: Thirty-six sorghum hybrids showing positive better-parent heterosis for head length

6.4.5 Combining ability effects

The GCA effects due to both male (GCAm) and female (GCAf) parents were significant ($P \leq 0.05$) for all traits except those due to females which were not significant for the number of leaves per plant (Table 6.4-1). Both GCAm and GCAf effects significantly ($P \leq 0.05$) interacted with the environmental effects for all traits except days to 95% maturity and the GCAf for number of tillers per plant (Table 6.4-1). The SCA effects were also significant for all traits and the SCA effects interaction with environmental effects were also significant for all but two traits, namely head length and days to 95% maturity (Table 6.4-1). The GCA effects for grain yield (t ha^{-1}) were positive and significantly (P≤0.05) increased from the mean by male parent ICSV700, ICSR165, S35, and IMDP97 and female parents ICSA4, ICSA724, and ICSA26 (Table 6.4-7). Eighteen crosses displayed significant (P≤0.05) SCA effects of up to 2200kg ha^{-1} for grain yield, nine of which involved parents of regional origin (Figure 6.4-3a). Head length was positively and significantly improved by ZLR1, Macia, S35, IMDP97, ISCA4, ICSA307, and ICSA26 (Table 6.4-7). The trait displayed significant SCA effects of up to 4.7cm (Figure 6.4-3b). The number of leaves was significantly (P≤0.05) increased by MRL15, ICSV700, ICSVP3046, S35, IMDP97, ICSA479, ICSA724, ICSA307, and ICSA623 (Table 6.4-7). Tillering was significantly increased by ZLR1, MRL15, ICSA307, and ICSA474 while days to 50% flowering and 95% maturity were significantly reduced by ZLR1, Macia, ZLR2, IMDP97, ICSA479, and ICSA474 (Table 6.4-7). Local parents generally reduced the number of days to both 50% flowering and 95% maturity compared to the introduced parents.



(a) Cross



(b) Cross

Figure 6.4-3: Sorghum crosses showing positive and significant SCA effects for (a) grain yield (SE = 253.5; SED = 358.5) and (b) head length (SE = 0.8; SED = 1.1) across six environments

Table 6.4-7: GCA effects for the sorghum male and female sorghum parents for grain yield and its components across six environments

	Grain yield (kg ha^{-1})	Head length (cm)	Number of leaves plant^{-1}	Number of tillers plant^{-1}	Days to 50% flowering	Days to 95% maturity
Male parents						
ZLR1	-112.8	2.0**	-1.7**	0.3*	-3.1*	-3.1*
MRL15	-198.8*	-0.7*	0.8**	0.3*	-0.6	-0.6
ICSV700	241.9*	-2.6**	0.4*	0.0	4.8**	4.8**
ICSVP3046	-672.6**	-2.2**	0.6*	-0.3*	4.0**	4.0**
Macia	87.6	2.0**	-1.5**	-0.1	-2.3*	-2.3*
ZLR2	-362.2*	-1.2**	-1.2**	0.1	-2.8*	-2.8*
ICSR165	312.6*	-1.8**	-0.3	-0.1	3.9**	3.9**
ICSR57	-442.1**	0.3	-1.2**	0.1	-0.4	-0.4
S35	704.1**	1.8**	2.2**	-0.2*	0.8	0.8
IMDP97	442.5**	2.4**	2.1**	-0.1	-4.3**	-4.3**
SE	91.2	0.3	0.2	0.1	0.8	0.9
SED	129.1	0.5	0.2	0.1	1.2	1.3
Female parents						
ICSA731	49.4	-0.7	-0.2*	0.0	0.8	0.8
ICSA479	-566.3**	-2.2**	0.5**	-0.3*	-2.2*	-2.2*
ICSA4	753.0**	1.6**	-0.4**	0.0	-0.3	-0.3
ICSA724	152.7*	0.4	0.4**	-0.2*	0.4	0.4
ICSA307	-226.8*	1.3**	0.3*	0.4**	4.4**	4.4**
ICSA474	-472.3**	-0.8*	-0.1	0.2*	-2.5*	-2.5*
ICSA26	190.7*	1.0*	-0.9**	0.1	0.5	0.5
ICSA623	119.9	-0.7*	0.4**	-0.2*	-1.2	-1.2
SE	96.8	0.3	0.1	0.1	0.8	0.8
SED	136.9	0.4	0.2	0.1	1.1	1.2

**,* = significant at P≤0.01 and P≤0.05, respectively

6.5 Discussion

6.5.1 Mean performance, heterosis and stability

The differences in mean grain yield performance between sites could be largely attributed to the sites' differences in temperature. The ideal sorghum temperatures were met at CRS in summer and RARS whereas MRS summer tended to be too hot for the crop, with maximum temperatures reaching as high as 40ºC. Temperatures at MRS in winter were too low which could have negatively affected the crop compared to CRS winter temperatures. Sorghum is well known for its sensitivity to cold temperatures, especially below 15°C (Peacock, 1982; Osuna-Ortega *et al*., 2003). Although the temperatures are ideal for sorghum during summer at URF, there was a cold spell at URF during seed set and soft dough stages during the trial which resulted in the development of ergot disease caused by *Claviceps africana.* This largely explained the low site and entry means observed at URF. Yield reduction in both quality and quantity has been reported in sorghum due to ergot disease by many authors including Blaney *et al*. (2000) and Frederickson and Leuschner (1997).

The observation that hybrids had a higher grain yield and took longer to flower and mature than parents and check varieties could be explained by high productivity in hybrids as a result of heterosis. Kenga *et al.* (2004) and Li and Li (1998) reported similar results for grain yield in hybrids and came to the same conclusions. However, check varieties were specifically bred for grain yield production, which could explain their having longer heads than the hybrid varieties, although this did not translate to higher yield. This was a result of the differences in the 1000 seed weight because hybrids and parents significantly outperformed the grain check varieties by 45% and 35%, respectively. The heavier seed could be attributed to a longer grain filling period observed for hybrids and parents compared to the grain check varieties.

Heterosis could also explain the high grain yield and its standard heterosis observed for hybrids, hence their domination of the top performers compared to parents and check varieties. The values observed in this study, up to 171% standard heterosis and up to 95% better parent heterosis compared with the upper limit reported in the literature. For example, Haussmann *et al*. (1999, 2000) reported relative hybrid superiority of 13 to 147.1% and Blum *et al.* (1990) reported heterosis of 23.9% to 39.6% for grain yield. This demonstrates the potential of exploiting heterosis from the current germplasm in developing new sorghum cultivars. Hybrids have greatly improved sorghum yields in China accounting for 90% of the area under sorghum (Li and Li, 1998). This led Haussmann *et al*. (1999) to conclude that hybrid production could play a significant role in increasing yield in semi-arid areas of Kenya. The current study results demonstrate the same potential for southern Africa. Further, the observation that 13 of the top 20 grain yield performers were constituted by three local parents and 10 hybrids involving local parents showed that using locally adapted germplasm for cultivar development could enhance performance due to improved adaptation to the local environment as reported by Rattunde *et al*. (2001). For example *Macia* was developed in Macia district in Mozambique and is arguably the most widely grown cultivar in the region, ZLR1 is popular in Zimbabwe and parts of Mozambique and South Africa, and MRL15 and IMDP97 have been demonstrated to be adapted to the region. This could imply that adapted parents are better grain yield performers in hybrid combinations (*inter se*) in the region, or that there might be high diversity between the local male parents and the introduced female parents which resulted in high levels of heterosis. Although diversity was not tested in the current, reports of high levels of heterosis from diverse germplasm have been made in sorghum by Rattunde *et al*. (2001) and Li and Li (1998).

The fact that the top grain performers were more stable and ranked highly compared to the bottom performers shows that breeding for general adaptation might be a viable option. This significantly reduces the cost of breeding programmes through reduced multilocation evaluation and the associated costs as reported by Lin and Binns (1988). The observation that the majority of the male parents displayed better cultivar superiority *per se* than *inter se* suggests that they were better cultivars for general adaptation as pure lines that in hybrid combinations with other parents. However, the magnitude of the differences was not large for some of the parents, suggesting that most of the male parents could be used to breed for general adaptation and breeding programmes using hybrid testing could be used to breed locally adapted materials for combining ability. The female lines' superiority *inter se* than *per se* could be attributed to the fact that they were developed for hybrid development and the importance of performance *inter se* could have been emphasised as a selection criterion during their development. Good combining ability is a chief criterion in selecting parental lines for hybrid programmes which could explain the better performance *inter se* than *per ser*

Presence of early and late entries, high and low tillering types, long and short head entries in the top grain yield performers gives scope for selection to meet the farmers' preferences in terms of production season, tillering and head types as well as general adaptation. The observation of significant correlation between grain yield and head length, number of leaves per plant and days to flowering suggest that apart from breeding for high grain yield, indirect gain might be realized through improvement of those traits. Further, the positive and significant correlation coefficient between 1000 seed weight and days to flowering suggested that seed weight could be improved through increasing the length of the growth cycle of the sorghum plant. This could be because increasing a crop's cycle also increases the grain filling period allowing more assimilates to be accumulated in the grain, resulting in an increase in seed weight. Generally, long season cultivars are higher yielding that their short season counterparts (Rehm and Schmitt, 1989; Klein, 2008). In contrast, the negative association between 1000 seed weight and head length suggest that as the head length increases, grain weight decreases. This can be a result of the competition for photo-assimilates between the developing grains because as head length increases, the numbers of grains per panicle usually increases. This is consistent with reports of improvement in seed weight as their number per panicle was reduced in some millet (*Pennisetum glaucum* (L.) germplasm (Seghatoleslami *et al*., 2008). However, increasing the growth cycle of the crop could result in cultivars that cannot fit in the relatively short growing seasons in the region which compromises adaptation to the region.

Significance of genotype by environment interaction was reflected by the differences between the mean performance and rank of the genotypes between the in-season and off-season environments. The low mean for grain yield during the off-season compared to the in-season environments can be partly explained by the low temperatures during the off-season production conditions (Figure 6.3-1). The observation of different composition of the top 20 grain yield performers between the in-season and off-season environments indicated that some of the genotypes might have specific adaptation to particular growing seasons. This observation was consistent with reports of significant genotype by environment interaction effects for grain yield performance in sorghum (Chapman et al., 2000). However, the presence of five entries common in the top 20 grain yield ranking suggested that these entries displayed general adaptation. This presents an opportunity of breeding cultivars that can be used during both in-season and off-season. This observation was supported by the positive and significant Spearman's correlation coefficient between the in-season and off-season, implying that the season generally ranked the entries in a similar way. This suggests that it might be possible to select for both growing periods during in-season which might reduce breeding costs associated with multi-environment evaluations. Nevertheless, when resources are not limiting, it is recommended to breed and test genotypes in the target environments because the Spearman's rank correlation of genotypes between the two environments was weak (r = 0.282).

6.5.2 Combining ability effects

The significance of both GCA and SCA effects suggested that both additive and non-additive gene effects controlled grain yield, head length, number of tillers per plant, number of leaves per plant, and days to both 50% flowering and 95% physiological maturity in sorghum. These results are consistent with earlier reports (Kirby and Atkins, 1968; Haussmann *et al*., 1999; Tadesse *et al*., 2008; Kenga *et al*., 2004) and they imply that improvement for the traits can be achieved through both selection and hybridisation. For grain yield, male parental lines ICSV700, ICSR165, S35 and IMDP97 and female parents ICSA4, ICSA724 and ICSA26 are potential parents for improving grain yield. These parents exhibited high GCA values, which showed high potential in developing superior hybrids. The hybrids S35×ICSA26, IMDP97×ICSA4 and the rest of the crosses shown in Figure 6.4-3a are potential crosses for further evaluation. It is also prudent to consider only those hybrids between parents with positive and significant GCA effects such as ICSR165×ICSA4 because genetic gain is realized in the presence of sufficient additive variances. In the same regard, most of the top grain-yield performing hybrids were observed to be constituted from crosses with both or one parent exhibiting significant GCA effects. Regardless of their significant SCA effects, crosses such as ZLR2×ICSA474 that are constituted from parents with negative and highly significant GCA effects for grain yield are not desirable due to insufficient additive variance. This is consistent with the notion that selection of parents for crop improvement programmes cannot be based on SCA effects alone, but in association with hybrid means and GCA effects of the parents involved (Marilia *et al*., 2001).

Tillering and number of leaves per plant can be used where sorghum is bred for alternative uses such as fodder and sweet stem that rely heavily on biomass volumes. Sorghum alternative uses can be found in the literature such as Patil (2007). Further, breeding for the region entails fitting the plants into the relatively short rainy period. The observed negative GCA effects for days to 50% flowering means that parental lines ZLR1, ICSV700, ICSVP3046 and all the others with negative and significant GCA effects (Table 6.4-7) can be exploited in breeding relatively short seasoned cultivars for the tropical lowland environments and medium maturing cultivars for the mid-altitude environments. Early maturing cultivars are advantageous in low rainfall areas because they are able to optimise the limited moisture. This mechanism of drought escape has been used in many crops including sorghum (Seetharama, 1995).

The significant interaction between male and female GCA effects and the crosses' SCA effects with the environmental effects demonstrates that the environment played a significant role in altering both the additive and non-additive gene effects. This shows the differential responses of hybrids to the environments, most likely resulting from temperature variations between environments. The implication is that both hybrids must undergo multilocation testing for GCA and SCA screening to select the best parents and potential crosses. The results also indicated that there is a possibility to breed for either general or specific adaptation from the current germplasm.

6.6 Conclusions

From the study, it can be concluded that there is potential for breeding grain yield hybrid cultivars that are superior for grain yield to those currently on the market and better than the parent lines for deployment in southern Africa. Hybrids were superior to pure line cultivars in both productivity and stability, and breeding hybrid cultivars can improve sorghum productivity in the region. In the study, genes with both additive and non-additive effects were shown to control grain yield, weight of 1000 seeds, head length, number of leaves per plant, number of tillers per plant, days to 50% flowering, and days to 95% maturity in sorghum. Therefore, a breeding programme based on selection and hybridisation is recommended. Parents ICSV700, ICSR165, S35, IMDP97, ICSA4, ICSA724 and ICSA26, with positive and significant GCA effects for grain yield and which showed significant SCA effects in single crosses are recommended as potential parents for inclusion in the breeding programme.

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CHAPTER 7

Relationship between grain yield components and stem sugar traits in dual-purpose sorghum germplasm

7.1 Abstract

Knowledge of the relationship between grain yield, stem sugar content and stem biomass would be useful in devising a breeding strategy for dual-purpose sorghum cultivars. Simple correlation and path-coefficients were computed between grain yield components and stem sugar traits using 100 sorghum genotypes grown in six environments covering tropical low and mid-altitude ecologies in southern Africa. Two studies were conducted, one with grain yield as the dependent variable while the rest of the traits were independent and the second with grain yield as the dependent variable and the other trait independent. Grain yield was positively and significantly ($P \leq 0.05$) correlated with stem biomass, days to 50% flowering, number of leaves per plant (number of leaves), plant height and stem diameter implying that selecting for improved stem biomass, late maturing and leafiness could result in improved grain yield. However, grain yield was negatively and significantly correlated with stem brix at maturity and stem juice score. This suggested that high grain yielding cultivars were generally low in stem sugar, but juicy cultivars were high in grain yield. However, the correlation coefficient of the two traits for the top 20 grain yield and stem brix performers was positive but not significant, suggesting that the traits were not mutually exclusive in this group. This was supported by the identification of hybrids that combined high performance for the two traits as well as stem biomass. Number of leaves had a high, positive and significant direct effect on grain yield while stem brix and stem juice score had negative and significant direct effects on grain yield. This implied that direct selection using these traits would be effective in cultivar development. Similarly, grain yield had a negative and significant direct effect on stem brix. High positive indirect effect through number of leaves was responsible for the overall positive and significant correlation observed between stem brix and most of the traits. Stem diameter and juice score had negative direct effects to stem brix and the correlation of the latter to stem brix was negative and high. This implied that breeding for improved stem brix could be achieved through breeding for juicy stems. Stem diameter and number of leaves were positively and significantly correlated with stem brix. This implied that thicker leafy plants had higher stem brix values than thinner ones. Further, the indirect effects of stem diameter on stem brix through the number of leaves were positive and high. High indirect effects of stem biomass weight, grain yield, days to 50% flowering and plant height on stem biomass through

number of leaves were observed. This suggested that stem brix could be directly improved through improving plant leafiness or indirectly as a correlated response to improving stem biomass, grain yield, days to 50% flowering and plant height. Overall, the study demonstrated that it is possible to develop cultivars with high grain yield, stem brix and stem biomass yield potential in one cultivar.

Keywords: dual-purpose sorghums, grain yield components, correlation, path-coefficients, stem sugar traits

7.2 Introduction

Success in breeding dual-purpose sorghum for grain and stem sugar depends on the understanding of the relationship between the two and their associated traits. The general notion is that improving grain yield results in a reduction in stem sugar yields. The argument is that the two represents two powerful sinks for the limited photo-assimilates. Based on this perception, it is assumed that high grain yielding cultivars are low in stem sugar and vice versa. However, there is no evidence to support this view. Reports on the relationship are scarce. Guiying *et al*. (2000) suggested a negative relationship between stem sugar and weight of 1000 seeds, grain yield components (r = -0.472). Conclusions based on studies including 1000 seed weight alone can be erroneous because the trait is dependent on the number and size of the seeds per plant. Therefore, using grain yield represents the most dependable results on the relationship. This necessitates the detailed studies on the relationship between grain yield components and stem sugar traits if acceptable dual-purpose sorghum cultivars are to be developed. Understanding this relationship helps breeders formulate and optimize the selection strategy. For example choosing between direct versus indirect selection or compromising between equally important traits showing strong negative relationships.

Relationships between plant traits have been studied using simple correlation analysis. These measure simple linear relationships among traits, that is, mutual association without regard to cause and effect. When used alone, correlation coefficients alone do not give a clear representation of the relationships (Makanda *et al*., 2009; Bidgoli *et al.*, 2006). This necessitates a further decomposition of the correlation coefficients into non-linear connecting paths of influence called path-coefficients (Bidgoli *et al.*, 2006; Dewey and Lu, 1959). Path-coefficients give both the direct and indirect (through other traits) influences of individual traits to the dependent variable (García del Moral *et al*., 2003). This is based on the fact that as the number of parameters influencing a particular dependent variable increase, so does the interdependence among the parameters (Ofori, 1996). This can be used to the breeder's advantage because traits can be improved indirectly capitalising on correlated responses during selection. Therefore, to fully study these relationships between traits, the use of both correlation coefficients and path-coefficients is the most prudent approach.

Correlation and path-coefficient analyses have been used to study relationships between traits in many crops. They have been used in sorghum (Mutengwa *et al.,* 1999; Maman *et al*., 2004), wheat (Aycicek and Yildirim, 2006), groundnuts (Bera and Das, 2000), bambara groundnuts (Makanda *et al*., 2009; Ofori, 1996), linseed (Akbar *et al*., 2001), safflower (Bidgoli *et al*., 2006), tomato (Rani *et al*., 2008) and cotton (Azhar *et al*, 1999). Although no reports were found in the literature on stem sugar traits and grain yield components, apart from that reported by Guiying *et al*. (2000), there are many studies reported for grain yield and its components. Grain yield was reported to be positively correlated with numbers of seeds per head and weight of 1000 seeds in sorghum (Maman *et al*., 2004). The authors reported direct effects of the traits on grain yield to be high with that of weight of 1000 seeds ranging between 0.39 and 0.48. Alam *et al*. (2001) and Ekshinge *et al.* (1983) reported positive and high correlation coefficients between grain yield and plant height (r = 0.942), head length (r = 0.947), biomass weight (r = 0.935), and days to flowering (r = 0.943). In the study by Alam *et al*. (2001), biomass weight was reported to be positive and significantly correlated with plant height, head length, and days to flowering. Giriraj and Goud (1983) reported the relationship between plant height and head length to be negative. These results suggest that improving plant biomass improves grain yield. This is consistent with earlier reports that heterosis in sorghum grain yield is, in part, attributed to increased plant height and biomass of hybrids at the same harvest index (Blum *et al*., 1990). However, these relationships are influenced by the environments (Maman *et al*., 2004), necessitating multi-environment evaluation to quantify the relationships.

Nevertheless, there are no such reports on dual-purpose sorghums and results obtained elsewhere do not necessarily reflect relationships in a different environment because the traits are influenced by it. There is need to perform similar studies on dual-purpose sorghum and under the target tropical low and mid-altitude environments. The most important relationships in dual-purpose sorghum are those between grain yield, stem brix, stem biomass, stem juiciness and maturity traits as they impact directly on breeding. Given the foregoing, the current study was initiated to study the relationships between grain yield components and stem sugar traits in dual-purpose sorghum using correlation and path-coefficients analyses. The following hypotheses were tested:

i. Grain yield, stem sugar and their components are independent of each other in breeding for dual-purpose sorghum,
ii. Grain yield and its components and stem sugar traits do not have direct or indirect influence on selections for stem sugar content,
iii. Stem brix and its components and grain yield components do not have direct or indirect influence on selections for grain yield

7.3 Materials and Methods

7.3.1 Study sites and germplasm

This study was based on data involving 100 sorghum genotypes that included 80 dual-purpose hybrids (generated by crossing 10 sweet and grain sorghums with eight cytoplasmic male-sterile lines in a North Carolina II mating scheme), their parents and check varieties were used in the study. The genotypes were generated and evaluated at Chokwe Research Station (Chokwe) (24° 31′ S; 33° 0′ E, 40m.a.s.l) in Mozambique and at Makhathini Research Station (Makhathini) (27º 24'S; 32º 11' 48" E, 72m.a.s.l.) in South Africa during off-season (May to September 2008) and in-season (November 2008 to April 2009). Further in-season trials were conducted at Rattray-Arnold Research Station (RARS) (17º 40' S; 31º 14' E, 1308m.a.s.l.) in Zimbabwe and at Ukulinga Research Farm (Ukulinga) (30º 24' E; 29º 24' E, 781m.a.s.l.) in South Africa. Standard agronomic practices for sorghum production were followed at all sites.

7.3.2 Data collection

Stem sugar content was measured in ºbrix, using an Atago PAL-1 digital hand-held pocket refractometer (with automatic temperature compensation ranging from 0 to 50°C) at the hard dough stage. At the hard dough stage of each entry, stems were harvested, divided into three equal parts (top, middle and bottom sections) and three brix measurements were taken at the middle internode of each section. Stalk juice was squeezed from the cut internode section into the sample stage of the refractometer using a pair of pliers. Carryover effects were avoided by rinsing the pliers and the refractometer between samples. A rating scale of 1 (juicy) to 9 (dry) was used to asses stem juiciness depending on the ease of squeezing and the amount of juice yields. Stem diameter was also measured from the three mid internode sections using a veneer calliper. Therefore, the average of the three measurements per stem were averaged to give the value for stem brix, diameter and juice score for the plant. Stem biomass was measured at the hard dough stage by removing all leaves and heads from the plant, then cutting at ground level and weighing the stems. Plant height was measured using a 3.0m ruler and number of days to 50% flowering (time in days taken for half of the plot to have reached anthesis) was also recorded. Grain was harvested by hand after the hard dough stage recorded on a kg ha^{-1} basis after adjusting to 12.5% grain moisture content. Number of tillers per plant (tillers that were taller than half of the main plant) and head length (measured with a 30cm ruler) were also measured.

7.3.3 Data analyses

In this study, the phenotypic correlations (r_p) were assumed to be equal to the genetic correlations (r_g) because the number of genotypes evaluated was high (100) over many environments (six) totalling 14 replications over sites. As the sample size, and the environments in which the genotypes were evaluated increase, r_p and r_g coincide due to the removal of the environmental effects by multilocation evaluation (Cheverud, 1988; Waitt and Levin, 1998). Analyses were combined across the six environments because correlation and path-coefficients were similar between the tropical low and mid-altitude environments. Three studies on correlations and path-coefficient studies were conducted, (i) using grain yield as the dependent variable, (ii) using stem brix as the dependent variable and the other traits (listed in equations 1 to 9 below) as the independent variable, and (iii) another correlation performed on a subsample of the top 20 performing genotypes on stem sugar, grain yield and stem biomass. Analysis (iii) was done to establish the relationship between the traits among the candidate "elite" genotypes based on performance in the current study.

Correlation coefficients (r) between all the traits were computed in GenStat computer package (Payne *et al.,* 2007). Further correlation coefficients were computed between the top 20 stem brix, grain yield and stem biomass performers to ascertain the general relationship observed with all the entries. Path-coefficients (P) were calculated by regression method based on the work of Wright (1921, 1960), Dewey and Lu (1959) and Cramer *et al.* (1999). In this procedure, all the independent variables (1 to n) are regressed against the dependent variable (X). The regression coefficient (*b*) of each of the independent traits (1 to n) is its direct effects to the dependent variable X (Cramer *et al*., 1999). The indirect effects are then computed by multiplying the correlation coefficient between each of the independent variables (1 to n) and the variable in its path (1 to n) by the direct effect, *b*, of the independent variable in the path to the dependent variable (Cramer *et al*., 1999). The equations for the multiplications are given below:

1. $r_{19} = P_{19} + r_{12}P_{29} + r_{13}P_{39} + r_{14}P_{49} + r_{15}P_{59} + r_{16}P_{69} + r_{17}P_{79} + r_{18}P_{89}$
2. $r_{29} = P_{29} + r_{12}P_{19} + r_{23}P_{39} + r_{24}P_{49} + r_{25}P_{59} + r_{26}P_{69} + r_{27}P_{79} + r_{28}P_{89}$
3. $r_{39} = P_{39} + r_{13}P_{19} + r_{23}P_{29} + r_{34}P_{49} + r_{35}P_{59} + r_{36}P_{69} + r_{37}P_{79} + r_{38}P_{89}$
4. $r_{49} = P_{49} + r_{14}P_{19} + r_{24}P_{29} + r_{34}P_{39} + r_{45}P_{59} + r_{46}P_{69} + r_{47}P_{79} + r_{48}P_{89}$
5. $r_{59} = P_{59} + r_{15}P_{19} + r_{25}P_{29} + r_{35}P_{39} + r_{45}P_{49} + r_{56}P_{69} + r_{57}P_{79} + r_{58}P_{89}$
6. $r_{68} = P_{69} + r_{16}P_{19} + r_{26}P_{29} + r_{36}P_{39} + r_{46}P_{49} + r_{56}P_{59} + r_{67}P_{79} + r_{68}P_{89}$
7. $r_{78} = P_{78} + r_{17}P_{19} + r_{27}P_{29} + r_{37}P_{39} + r_{47}P_{49} + r_{57}P_{59} + r_{67}P_{69} + r_{78}P_{89}$
8. $r_{89} = P_{89} + r_{18}P_{19} + r_{28}P_{29} + r_{38}P_{39} + r_{48}P_{49} + r_{58}P_{59} + r_{68}P_{69} + r_{78}P_{79}$

Where: 1 = Grain yield; 2 = stem biomass weight; 3 = Days to 50% flowering;4 = Head length; 5 = stem juice score; 6 = Number of leaves per plant; 7 = plant height; 8 = stem diameter and 9 = Stem brix at maturity, the dependent variable. When using grain yield as the dependent variable (9), then stem brix becomes an independent variable (1).

Taking equation (2) above for example,

r_{29} = the correlation coefficient between 2 (stem biomass) and 9 the dependent variable (grain yield or stem brix at maturity depending on the one used as the response);

P_{29} = the direct path coefficient of stem biomass on the dependent trait 9 (stem brix or grain yield);

$r_{12}P_{29}$ = the indirect path coefficient of stem biomass on trait 9 through trait used as 1 (either grain yield or stem brix);

$r_{23}P_{39}$ = the indirect path coefficient of stem biomass on trait 9 through trait 3 (days to 50% flowering);

$r_{24}P_{49}$ = the indirect path coefficient of stem biomass on 9 through trait 4 (head length);

$r_{25}P_{59}$ = the indirect path coefficient of stem biomass on trait 9 through trait 5 (stem juice);

$r_{26}P_{69}$ = the indirect path coefficient of stem biomass on 9 through trait 6 (number of leaves per plant);

$r_{27}P_{79}$ = the indirect path coefficient of stem biomass on 9 through trait 7 (plant height); and

$r_{28}P_{89}$ = the indirect path coefficient of stem biomass on trait 9 through trait 8 (stem diameter).

The relationships are presented diagrammatically in Figure 7.3-1 below where the thick one-headed arrows represent the direct effects and the thin double headed arrows represent the correlation coefficients between the determinant traits.

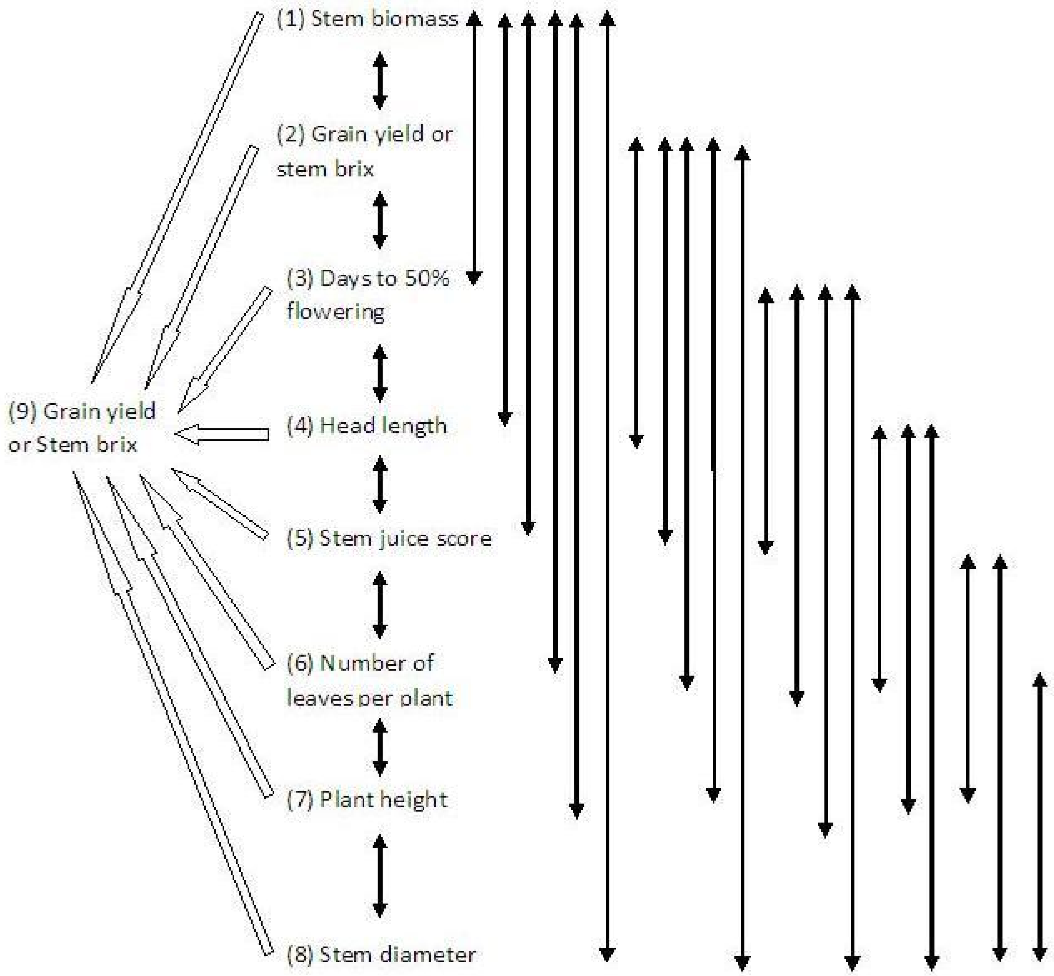

Figure 7.3-1: Path diagram showing relationships between grain yield or stem brix against stem biomass, grain yield/stem brix, head length, stem juice score, number of leaves per plant, plant height and stem diameter,

In addition to the correlation and path-coefficient analysis, a selection of the hybrid showing performance was used to help answer the question of whether it is possible to breed dual-purpose sorghum with high stem sugar, high stem biomass and high grain yield potentials. Top 20 and bottom five stem brix performers were selected and compared for grain and stem biomass yields in relation to stem brix so as to identify possible dual-purpose entries. In this section, the overall means over environments and the means for the tropical low (Chokwe and Makhathini) and mid-altitude (RARS and Ukulinga) environments are presented (Table 7.4-4). The data on standard heterosis and cultivar superiority indices (P*i*) is also presented (Table 7.4-4). The P*i* is the distance mean square between the response observed for a cultivar in a particular environment and the maximum response observed for the same environments. A cultivar with a low P*i* is superior in performance across environments and selected over another with a high P*i* because it shows consistency in performance across environments (Lin and Binns, 1988).

7.4 Results

7.4.1 Relationships between grain yield components and stem sugar traits

The correlation coefficient between grain yield components and stem sugar traits are presented in Table 7.4-1. There was a positive and significant (P≤0.05) correlation coefficient between stem biomass and (i) head length, (ii) number of leaves per plant; (iii) plant height, and (iv) stem diameter. Days to 50% flowering were positively and significantly (P≤0.05) correlated with number of leaves per plant and negatively and significantly (P≤0.05) correlated with stem juice score. Head length was positively and significantly correlated with plant height and stem diameter while the correlation coefficient with number of leaves per plant was negative and significant (P≤0.05). There was a positive and significant (P≤0.05) correlation coefficient between number of leaves per plant and both plant height and stem diameter. Plant height was in turn positively and significantly correlated with stem diameter.

Table 7.4-1: Correlation coefficients between grain yield and stem sugar content with selected agronomic traits in sorghum

	SBX	GY	SBW	DT50F	HDL	SJS	NLP	PHT
Stem brix (SBX)	1.000							
Grain yield (GY)	0.071**	-1.000						
Stem biomass weight per hectare (SBW)	0.102	0.046**	1.000					
Days to 50% flowering (DTF)	0.117	0.049*	-0.076	1.000				
Head length (cm) (HDL)	0.084*	0.024*	0.226**	-0.253	1.000			
Juice score (SJS)	-0.265**	-0.049*	-0.117	-0.110**	-0.230	1.000		
Number of leaves per plant (NLP)	0.458**	0.124**	0.181*	0.387*	-0.113**	-0.081	1.000	
Plant height (cm) (PHT)	0.183*	0.070**	0.434**	0.144	0.134*	-0.032	0.404**	1.000
Stem diameter (mm) (SD)	0.005	0.093**	0.172*	0.443	0.132**	-0.316**	0.302**	0.193**

**, * significant at P≤0.01 and P≤0.05, respectively

7.4.2 Path-coefficient analysis of sorghum traits on grain yield and stem brix at maturity

The regression of all the traits on both stem brix at maturity and grain yield were significant (P≤0.001). The significant of some correlation coefficients and the regression analysis indicated that it was prudent to proceed with path coefficient analysis on the traits. The regression coefficients (*b*) for the traits, which are their direct effects of those traits on the response variable are presented for both grain yield and stem brix in Tables 7.4-2 and 7.4-3, respectively. Their significance at P≤0.01 and P≤0.05 is also indicated.

The direct and indirect path coefficients of stem sugar traits and grain yield components to grain yield are presented in Table 7.4-2. Total correlation coefficients are presented in Table 7.4-1. Stem biomass had a positive and significant (P≤0.01) correlation coefficient with grain yield although the direct and indirect effects were low and non-significant. Stem brix at maturity had a negative and significant (P≤0.01) correlation coefficient and direct effect on grain yield. The indirect effect was low. The correlation coefficient between grain yield and days to 50% flowering, head length, plant height and stem diameter were significant with low direct effects. Stem juice score exhibited a significant (P≤0.01) and negative correlation coefficient and direct effect on grain yield. Number of leaves per plant displayed a positive and high correlation coefficient and direct effect on grain yield. The indirect effects of all the traits to grain yield were generally low.

Table 7.4-2: Direct and indirect path coefficients of selected sorghum traits on grain yield across six environments

	†Direct path coefficient on grain yield	**Indirect path values through:**							
		SBW	**SBX**	**DTF**	**HDL**	**SJS**	**NLP**	**PHT**	**SD**
SBW	0.0000		0.0050	-0.0003	0.0075	0.0052	0.0241	0.0004	0.0044
SBX	-0.1042**	0.0000		0.0006	0.0021	0.0093	0.0228	0.0000	-0.0017
DTF	0.0041	0.0000	-0.0142		-0.0084	0.0049	0.0513	0.0001	0.0114
HDL	0.0332	0.0000	-0.0065	-0.0010		0.0102	-0.0149	0.0001	0.0034
SJS	-0.0443*	0.0000	0.0220	-0.0004	-0.0076		-0.0108	0.0000	-0.0081
NLP	0.1326*	0.0000	-0.0179	0.0016	-0.0037	0.0036		0.0003	0.0078
PHT	0.0008	0.0000	0.0039	0.0006	0.0044	0.0014	0.0536		0.0050
SD	0.0257	0.0000	0.0071	0.0018	0.0044	0.0140	0.0401	0.0002	

† = direct path coefficients synonymous with the regression coefficient (*b*) of the trait; **, * significant at P≤0.01 and P≤0.05, respectively; SBX = stem brix at maturity; SBW = stem biomass weight; DTF = days to 50% flowering; HDL = head length; SJS = stem juice score; NLP = number of leaves per plant; PHT = plant height; SD = stem diameter

The direct effects, indirect effects and correlation coefficients between stem brix at maturity and both its associated traits and grain yield and its components are presented in Table 7.4-3. Total correlation coefficients are presented in Table 7.4-1. Grain yield had a positive and significant (P≤0.01) correlation coefficient with stem brix at maturity but its direct effect was negative and significant. A positive indirect effect of grain yield on stem brix at maturity was observed through number of leaves per plant. Although the correlation coefficient between days to 50% flowering and head length with stem brix at maturity was not significant, their direct effects were significant. The indirect effect of days to 50% flowering through number of leaves per plant was positive and high while that through stem diameter was negative and also high. Stalk juice score displayed a significant (P≤0.01) and negative correlation coefficient and direct effect on stem brix at maturity. Number of leaves per plant and plant height had significant (P≤0.01) and positive correlation coefficients with stem brix at maturity but only the direct effect of numbers of leaves per plant was high and significant. The correlation coefficient between stem diameter and stem brix at maturity was not significant but the direct effect was negative, significant (P≤0.01) and high. The indirect effect of stem diameter and plant height via number of leaves per plant was high and positive.

Table 7.4-3: Direct and indirect path coefficients of selected sorghum traits on stem brix at maturity across six environments

	†Direct path coefficient on stem brix	Indirect path coefficients through							
		SBW	SBX	DTF	HDL	SJS	NLP	PHT	SD
SBW	0.0000		-0.0001	-0.0029	0.0285	0.0321	0.0943	-0.0032	-0.0465
GY	-0.0006**	0.0000		0.0055	0.0191	0.0408	0.1344	-0.0017	-0.0772
DTF	0.0381**	0.0000	-0.0001		-0.0319	0.0303	0.2012	-0.0011	-0.1199
HDL	0.1261*	0.0000	-0.0001	-0.0096		0.0633	-0.0586	-0.0010	-0.0356
SJS	-0.2753**	0.0000	0.0001	-0.0042	-0.0290		-0.0422	0.0002	0.0856
NLP	0.5200**	0.0000	-0.0002	0.0147	-0.0142	0.0224		-0.0030	-0.0819
PHT	-0.0074	0.0000	-0.0001	0.0055	0.0169	0.0089	0.2102		-0.0524
SD	-0.2709**	0.0000	-0.0002	0.0169	0.0166	0.0869	0.1572	-0.0014	

† = direct path coefficients synonymous with the regression coefficient (*b*) of the trait; **, * significant at P≤0.01 and P≤0.05, respectively; GY = grain yield per hectare; SBW = stem biomass weight; DTF = days to 50% flowering; HDL = head length; SJS = stem juice score; NLP = number of leaves per plant; PHT = plant height; SD = stem diameter

The correlation coefficients between grain yield and stem brix at maturity (r = 0.1470) and stem brix and stem biomass (r = -0.2344) for the top 20 performers were not significant. Only the relationship between grain yield and stem biomass was high and positive and significant (P≤0.01).

The top and bottom performers based on stem brix, grain yield and stem biomass are presented in Table 7.4-4. These entries, in addition to the correlation and path coefficients analysis were used to discuss the feasibility of breeding dual-purpose sorghum cultivars.

Table 7.4-4: Stem brix, stem biomass and grain yield performance and cultivar superiority of selected sorghum hybrids and parents across six environments

Entry	Stem brix (°brix)					Stem biomass (kg ha^{-1})					Grain Yield (kg ha^{-1})				
	MA	**TL**	**Mean**	**StdH**	**P*i***	**MA**	**TL**	**Mean**	**StdH**	**†P*i***	**MA**	**TL**	**Mean**	**StdH**	**P*i***
Top 20 stem brix performers															
ICSVP3046×ICSA4	14.8	12.5	13.5	125	35.4	41272	29669	32948	97	0.47	1505	1018	1261.6	72	11.2
ICSV700×ICSA731	14.4	12.3	13.2	122	22.3	51497	38325	42088	124	1.28	2810	3261	3035.6	173	6.3
ICSR165×ICSA307	13.9	12.0	12.8	118	19.6	51641	49615	50194	147	1.30	2410	2552	2481.0	141	6.8
ZLR1×ICSA26	13.9	11.4	12.4	114	28.3	57868	30218	38118	112	1.58	2271	1807	2039.0	116	8.3
ZLR1×ICSA307	15.0	10.5	12.3	113	28.0	43023	25194	30288	89	1.59	1446	1072	1259.2	72	11.4
MRL15×ICSA26	12.9	11.9	12.2	112	29.6	19935	34804	30556	90	1.58	2754	2118	2435.8	139	6.6
ICSB479	14.8	10.8	12.1	112	19.4	30333	15837	20669	61	1.88	869	764	816.5	412	14.2
Saccaline	13.5	9.2	12.0	111	13.0	36363	24673	32466	95	1.45	3879	1348	2613.5	142	5.6
ICSR165×ICSA724	14.5	10.4	12.0	111	29.4	41418	32817	35275	104	1.08	2865	1930	2397.4	136	7.0
MRL15×ICSA4	14.6	10.2	11.9	110	26.5	51205	32115	37570	110	1.75	1045	5168	3106.6	177	5.1
ICSR165×ICSA4	12.8	10.7	11.8	109	25.0	49441	37592	40978	120	1.84	4437	3555	3995.8	227	1.7
ICSV700×ICSA307	13.1	11.1	11.8	109	28.9	48229	34444	38686	114	1.82	3956	4071	4013.4	228	3.4
ICSR57	14.3	9.2	11.7	108	38.2	21402	16231	17708	52	1.99	1935	1932	1933.4	110	8.2
ICSR165×ICSA479	16.0	7.4	11.7	108	32.2	59048	25797	33186	97	2.05	4187	2310	3248.3	184	5.5
ICSR165×ICSA26	14.0	9.3	11.6	108	23.7	81346	42432	51588	152	2.01	4076	2386	3231.0	183	3.3
S35×ICSA4	12.2	10.9	11.5	107	28.7	34826	57248	43795	129	2.09	5332	4999	5165.7	294	1.8
ICSV700	13.2	10.3	11.4	106	22.2	40725	30147	33994	100	2.19	1751	2385	2067.8	118	10.2
Macia×ICSA307	10.7	12.2	11.4	106	38.3	24485	21974	22746	67	1.72	1840	1780	1809.8	103	8.9
ICSVP3046×ICSA731	11.7	11.0	11.3	104	36.3	45288	40314	41844	123	2.26	2193	1733	1962.8	112	8.0
ICSV700×ICSA4	13.3	9.9	11.2	104	25.5	21917	32625	29565	87	2.11	1774	2280	2027.0	115	8.9
Bottom 5 stem brix performers															
MRL15×ICSA724	10.4	5.9	7.4	68	66.0	23594	24651	24299	71	4.11	2384	1766	2074.8	118	7.5
ZLR2×ICSA724	9.6	6.0	7.2	66	65.5	28389	25816	26551	78	4.07	2537	1496	2016.4	115	7.2
Msinga	7.1	7.1	7.1	65	52.9	19899	22457	21434	63	4.27	2201	960	1580.3	90	7.7
ICSV700×ICSA474	7.3	6.9	6.9	63	62.9	44844	38715	40466	119	4.10	1836	2230	2032.8	116	9.0
Robbocane 11/59	7.4	6.5	6.8	63	61.9	16717	12064	13756	41	3.33	2389	970	1679.3	96	7.2
ZLR2×ICSA307	6.1	7.1	5.8	53	77.7	10095	27861	21939	64	4.46	459	395	427.0	24	18.7
Standard check varieties															
Stem sugar and biomass check (ZLR1)	10.6	10.8	10.7	100	10.4	44598	23512	34055	100	1.19					
Grain yield check (Macia)											1976	1541	1758.3	100	11.4
Environment mean	11.4	9.2	10.5			29130	34166	31648			2559	1972	2265.7		
P-value			<0.01					<0.01					<0.01		
SED			1.52					7694					823.0		

MA = Mid-altitude environment; TL = Tropical-lowland environment; StdH = Standard heterosis; P*i* = Cultivar superiority index; SED = Standard error of difference; † = data divided by 100 million

7.5 Discussion

7.5.1 Relationships between grain yield components and stem sugar traits

The positive correlation between stem biomass and (i) head length, (ii) number of leaves per plant; (iii) plant height, and (iv) stem diameter could be attributed to the fact that plant height and stem diameter are major components of stem biomass. These findings are consistent with earlier reports in sorghum (Alam *et al*., 2001; Ekshinge *et al*., 1983; Piper and Kulakow, 1994; Ezeaku and Mohammed, 2006). Piper and Kulakow (1994) found that 42 to 74% of grain yield was attributed to plant biomass, results that are consistent with the positive and significant correlation coefficient between the two traits observed in the current study. Head length and number of leaves per plant also increases with increasing plant height and subsequently stem biomass. This can explain the positive and significant correlation coefficient observed between the traits. The same can be said for the positive correlation between plant height and both head length and stem diameter, which was consistent with earlier reports in sorghum (Alam *et al*., 2001) and in rice (Babar *et al*., 2007). Most tall plants have longer heads than their shorter counterparts. This was given as an explanation for heterosis in sorghum (Patanothai and Atkins, 1971) and can explain the positive correlation coefficient between the two traits. Similar results were reported by Alam *et al*. (2001). However the negative correlation between head length and number of leaves per plant could be as a result of more assimilates being translocated for leaf development at the expense of the head. This implies that breeding for high grain yield can be achieved indirectly through breeding for reduced leafiness to optimum levels. However, these optimum levels have to be established for each cultivar because it is logical that differences in plant height and environmental conditions result in varying photosynthetic levels and efficiencies. The positive relationship between stem diameter and number of leaves per plant can be attributed to more photo-assimilates from more leaves that are used to build tall and thick stemmed plants. This can be used to explain the positive and significant correlation between stem diameter and plant height because plant growth occurs both in height and girth.

7.5.2 Path-coefficient analysis on grain yield and stem brix at maturity

The results from this study confirmed the long held notion that breeding for high grain yield directly reduces stem sugar in sorghum and vice versa. This has major implication on dual-purpose sorghum breeding programmes because it implies that a compromise has to be reached between the two traits. Chances are that the compromise may follow market trends such that when grain is in high demand, varieties with more of grain yield than stem sugar are desirable. However, when high incomes are needed more, then cultivars with higher stem sugars and moderate grain yield potential are required. However, the observation that the correlation coefficient the two traits for the top 20 performers (across stem brix, grain yield and stem biomass) was not significant (and even positive) suggested that high grain yield and high stem brix were not mutually exclusive.

Cultivar development depends on the identification of the combinations that meet the breeding objectives. Hybrids ICSV700×ICSA731, ICSR165×ICSA307, ZLR1×ICSA26, ICSR165×ICSA4, ICSV700×ICSA307, ICSR165×ICSA479, ICSR165×ICSA26, and S35×ICSA4 (Table 7.4-4), which combined high performance for grain yield, stem brix and stem biomass demonstrated that it was possible to combine the traits in one cultivar. This is irrespective of the negative correlation coefficient and direct effects observed between grain yield and stem brix at maturity in this study (Table 7.4-2) and the negative correlation reported by Guiying *et al.* (2000). However, this was consistent with the positive and significant relationship between grain yield and stem biomass observed in this study and reported in the literature (Alam *et al*., 2001). Therefore, the general negative relationship between stem brix and grain yield could have been brought about by the predominance of cultivars that exhibited high performance on one trait and poor performance on the other, for example entries ICSB4 and ICSR57 (Table 7.4-4). Further, the presence of very low indirect effects of stem brix and grain yield on each other through other traits suggests that direct selection is effective and undesirable correlated responses are minimal.

The significant and positive correlation coefficient between stem biomass and grain yield suggests that improving stem biomass results in an improvement of grain yield potential. This is desirable because dual-purpose sorghum need high biomass production potential to be attractive to the biofuel industry. This is consistent with previous reports (Piper and Kulakow, 1994). Although the non-significant direct effect of stem biomass on grain yield recorded in this study contrasts reports by Piper and Kulakow (1994) that grain yield is a linear function of plant biomass, the positive and significant correlation coefficient confirmed these reports. This coupled with the low and non significant correlation coefficient and direct effect of stem biomass on stem brix at maturity further point to the possibility of developing high biomass and high brix cultivars that are attractive to the industry. The positive direct effect of number of days to 50% flowering and stem sugar implies that breeding for long season varieties improves stem sugar yield. This means that breeding for the small-scale and resource-poor farmers in the tropical low and dry mid-altitude environments entails compromising stem sugar yields to fit the varieties into the relatively short growing cycles. This is confirmed by the negative and high direct effect of stem diameter, a stem biomass trait, on stem brix at maturity.

Breeding for higher numbers of leaves per plant directly improves grain yield as shown by the positive and high direct effect and correlation coefficient of the trait to grain yield. Number of leaves per plant, which translates to more stalk sugar production from large photosynthetic areas, is in turn increased by breeding late maturing cultivars, hence the high indirect effect of days to 50% flowering to stem brix at maturity through the trait. This is because most long season plants are tall which results in more leaves per plant because of the many nodes found in tall plants. The negative direct effects of stem juice score on both stem brix at maturity and grain yield suggested that improving stem juiciness resulted in improved grain yield and stem brix at maturity in sorghum. This might be because juicy cultivars have the capacity to accumulate more photo-assimilates in their stalk juices as reported by Makanda *et al.* (2009). Lastly, the observed mixture of low and high cultivar superiority among the high performers (Table 7.4-4) demonstrated that apart from being feasible, dual-purpose sorghums can be bred for either general or specific adaptation.

7.6 Conclusions

From this study, it can be concluded that:

1. The independence of grain yield and stem brix at maturity from the correlation studies among the top 20 performers suggests the independence of the traits and that selection for both traits in one cultivar is feasible for developing dual-purpose sorghum cultivars.
2. The non-significant relationship between stem biomass and stem brix at maturity implied that breeding for high biomass yield has no effects on stem brix. The positive and significant relationship between stem biomass and grain yield suggested that improving the former would indirectly improve stem brix.
3. The negative and significant relationship between days to 50% flowering and stem brix at maturity implied that breeding for short cycle crops reduces stem brix, but this can be countered by improving the numbers of leaves per plant and stem juiciness due to positive indirect effects of the traits through the number of leaves per plant.

4. Stem biomass, grain yield, days to 50% flowering, plant height and stem diameter indirectly improved stem brix at maturity through number of leaves per plant.
5. Overall, the study showed that it was possible to breed dual-purpose sorghum cultivars for grain and stem sugar.

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CHAPTER 8

Fertility restoration capacities of southern African and introduced sorghum lines as measured by hybrid seed set across tropical low and mid altitude environments

8.1 Abstract

Effective exploitation of the male-sterility system for sorghum hybrid production depends on full restoration of fertility in the F_1 hybrids. To study this phenomenon, 10 male-fertile parents were crossed with eight cytoplasmic male-sterile lines in accordance with a North Carolina II mating scheme. The resultant hybrids were evaluated for fertility restoration indirectly by protecting the heads with pollination bags at the onset of anthesis and visually scoring for seed set using a scale of 0 (no seed set) to 100% (complete seed set) at the hard dough stage. The trials were laid out at Makhathini and Ukulinga in row column α-lattice designs during the 2008/09 season. There were significant (P≤0.01) differences among hybrids for fertility restoration. Out of the 63 hybrids tested, six displayed high sterility levels above 60% and three, above 95% sterility. That male lines exhibited significant differences in their fertility restoration capacities on the females probably because of the significant interactions with female genetic backgrounds. Male parents ICSV700, ICSVP3046 and MRL15 displayed complete failure to restore fertility in one hybrid each although they showed complete restoration in the other seven crosses. General combining ability (GCA) effects due to both male and female parents and specific combining ability (SCA) effects were significant (P≤0.01) suggesting that restoration of fertility was influenced by genes with both additive and non-additive effects. Both GCA and SCA effects interacted significantly with the site effects, suggesting that genotype x environment interaction effects were important for restoration of hybrid fertility. Based on hybrid fertility data, the parent ICSA724 was a potential donor of male-sterility-inducing cytoplasm for MRL15; ICSA26 for ICSV700; and ICSA474 for ICSVP3046. Southern African adapted lines Macia, ZLR1 and IMDP97 exhibited high restoration capacity in most of their hybrids. These would be recommended for use as restorer lines for the cross combinations in which they showed restoration.

Keywords: general combining ability, male sterility, fertility restoration, sorghum hybrids, specific combining ability

8.2 Introduction

One way of enhancing productivity of sorghum in sub-Saharan Africa is through the introduction of hybrids that are adapted to the region. Most sorghum breeding programmes are moving from pure line sorghum varieties to hybrid cultivars that were long ago demonstrated to be more productive. The large sorghum producing countries have recorded growth in the crop due to adoption of hybrid cultivars. Hybrid sorghum dominates production in China, India and the USA and has seen major increases in the crop's productivity (Belum *et al*., 2006; Li and Li, 1998; Kenga *et al*., 2004; Acquaah, 2007). Successful development of hybrid cultivars depends on the identification of adapted, stable and effective male sterile and restorer lines that are heterotic. Li and Li (1998) demonstrated in India that the use of Chinese germplasm with foreign lines gave high heterosis in hybrid sorghum production. This can be largely attributed to high levels of diversity that normally exists between the introduced and local germplasm.

Sorghum hybridisation can be effected through a number of techniques but the use of male-sterile lines is by far the most viable. The origin and genetics of the different male-sterility systems has been thoroughly discussed in the literature (Sleper and Poehlman, 2006; Rooney, 2000; Rooney and Smith, 2000). The cytoplasmic genetic male sterile (cms) system is the most important and has made it possible to commercialise sorghum hybrids worldwide (Schertz, 1994; Rooney, 2000; Belum *et al*., 2006; Sleper and Poehlman, 2006). Within the cms systems, the A1 system is the most commonly used due to its superior stability compared to the A2, A3, A4 and A5 systems (Sleper and Poehlman, 2006). It is based on a cytoplasmic male sterility-fertility restorer gene which came about by the introduction of kafir chromosomes into milo cytoplasm (Schertz, 1994). Fertility restoration is conferred by a one gene locus that can be either Ms_{c1} or Ms_2 with the homozygous recessive conditions ms_1ms_1 or ms_2ms_2 being male sterile (Sleper and Poehlman, 2006; Rooney and Smith, 2000). Another dominant gene, Rf_1 (restorer gene) restores male fertility (Brengman, 1995) but the relationship between Rf_1 and Ms_1 or Ms_2 genes is not fully understood to date. In some backgrounds, additional modifier genes such as the Pf_1 and Pf_2 described by Miller and Picket (1964) and Sleper and Poehlman (2006) are needed for the full expression on the restorer gene. This explains the reports of complete fertility restoration on some A lines but not others (Andrews *et al*., 1997). The modifier and restorer genes are reported to act in an additive and epistatic manner (Rooney, 2000). Although this presents a seemingly simple phenomenon, the observed variation in sterility and fertility in sorghum is evidence of the complexity of the inheritance of the trait (Rooney, 2000). However, regardless of the A1 system being the most stable of the systems, restoration has been shown in the foregoing to depend on additional additive genes in some genetic backgrounds and is also altered by the environment. For example, low temperatures have been reported to affect seed set in sorghum (Peacock, 1982). Therefore, the potential male parents should be tested in different environments to confirm their restoration capacity in their F_1 hybrids regardless of their restoration status in different regions and genetic backgrounds.

Most countries, especially in Africa rely on introduced male sterile lines of sorghum, especially those developed by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT). Due to challenges encountered in adaptation of the introduced materials, many regions are moving towards developing their own male-sterile and restorer lines from adapted germplasm. However, before the regional cytoplasmic male-sterile lines are developed, the reliance on introduced lines is inevitable. Combining ability studies on both the introduced male sterile lines and the male parents is therefore important. The GCA effects give an indication of the extent to which gene additivity influences fertility restoration. Although a major dominant gene is known to control restoration, minor genes modifying its expression have been reported in some genetic backgrounds (Sleper and Poehlman, 2006; Miller and Picket, 1964). It is important to study the action of these modifier genes. In addition to GCA effects, SCA effects give an indication of the extent to which the interaction of the two parental genotypes influences fertility restoration in hybrids. The interaction between the male and female genetic backgrounds has been reported to influence the expression of restoration in sorghum hybrids (Sleper and Poehlman, 2006).

Sorghum can be generally grouped into two groups, the A/B and R groups in breeding programmes, although Menz *et al*. (2004) and Ahnert *et al*. (1996) reported that races might be the bases for grouping sorghum into heterotic groups. The female lines in the A/B groups must be heterotic to the R group for a successful hybrid programme. One group is used as a tester for the other during line development (Acquaah, 2007). Given the foregoing, local germplasm must be tested for heterosis with introduced A/B lines to identify heterotic combinations; the productive male lines would then qualify for direct use or improvement for use as restorer lines in regional programmes that aim to develop hybrids. For sustainable development of hybrid programmes, development of locally adapted male-sterile and restorer lines is desirable in the long run and can boost sorghum hybrid production. Therefore local landraces or pure lines should be evaluated for their potential use as restorers. This has been done in other regions, for example, the majority of the restorer lines used to produce very productive hybrids in China were identified among Chinese materials (Li and Li, 1998). It has been shown that there is a possibility that the lines used as male parents can exhibit varying fertility restoration capacities in different environments or as a result of the interaction between the male and female genetic backgrounds.

Therefore, this study aimed at identifying (i) potential male parents from both introduced and southern African (regional) germplasm for hybrid development and (ii) possible interactions that could render the restorer lines ineffective. The information to be generated would form the basis of establishing a viable hybrid breeding program. The hypotheses tested were:

i. Introduced and regional sorghum lines used as male in the current study have the ability to restore fertility in their hybrids,
ii. Genes with both additive and non-additive effects are not important in controlling fertility restoration in dual-purpose sorghum hybrids, and
iii. Hybridisation between the introduced and regional male sorghum lines and the introduced male sterile sorghum lines does not affect the male fertility restoration capacities in hybrids.

8.3 Materials and Methods

8.3.1 Germplasm and experimental sites

Experimental hybrids for the study were generated from crosses involving 18 parents, comprising 10 males and eight female lines (Table 8.3-1). The males were constituted from five introduced and five regional germplasm. All the females were cms A-lines obtained from ICRISAT in India (Table 8.3-1). Each male parent was crossed to all the eight female parents in accordance with a North Carolina II mating scheme to generate 80 hybrids; but 17 hybrids did not produce sufficient seed for evaluation in trials. Therefore, 63 hybrids were evaluated in the same trials with all parents. The parent lines were used as restoration check varieties with the B-lines being used in lieu of their respective male sterile A-lines in the trials. Parent lines Macia, ZLR1, ZLR2, MRL15 and IMDP97 have been tested and reported to be adapted to the Southern African region hence they were designated "regional parents". Arguably Macia and ZLR1 are among the most widely grown grain and sweet sorghum varieties, respectively, in the smallholder sector in eastern and southern Africa. Lines of Mozambican, South African, Zimbabwean and unknown origin were considered regional materials, while those from India were introductions.

Table 8.3-1: Name and origin of the lines used in this study

No.	Name	Origin	Pedigree	Role in crosses	Germplasm type
1	ZLR1	Zimbabwe	Landrace	Male	Regional
2	MR15	-	-	Male	Regional
3	ICSV 700	ICRISAT India	(IS 1082 x SC 108-3)-1-1-1-1-1	Male	Introduced
4	ICSVP3046	ICRISAT India	(ICSV 700 x ICSV 708)-9-1-3-1-1-1	Male	Introduced
5	Macia	Mozambique	SDS 3220	Male	Regional
6	ZLR2	Zimbabwe	Landrace	Male	Regional
7	ICSR165	ICRISAT India	SPV 422	Male	Introduced
8	ICSR57	ICRISAT India	(SC 108-3 x 148)-12-5-3	Male	Introduced
9	S35	ICRISAT India	-	Male	Introduced
10	IMDP97	South Africa	-	Male	Regional
11	ICSA731	ICRISAT India	ICSV 1171BF	Female	Introduced
12	ICSA479	ICRISAT India	[9ICSB 70 x ICSV 700) × PS 19349B]-5-4-1-2-2	Female	Introduced
13	ICSA4	ICRISAT India	[(BTx 622 × UChV2)B lines bulk]-10-1-1	Female	Introduced
14	ICSA724	ICRISAT India	ICSP 1B/R MFR-S 7-303-2-1	Female	Introduced
15	ICSA307	ICRISAT India	[(ICSB 26 × PM 1861)×(ICSB 22 × ICSB 45) × (ICSB 52 × ICSB 51)]1-3-12-3-1	Female	Introduced
16	ICSA474	ICRISAT India	(IS 18432 x ICSB 6)11-1-1-2-2	Female	Introduced
17	ICSA26	ICRISAT India	[(296B x BTx 624)B lines bulk]-2-1-1-3	Female	Introduced
18	ICSA623	ICRISAT India	(ICSB 11 x PM 17467B)5-1-2-1	Female	Introduced

- = unknown information

The experiment was conducted at Makhathini Research Station (27º 24'S; 32º 11' 48" E; 72m.a.s.l.) and Ukulinga Research Farm (29.5º 24' E; 29º 24' E; 781m.a.s.l.), in South Africa, during November 2008 to April 2009. Makhathini Research Station (Makhathini) represents the lowland tropical environment, while Ukulinga Research Farm (Ukulinga) represents the mid-altitude environment in southern Africa. Both sites have annual rainfall of around 800mm and mean temperatures of 19-28^{0}C which are ideal for sorghum production (Figure 8.3-1).

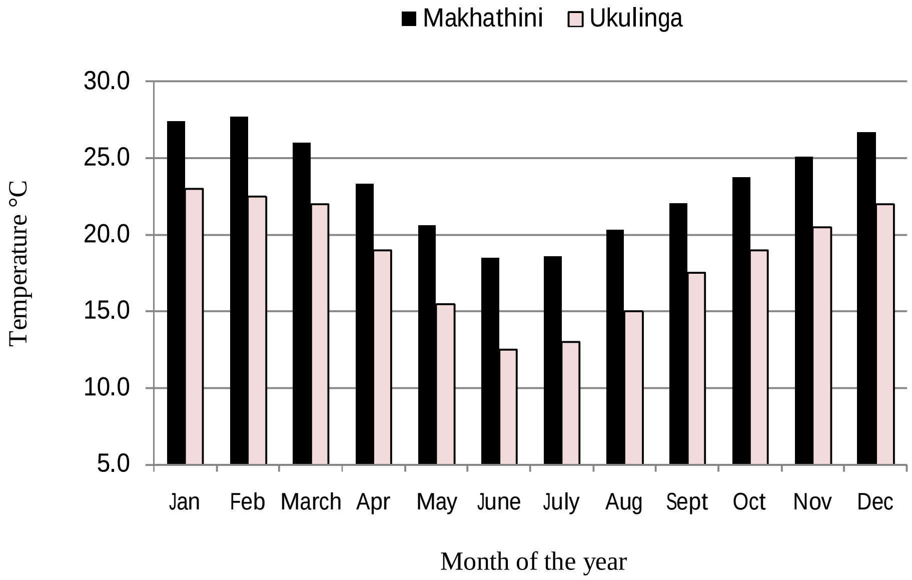

Figure 8.3-1: Mean annual temperature data for Makhathini Research Station and Ukulinga Research Farm during the trial [Data source: Agricultural Research Council-ISCW AgroMet Potchefstroom (2009)]

8.3.2 Experimental design and management

The experiment was laid out as a 10 row × 10 column α-lattice design with two replications at each site with check and filler entries. Seeds of each entry were planted by hand in two-row plots of 3.0m length at 0.75m inter-row and 0.20m intra-row (about 66 667 plants ha^{-1}). At both sites rainfall was supplemented with irrigation to achieve at least 800mm moisture. An application of 250kg ha^{-1} basal fertiliser (2:3:4, N:P:K) and 200kg ha^{-1} top dressing fertiliser (Lime Ammonium Nitrate with 28% N) was made and the fields were kept weed free by hand weeding. Five plants were covered by a khaki pollination bag just before anthesis of each genotype (hybrids and parents) to ensure total self pollination. The pollination bag was removed at the soft dough stage and the heads were covered with fine mesh bags to prevent bird predation on the developing grain. At the hard dough stage, entries was assesses for seed set on selfed heads using a visual rating scale of 0% to 100%. In this scale, 0% represented a completely sterile head without seed set, while a 100% represented a completely fertile head with complete seed set (Table 8.3-2).

Table 8.3-2: Rating scale for seed set of sorghum hybrids at two sites in South Africa

Seed set (%)	Description	Range (%)
100	When the whole head is filled with grain, total seed set	100
90	Heads almost entirely filled, above three quarters of head showing seed set	80 to <100
70	Just above two thirds of the head showing seed set	60 to <80
50	When half of the total head showing seed set	40 to <60
30	When about a quarter of the head showing seed set	20 to <40
10	Less than a quarter of the head showing seed set	1 to <20
0	Total sterility, no seed set on the head	0

8.3.3 Data analysis

Combining ability analysis of sorghum lines for hybrid seed set were performed in GenStat computer package (Payne *et al.*, 2007) as described by Hallauer and Miranda (1988) and Kearsey and Pooni (1996) following the fixed effects model below using the REML procedure:

$$Y_{ijkl} = \mu + s_i + r_j(s_i) + b(r_j*s_i) + m_k + f_l + mf_{kl} + s_i*m_{ik} + s_i*f_{ij} + s*mf_{ikl} + e_{ijkl}$$

Where: Y_{ijk} = observed hybrid response; μ = overall population mean; s_i = effect of the i^{th} environment; $r_j(s_i)$ = effects of the j^{th} replication in the i^{th} environment; $b(r_j*s_i)$ = effects of the blocks in the j^{th} replication in the i^{th} environments; m_k = effect of the k^{th} male parent; f_l = effect of the l^{th} female parent; mf_{kl} = interaction effect of the k^{th} male and the l^{th} female parents; s_i*mf_{kl} = interaction effect of the i^{th} environments and the interaction effects between the k^{th} male and the l^{th} female parents; and e_{ijkl} is the experimental error.

The hybrid variation was partitioned into male and female parent main effects giving two independent estimates of GCA effects, while the male × female interaction estimates the SCA effects (Hallauer and Miranda, 1988; Kearsey and Pooni, 1996). The GCA effects for the parents and SCA were calculated according to Kearsey and Pooni (1996). The standard error (SE) and standard error of a difference (SED) for male and female GCA effects were calculated according to Dabholkar (1992) separately because the numbers of males and females were not balanced. The hybrids were also evaluated for grain yield, stem brix and stem biomass yield following standard cultural practices in six environments in Southern Africa (detailed analyses and results presented in Chapters 5 and 6). Part of these results will be presented in this chapter to help explain some concepts.

8.4 Results

8.4.1 Fertility restoration capacity of hybrids

The hybrids differed significantly (P≤0.01) for seed set (Table 8.4-1) with significant (P≤0.01) differences also obtained between the two sites. The hybrid x site interaction effects were also significant (P≤0.01) (Table 8.4-1).

Table 8.4-1: Mean squares and significance of sorghum hybrids and parents at Makhathini Research Station and Ukulinga Research farm during the 2008/09 summer rainy season in South Africa

Source	d.f.	Mean square	F statistic	F pr
General analysis (hybrids)				
Site	1	23.14	23.14	<0.001
Replication (Site)	2	3.49	1.75	0.183
Hybrid	62	265.35	4.21	<0.001
Site × Hybrid	62	127.37	3.86	<0.001
Combining ability Analysis				
Males	9	52.77	5.86	<0.001
Females	7	45.00	6.43	<0.001
Males × Females	46	166.69	3.62	<0.001
Site × Males	9	26.94	2.99	0.005
Site × Females	7	31.00	4.43	<0.001
Site × Males × Females	17	76.76	4.52	<0.001
Residual	250	402.10		

The mean restoration was lower at Ukulinga (74%) than at Makhathini (83%). Results in Table 8.4-2 show mean differences among hybrids for seed set with 48 and 44 hybrids exhibiting above 60% seed set at Makhathini and Ukulinga, respectively (Table 8.4-2). Forty-three and 37 hybrids had complete seed set at Makhathini and Ukulinga, respectively. Three hybrids ICSV700×ICSA26, ICSV3046×ICSA474, and ICSR57×ICSA731 were 100% sterile with no seed at Makhathini, while seven hybrids ICSR57×ICSA724, ICSV700×ICSA26, ICSVP3046×ICSA474, ICSVP3046×ICSA731, MRL15×ICSA724, S35×ICSA724, and ZLR2×ICSA724 were completely sterile at Ukulinga (Table 8.4-2). All the male parents displayed 100% seed set in crosses with female parent ICSA4, except for ICSVP3046 at Ukulinga. Other males showed variable seed set with the females (Table 8.4-2). All the male parents and B lines showed complete seed set at all sites (Table 8.4-2). All hybrids of the female line ICSA4 displayed high seed set at all sites except the hybrid ICSVP3046×ICSA4 at Ukulinga (Table 8.4-2).

Table 8.4-2: Seed set percentages of sorghum hybrids at Makhathini Research Station and Ukulinga Research farm during the 2008/09 summer rainy season in South Africa

Male parents	**Female parents**								**Parent's *per se* mean**
	ICSA26	**ICSA307**	**ICSA4**	**ICSA474**	**ICSA479**	**ICSA623**	**ICSA724**	**ICSA731**	
Makhathini									
ICSR165	77.5	100.0	100.0	94.5	-	100.0	38.5	61.0	100.0
ICSR 57	100.0	100.0	100.0	100.0	-	100.0	100.0	0.0	100.0
ICSV 700	0.0	100.0	100.0	100.0	100.0	-	100.0	100.0	100.0
ICSVP 3046	27.5	61.0	100.0	0.0	100.0	-	100.0	94.5	100.0
Macia	100.0	100.0	100.0	-	100.0	50.0	100.0	100.0	100.0
MRL15	100.0	-	100.0	100.0	50.0	100.0	11.0	55.5	100.0
S35	-	55.0	100.0	-	-	100.0	100.0	22.0	100.0
IMDP97	-	55.0	100.0	-	100.0	100.0	94.5	100.0	100.0
ZLR1	100.0	77.5	100.0	-	100.0	-	100.0	100.0	100.0
ZLR2	-	-	100.0	-	-	100.0	55.5	100.0	100.0
Parent's *per se* mean	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
Ukulinga									
ICSR165	77.5	22.0	100.0	94.5	-	100.0	38.5	22.0	100.0
ICSR 57	100.0	100.0	100.0	100.0	-	100.0	0.0	100.0	100.0
ICSV 700	0.0	100.0	100.0	100.0	100.0	-	100.0	100.0	100.0
ICSVP 3046	100.0	22.0	22.0	0.0	22.0	-	55.0	0.0	100.0
Macia	100.0	55.0	100.0	-	100.0	89.0	100.0	100.0	100.0
MRL15	100.0	-	100.0	89.0	50.0	100.0	0.0	100.0	100.0
S35	-	55.0	100.0	-	-	100.0	0.0	77.5	100.0
IMDP97	100.0	77.5	100.0	-	100.0	100.0	55.0	11.0	100.0
ZLR1	100.0	77.5	100.0	-	100.0	-	100.0	100.0	100.0
ZLR2	-	-	100.0	-	-	100.0	0.0	55.0	100.0
Parent's *per se* mean	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	

- = missing data

8.4.2 Combining ability effects

Analyses of the array means indicated that male parents differed significantly differences in their ability to restore seed set (*inter se*) in their F_1 hybrids (Table 8.4-3). The male and female GCA effects and the SCA effects were significant (P≤0.01) for hybrid fertility (Table 8.4-1). Both GCA and SCA effects significantly (P≤0.01) interacted with the environmental effects (Table 8.4-1). In this study, positive GCA and SCA effects for seed set percentages are desirable. Male parents Macia, IMDP97 and ZLR1 and female parents ICSA4, ICSA479 and ICSA623 which displayed positive and significant GCA effects for seed set, improved seed set in their hybrids (Table 8.4-3). The male parent ICSVP3046 and female parents ICSA724 and ICSA731 which displayed negative and significant GCA effects for seed set percentages significantly reduced seed set in their hybrids (Table 8.4-3).

Table 8.4-3: Parental GCA effects for sorghum hybrid seed set percentages across two environments

Male parents			**Female parents**		
	Inter se mean seed set (%)	GCA effects (% seed set)		*Inter se* mean seed set (%)	GCA effects (% seed set)
ICSR165	73.3	-5.1	ICSA26	78.8	-2.6
ICSR57	85.7	2.1	ICSA307	72.3	-4.1
ICSV700	85.7	4.5	ICSA4	96.1	16.2**
ICSVP3046	50.3	-24.7**	ICSA474	77.8	-3.0
Macia	92.4	11.4*	ICSA479	85.2	6.1*
MRL15	75.4	-6.3	ICSA623	95.6	13.5**
S35	71.0	-6.9	ICSA724	62.4	-14.6**
IMDP97	84.6	8.3*	ICSA731	69.9	-10.7*
ZLR1	96.3	15.1**			
ZLR2	76.3	-0.7			
SE		3.54	SE		3.17
SED		5.01	SED		4.48

*, ** = significant at P≤0.05 and P≤0.02, respectively; SE = standard error; SED = standard error of difference

Ten crosses had positive and significant (P≤0.05) SCA effects for seed set of up to 228.5% for the cross ICSVP3046×ICSA724, while 10 other crosses had negative and significant (P≤0.05) SCA effects as low as -67.7% for the cross MRL15ICSA724 (Figure 8.4-1). Regional lines were equally prominent in crosses displaying positive and negative SCA effects for seed set (Figure 8.4-1).

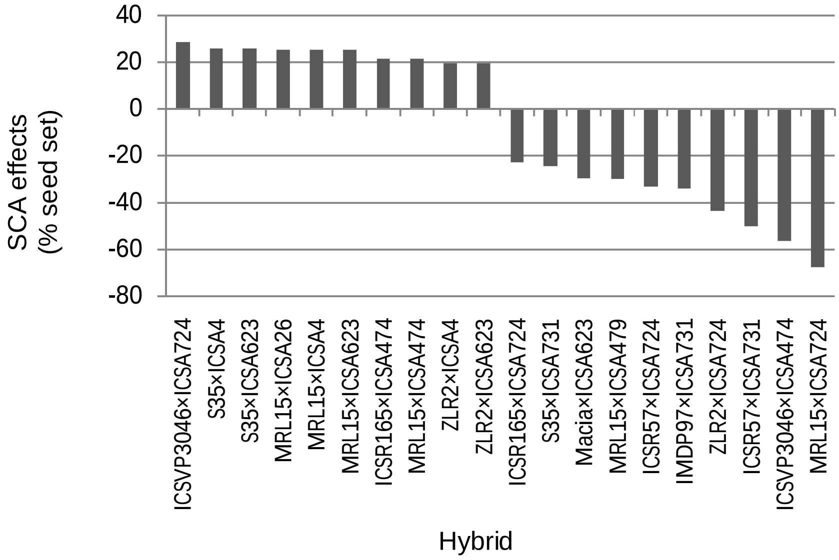

Figure 8.4-1: Crosses showing significant ($P \leq 0.05$) SCA effects for sorghum seed set (SE =10.02; SED = 14.18)

8.4.3 Hybrid fertility restoration versus performance

Among the fertile, partially fertile and sterile hybrids that are shown in Table 8.4-1, there were genotypes that displayed high performance across six environments for the major traits of interest such as grain yield, stem brix and stem biomass (Table 8.4-1). Hybrids S35×ICSA4, IMDP97×ICSA26 and ICSV700×ICSA731, which displayed complete seed set in hybrid fertility, showed high performance, exhibited high better parent and standard heterosis, and showed positive and significant SCA effects for the three traits (Table 8.4-4). Partially fertile hybrids showing similar trends for at least two of the traits were also observed (Table 8.4-4). Among the completely sterile hybrids with 0% seed set, there were some that displayed high performance for the traits. For example, MRL15×ICSA724 showed high grain yield and high standard heterosis, although it had negative SCA effects and better parent heterosis for the trait (data not shown). Another hybrid with low seed set, ICSV700×ICSA26, displayed high stem biomass yields with positive SCA effects and better parent heterosis and high standard heterosis of 15%.

Table 8.4-4: Performance data over six environments for selected hybrids differing in seed set levels across two sites

Fertility status	Hybrid seed set (%)	Grain yield				Stem brix				Stem biomass yield			
		Mean (t ha^{-1})	SCA (t ha^{-1})	BPH (%)	SH (%)	Mean (ºbrix)	SCA (ºbrix)	BPH (%)	SH (%)	Mean (t ha^{-1})	SCA (t ha^{-1})	BPH (%)	SH (%)
Fertile													
S35×ICSA4	100	4.96	1.45	57.9	282	11.54	1.04	11.2	107	45.86	8.34	27.7	137
IMDP97×ICSA26	100	2.66	0.78	11.8	151	11.35	2.07	13.8	105	42.64	9.59	26.9	125
ICSV700×ICSA731	100	2,56	-0.24	11.7	146	13.21	2.59	23.6	122	42.63	5.50	27.5	125
ZLR1×ICSA724	100	3.43	1.23	25.5	195	9.36	-0.21	-11.9	86	47.49	15.90	35.4	139
Macia×ICSA4	100	3.22	0.46	96.2	183	10.61	-0.16	-3.4	98	36.09	8.00	5.3	106
Partially fertile													
MRL15×ICSA474	81	1.62	0.16	-41.0	92	10.83	1.25	7.9	100	52.17	11.56	26.6	153
ICSVP3046×ICSA731	52	1.68	0.15	-18.0	95	11.26	1.24	11.0	104	41.18	4.40	11.9	121
ICSR57×ICSA731	30	1.68	-0.15	-11.1	96	9.53	0.03	-3.18	88	33.77	9.64	1.6	99
ICSR165×CSA26	78	2.88	0.10	-11.2	164	11.6	-0.29	2.4	107	55.55	7.47	21.6	163
ZLR1×ICSA307	78	1.09	-0.67	-55.6	62	12.3	0.71	11.1	113	30.38	-8.55	-20.6	89
MRL15×ICSA479	50	0.79	-0.70	-73.2	45	11.0	0.48	5.3	102	28.90	-3.34	-12.2	85
IMDP97×ICSA724	75	3.21	0.83	12.4	183	7.62	-0.69	-18.4	70	29.28	-1.02	-10.5	86
Macia×ICSA623	70	1.78	-0.62	1.8	101	8.81	-0.06	-9.7	81	16.70	1.11	-31.8	49
ICSA165×ICSA724	39	2.40	-0.29	-24.7	136	12.00	1.72	6.27	111	36.06	-4.74	-16.9	106
S35×ICSA731	50	1.86	-0.81	-32.7	105	9.54	0.12	0.01	88	30.00	-9.66	-28.2	88
Sterile													
ICSV700×ICSA26	0	1.65	-1.02	-19.4	94	8.53	-1.68	-10.9	79	39.18	0.26	11.1	115
ICSVP3046×ICSA474	0	0.63	-0.37	-66.1	36	9.67	-0.44	-8.85	89	33.01	-10.30	-14.3	97
MRL15×ICSA724	7	1.95	-0.16	-30.8	111	7.40	-1.49	-25.1	68	22.99	-5.57	-24.8	68
Trial mean		2.13				9.95				30.70			
SE		0.26	0.25			0.67	0.65			4.16	0.16		
SED		0.40	0.36			0.95	0.92			5.89	0.23		

SCA = specific combining ability; BPH = better parent heterosis; SH = standard heterosis

8.5 Discussion

Lower mean temperatures at Ukulinga compared to Makhathini could have resulted in the low hybrid seed set supporting previous studies by Peacock (1982). The differences in fertility observed among hybrids could be attributed to the variability in restoration capacities by the male parents, the specific interaction between the male and female parent genotypes and the environmental influences. Restoration was reported to be influenced by the genetic background in which the restorer gene requires additional modifiers to improve its efficacy (Miller and Picket, 1964). The presence of modifiers could be responsible for the significant GCA effects for both male and female parents recorded in the study. This implied that genes with additive effects modified the expression of the restorer genes. Therefore, although restoration is known to be under qualitative inheritance, there are underlying quantitative genes that act in an additive manner to influence its expression. The presence of modifier genes has been reported to be necessary in some genetic backgrounds, for example the Ms_{c1} and Ms_{c2}, modifier genes that enhances the expression of the R gene thereby improving fertility restoration and seed set (Sleper and Poehlman, 2006). The significant interaction between the GCA male and female effects and the environments implied that these modifier genes' expression was influenced by the environment. This finding implies that although the R gene is dominant, it can be influenced indirectly by the environment through the modifier genes. Male parents Macia, IMDP97 and ZLR1 and female parents ICSA4, ICSA749, ICSA623 with positive and significant GCA effects showed a preponderance of genes for hybrid fertility. In contrast, male parents ICSVP3046 and female parents ICSA724 and ICSA731 with negative and significant GCA effects for hybrid fertility restoration showed preponderance of genes for hybrid sterility. This is consistent with presence of modifier genes reported in the literature (Sleper and Poehlman, 2006; Andrews *et al*., 1997; Miller and Picket, 1964).

The significant SCA effects also implied an interaction between the genetic backgrounds of the male and female parents that contributed to variable seed set on the hybrids. For example, the male parent ICSV700 showed total restoration on all but one female line where it produced a completely sterile hybrid ICSV700×ICSA72426. The same trend was observed for ICSVP3046, MRL15 and ZLR2 with various female lines (Table 8.4-1). This suggests the presence of some specific nuclear-cytoplasmic interaction effects between crosses that resulted in the variable expression of restoration. Although this has not been reported for hybrid fertility traits, nuclear × cytoplasmic gene interaction effects were reported to interact with the male parents in some sorghum traits (Moran and Rooney, 2003). This was supported by the observation that male-fertile male and B lines showed 100% seed set across the two environments. Further, confirmed R lines ICSR165 and ICSR57 had hybrids with less than 50% restoration and showed contrasting restoration on ICSA307 and on ICSA724, respectively at Makhathini and Ukulinga. This demonstrates the strength of the environmental effects on restoration. Such phenomena could have resulted in the significant hybrid × environmental interaction effects and SCA × environment interaction effects for fertility restoration in hybrids. This observation is consistent with earlier reports that the environment plays an important role in influencing the male-fertility characteristics and its stability in sorghum (Reed *et al*., 2002; Sleper and Poehlman, 2006). The instability of the male-sterility system has also been reported in pearl millet (*Pennisetum glaucum* (L.) R. Br.) (Rai *et al*., 1996).

The observation of 100% restoration coupled with high mean performance and high heterosis among some hybrids involving regional lines implied that these combinations were potential hybrid cultivars (Table 8.4-4). Hybrids showing heterosis but with partial restoration can be used in the programme for grain yield after improving the male lines for restoration capacities. ICSR165 and IMDP97 fall into this category in hybrid combination with ICSA26 and ICSA724. However, for stem sugar and biomass production, hybrids showing partial restoration can be used directly if they display heterosis for the traits. Such hybrids include ICSVP3046×ICSA731 and MRL15×ICSA474. Regardless of their restoration capacities, lines showing low heterosis in hybrid combinations are of little use in the programme. The only usable ones are those displaying hybrid sterility, which can be converted to male-sterile lines using their counterparts as male sterility inducing cytoplasm donors. Macia in hybrid combination with ICSA623 and S35 with ICSA731 displayed such a relationship. Therefore, Macia and S35 can be converted into male sterile lines using ICSA623 and ICSA731, respectively. This need for conversion can arise in a situation where the introduced male sterile line is poorly adapted and a similar (not heterotic) adapted line showing no restoration but is heterotic to other lines in the programme is available. The adapted line can therefore be converted into a male sterile line through backcross breeding. The adapted line can be used as the recurrent parent and the introduced line as the donor of the male sterility-inducing cytoplasm. This view is based on the fact that lines displaying low heterosis belong to the same heterotic group and they can substitute each other in hybrid combinations.

8.6 Conclusions

While further studies across many sites and seasons, for the promising hybrids, might be necessary to substantiate these findings, the following conclusions can be made from the current study.

1. Regional lines ZLR1 could be used to produce hybrids showing high seed set with all female lines in this study with fertile hybrids except with ICSA307. The other regional line MRL15 can be used as restorer with ICSA26, ICSA4, ICSA474 and ICSA623; Macia with all female lines but ICSA307 and ICSA623; and IMDP97 with ICSA26, ICSA4, ICSA479 and ICSA623. Introduced line ICSR165 can be used as a restorer with ICSA4, ICSA474, and ICSA623; ICSR57 with all but ICSA724 and ICSA731; ICSV700 with all but ICSA26; and S35 with ICSA4 and ICSA623, and
2. Fertility restoration as evaluated through seed set on hybrids is under the control of genes with both additive and non-additive action. However, since restoration is conferred by a single dominant gene, this could have arisen from the action of the modifier genes reported to influence the expression of the R gene.
3. Crosses IMDP97×ICSA731, IMDP97×ICSA724, ICSR165×ICSA26 and ICSVP3046×ICSA731 and MRL15×ICSA474 which showed high better parent heterosis on two of three traits (grain yield, stem brix and stem biomass) and displayed partial seed set were identified as potential hybrids after improving the male parents' restoration capacities through backcrossing to incorporate the modifier genes.

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CHAPTER 9

An overview of the research findings

9.1 Introduction and objectives of the study

Information on gene action, levels of heterosis and cultivar stability is important for traits of interest in any cultivar development programme. For dual-purpose sorghum cultivar development programmes that are aimed at delivering high grain and bioenergy yield, the important traits are grain yield, stem sugar content and stem biomass. This chapter summarises the findings from a study conducted in Mozambique, South Africa and Zimbabwe to generate this information. The study objectives are highlighted followed by a summary of the findings and then the implications of the findings for dual-purpose cultivar development and the challenges encountered. The final section dwells on suggestions for future studies and direction in dual-purpose sorghum cultivar development.

To recap, the objectives of this study were to:

i. solicit farmers and non-farmer stakeholders' views and perceptions on dual-purpose sorghum and the feasibility of dual-purpose sorghum utilisation;
ii. screen sorghum germplasm for grain yield potential and stem sugar traits;
iii. investigate the gene action involved in the inheritance of grain yield potential and stem sugar traits in dual-purpose sorghum cultivars across selected tropical low and mid altitude environments in southern Africa;
iv. determine the levels of heterosis and cultivar stability for grain yield components and stem sugar traits in dual-purpose sorghum cultivars across selected tropical low and mid altitude environments in southern Africa;
v. establish the relationship between grain yield potential and stem sugar traits in dual-purpose sorghum cultivars across selected tropical low and mid altitude environments in southern Africa; and
vi. evaluate fertility restoration capacities of introduced and regional sorghum germplasm on male sterile lines as affected by the genetic background of the hybrids and the environment across selected tropical low and mid altitude environments in southern Africa.

9.2 Research findings in brief

9.2.1 Stakeholders' views and perceptions on dual-purpose sorghum and the feasibility of their utilisation

- The stakeholders (small-scale and resource-poor farmers, scientists, plant breeders, agronomists, engineers, academics and political leaders) concurred in the view that development of dual-purpose sorghum varieties was a viable option that could alleviate poverty, enhance food security, create rural employment and boost rural development in southern Africa directly and through possible multiplier effects.
- Small-scale and resource-poor farmers had limited knowledge on dual-purpose sorghums and the use of the crop for bioenergy production.
- All stakeholders showed willingness to participate in implementing the technology.
- Engineers from the sugar industries reported the possibility of feeding the dual-purpose sorghum stalks into the established sugarcane mills for stem sugar extraction after some minor modifications to the equipment.
- The farmers' ideal variety was identified as medium to tall, combining high grain yield potential with early to medium maturity and high stem sugar content.
- Generally, stakeholders were optimistic of the technology and the major crop challenges raised by the industry could be grouped into three categories, that is, the crop, technical and economic challenges.
    - Crop challenges were lack of sufficient biomass, low stem sugar concentration, unsuitable varieties, seasonality of the crop and lack of an established seed supply system.
    - Technical challenges included lack of farmer education on dual-purpose sorghum, lack of widespread infrastructure, small land holdings for large scale production, environmental degradation due to clearing of large tracks of land for the sorghum monoculture, processing machinery and storage of biomass.
    - The economic challenges were running costs, high capital required, possible competition from other enterprises like maize and cotton.
- Farmers' major constraints included access and timely acquisition of inputs, lack of markets for most crops, poor seed quality, inappropriate varieties, drought, bird

damage in sorghum and pearl millet, and poor soil fertility.

9.2.2 Quantification of genetic variability and screening for grain yield potential and stem sugar traits in sorghum

- The study demonstrated that there was high genetic variability for the development of dual-purpose sorghum varieties from within the sorghum germplasm collection held at the University of KwaZulu-Natal and some introduced materials from southern Africa and the International Crops Research Institute for the Semi-Arid Tropics in India.
- Varieties such as MRL15, ICSV700, ZLR1, ICSVP3046 and ICSB731 which combed appreciable levels of stem brix values, grain yield, stem biomass and were of medium to early maturity time levels were selected for use as source germplasm for the dual-purpose sorghum breeding programme at the University of KwaZulu-Natal.

9.2.3 Gene action and heterosis levels attainable for stem sugar traits in dual-purpose sorghum cultivars in southern Africa

- The study demonstrated that it is possible to develop and produce superior sweet sorghum cultivars in southern Africa.
- Both additive and non-additive gene effects were shown to be important in controlling stem brix, stem biomass and the associated traits in sorghum.
- The hybrids displayed high levels of better-parent heterosis and cultivar stability.
- Crosses ICSV700×ICSA307, ICSVP3046×ICSA731, ZLR1×ICSA307, S35×ICSA4, MRL15×ICSA26, IMDP97×ICSA26, ICSR165×ICSA307, ZLR1×ICSA26, ICSVP3046×ICSA4 and ICSV700×ICSA731 were heterotic for stem brix at maturity displaying better parent heterosis values ranging from 10% to 23%, respectively.
- Parental lines which showed positive and significant GCA effects and in single cross combination displayed positive and significant SCA effects for stem brix, stem biomass and associated traits were identified as potential source germplasm for dual-purpose sorghum hybrids development.

9.2.4 Gene action and heterosis levels attainable for grain yield potential in dual-purpose sorghum cultivars in southern Africa

- The study found that there is potential for breeding high grain yield hybrid cultivars that are superior to those currently on the market and parents for deployment in southern Africa.
- Hybrids, which displayed high levels of better parent heterosis for grain yield and its components and showed performance stability, were identified.
- Crosses IMDP97×ICSA724, Macia×ICSA724, ICSR57×ICSA479, ICSR165×ICSA4, ICSV700×ICSA479, ZLR1×ICSA724, ZLR2×ICSA623, Macia×ICSA26, ICSR57×ICSA474, ICSV700×ICSA724, ZLR2×ICSA4, ZLR2×ICSA474, IMDP97×ICSA4, S35×ICSA4, S35×ICSA26, Macia×ICSA731, ZLR2×ICSA731 and Macia×ICSA4 were heterotic for gain yield with heterosis values ranging from 10% to 95%, respectively.
- Genes with both additive and non-additive effects were demonstrated to control grain yield, weight of 1000 seeds, head length, number of leaves per plant, number of tillers per plant, days to 50% flowering, and days to 95% maturity in sorghum.
- Parents with positive and significant GCA effects for grain yield, and also showed significant SCA effects in single cross combinations were identified and recommended as potential parents for inclusion in the breeding programme.

9.2.5 Relationship between grain yield potential and stem sugar traits in dual-purpose sorghum cultivars in southern Africa

- The study showed that there was a general negative relationship between grain-yield potential and stem brix and a positive relationship between stem biomass and grain yield. However, among the top 20 performers for grain yield, stem brix and stem biomass, the relationship between grain yield and stem brix was positive but non-significant. Plant biomass and stem brix were independent of each other.
- There was a negative relationship between days to 50% flowering and stem brix at maturity. Stem biomass weight, grain yield, days to 50% flowering, plant height and stem diameter all positively and indirectly improved stem brix at maturity through numbers of leaves per plant.

- The independence of grain yield and stem brix at maturity among the top 20 performers was confirmed by the identification of cultivars that combined high performance across both grain yield and stem brix as well as stem biomass. These were ICSV700×ICSA731, ICSR165×ICSA307, ZLR1×ICSA26, ICSR165×ICSA4, ICSV700×ICSA307, ICSR165×ICSA479, ICSR165×ICSA26, and S35×ICSA4.

9.2.6 Fertility restoration capacities of introduced and regional sorghum germplasm on male sterile lines as evaluated through hybrid seed set in selected tropical low and mid-altitude environments in South Africa

- The study demonstrated that fertility restoration was influenced by the hybrid combination and environment within which the restoration gene Rf_1 was operating.
- Combinations that showed complete hybrid fertility restoration and could be used directly for dual-purpose sorghum hybrid production were identified.
- Fertility restoration as evaluated through seed set on hybrids was under the control of genes with both additive and non-additive action. However, since restoration was conferred by a single dominant gene Rf_1, this could have arisen from the action of the modifier genes that influenced the expression of the Rf_1 gene.

9.3 Implications of the research findings for breeding dual-purpose sorghum cultivars

- The stakeholder survey showed that dual-purpose sorghum cultivars for grain and bioenergy have a place in both the small-holder farming communities and the industry. There is, therefore, need for a concerted breeding and research effort for appropriate cultivars and associated technologies for this purpose.
- The major areas requiring intervention for the dual-purpose sorghum cultivar technology to work are:
    a. Breeding for high biomass, high stem sugar and cold tolerance to expand production into the warmer tropical lowlands. Part of this work demonstrated that it was possible to produce sorghum with reasonable stem biomass and sugar concentrations in the tropical lowlands (Makanda *et al*., 2009);
    b. Farmer education, infrastructural investment requiring commitment from the

government and industry and agronomic research for soil and fertility management;

c. Reposition sorghum as a cash crop to make it attractive to investors and farmers; and

d. Farmer aid in the form of input schemes, market facilitation and the possible entry of the private business once sorghum is recognised as a cash crop. The latter will ensure the timely supply of quality seed of appropriate cultivars and back up agronomic service.

- Large genetic variability identified for grain yield potential and stem sugar traits in the sorghum germplasm collection at the University of KwaZulu-Natal collections implied that there is room for selection of source germplasm for breeding the dual-purpose cultivars.

- The finding that genes with both additive and non-additive action control grain yield and its components and stem sugar traits implied that breeding gain can be realised through hybridisation and selection. Therefore, selection of parents that are high general combiners and hybridising them is the way forward in breeding dual-purpose sorghum cultivars with high performance across the traits. This addresses the concern of general low productivity in sorghum raised by stakeholders as a possible limitation to dual-purpose sorghum cultivar utilisation. This can also make the dual-purpose sorghums attractive to the farmers given the challenge of limited land holdings reported by farmers in Chivi district in Masvingo, in Zimbabwe.

- The observation of high better parent and standard heterosis for grain yield, stem brix and stem biomass yields implied that dual-purpose sorghum productivity could be enhanced by the development of hybrid cultivars in both tropical low and mid-altitude environments. This increases production without necessarily expanding the area under production

- The observation of genotypes exhibiting high better-parent heterosis for grain yield, stem brix and stem biomass like S35×ICSA4 answers the question on whether heterosis can be expressed for the two traits in one cultivar. This implied that high performing dual-purpose sorghum hybrid cultivars can be developed and addresses the concern of low sugar concentrations and low biomass levels raised by stakeholder during the survey.

- The possibility of production during off-season demonstrated in the current study suggests that the concern of seasonality of the stalks raised by the stakeholders can be addressed through large scale off-season production in the tropical lowland ecologies in the Zambezi, Limpopo and Shire river valleys in southern Africa.
- The general negative relationship between grain yield and stem brix implied that there is need for a compromise between the traits in breeding dual-purpose sorghum cultivars. The observation of a positive and non-significant relationship between the two traits among the top 20 performing entries for grain yield, stem brix and stem biomass demonstrated that the two traits were independent in dual-purpose sorghums and therefore combining high grain yield potential and high stem sugar potential in one cultivar was possible. This was affirmed by the observation of hybrids that combined the two traits.
- The positive relationship between grain yield and stem biomass implies that breeding high biomass dual-purpose sorghums improves grain yield, which indirectly improves stem sugar yield per unit area.
- The influence of the cross and the environment on fertility restoration when using cytoplasmic male-sterile lines in sorghum implies that it is prudent to evaluate the hybrids in their recommendation domain for fertility restoration if grain yield is a major trait.
- The importance of both additive and non-additive gene action in controlling fertility restoration suggested that hybridisation and selection was important in restorer line development. That is, background selection for modifier genes is important in developing restorer lines in situations where the modifiers are important for full fertility restoration.
- The observation of partial restoration and complete hybrid sterility can be exploited in situations where sweet stalks are required without the need for the grain, that is, in the production of specialised sweet sorghum cultivars. This can also benefit the industry in terms of seed sales because the farmers will buy seed every season without the possibility of retaining seed from the previous harvest. Further, hybrid sterility can improve stem sugar in genotypes that showed evidence of photo-assimilate remobilisation from the stem to the developing grain.

9.4 Challenges encountered and recommendations

- Although the potential for winter production was demonstrated to be feasible in this study, challenges encountered included delayed plant germination, depressed stem biomass, and ergot disease attack on some genotypes. This calls for the need to breed for cold tolerance and resistance to ergot diseases for winter production, especially in areas like Makhathini in South Africa where the winters experience cold spells of below 10ºC.

- There was no improved dual-purpose sorghum base germplasm for use as parents and in developing hybrid cultivars. Population improvement programmes to develop dual-purpose sorghum base germplasm, that is, accumulating genes for stem sugar content and grain yield potential in individual lines for use as parents in hybrid development programmes could enhance superior dual-purpose sorghum cultivar delivery for both in-season and off-season environments. The identification of major genes and markers for stem sugar accumulation through QTL analyses could enhance selection for high stem sugar content in sorghum. The work of Natoli *et al*. (2002) and Ritter *et al*. (2006) made some inroads in this regard.

- The region lacked locally developed male sterile and maintainer lines and established restorer lines of confirmed restoration. This resulted in the use of parents on unknown restoration capabilities thereby serving a double purpose of genetic studies as well as identification of potential restorer lines from the germplasm. Characterisation of all the potential parental male germplasm for restoration capabilities and the identification of heterotic groups between and within the A/B and R line groups from both introduced and local germplasm collection could further improve gains from hybridisation in dual-purpose hybrid cultivar development. An economic analysis of the benefits versus costs of the dual-purpose sorghum technology in the farming and industrial communities can help the stakeholders make informed decision on the technology.

- Some parents used as males showed partial fertility restoration on the male-sterile lines used as females. Some of them showing desirable attributes of dual-purpose sorghums, that is high SCA and heterosis for grain yield, stem brix and stem biomass (Table 8.4-4). This problem could be solved by identifying alternative restorer lines that are heterotic to the male-sterile female lines but showing complete restoration. In cases where the male showing partial restoration has farmer desired traits, then improvement in restoration capacities can be attempted. Although no reports in the literature were found regarding a breeding programme to improve restoration capacities of restorer lines, this might be done following two procedures. The first procedure is a background selection for fertility modifiers in the cases where markers are present for the modifier genes. However, no such markers have been developed. Their identification can facilitate background selection for the modifier genes which can speed up the restoration capacities improvement programmes due to the removal of the progeny tests. Alternatively, the line can be improved for restoration capacities through backcrossing, the restorer line being the recurrent parent and another restorer line that completely restores fertility on the male sterile female line but not desired by farmers being the donor line of the modifier genes. Since the modifier genes are not easily recognizable in the progeny, the backcross procedure would follow the approach of incorporating a recessive gene as described for rust resistance gene by Sleper and Poehlman (2006). Each of the backcross progenies is crossed to the recurrent parent and the heterotic male-sterile line. Progenies showing improved restoration and maintaining high heterosis with the male-sterile line in the progeny test will have its backcross seed from the cross with the recurrent parent selected and entered into the next backcross and progeny test cycle. This is continued until the genotype of the recurrent parent has been reconstituted but with the addition of the modifier genes. If markers are identified for the modifiers, they will be useful in selection hence rapid delivery of lines with improved restoration capacities. This approach might improve also select for compatible combinations in cases where the partial restoration is a result of either the interaction between the male and female genotypes, a result of the genes in the female parent or is environmentally induced. The backcross breeding approach is clearly outlined in standard plant breeding books such as Sleper and Poehlman (2006).

- Advancing the promising hybrids identified in this study for further multi-environment evaluation to identify genotypes with specific and general adaptation to the environments of southern Africa.

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