Breeding Sorghum [*Sorghum bicolor* (L.) Moench] for Drought Tolerance and Medium-Maturity

By

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Thesis Abstract

In Ethiopia, sorghum is one of the major food cereals, after maize and tef, with a current mean grain yield of 2.4 tons ha^{-1}. Despite its ability to grow in the arid and semi-arid areas of Ethiopia, the yield and quality of sorghum is affected by a wide array of production constraints. Drought is the most important cause of yield reduction in sorghum. Farmers in the north eastern Ethiopia are still cultivating drought-susceptible, long-maturing and low yielding local landraces. Development of sorghum varieties with drought tolerance and early or medium maturity would have significant value in the farming system of the north eastern Ethiopia. The overall goal of this study was to enhance sorghum production and productivity in Ethiopia with the aim of improving food security in the country, through the breeding of drought-tolerant sorghum genotypes with farmer-desired traits. The specific objectives were: (1) to determine the impact of drought on sorghum production and productivity over time and space, and to identify farmers' production constraints and coping strategies when dealing with drought in north eastern Ethiopia; (2) to characterise sorghum landraces for drought tolerance and to select farmer-preferred medium-maturing genotypes under managed stress condition; (3) to assess the genetic diversity present among diverse medium-maturing sorghum genotypes based on simple sequence repeat (SSR) markers and phenotypic traits to select unique genotypes for breeding; and (4) to determine combining ability, heterosis and heritability of yield and yield-related traits in medium-maturing sorghum genotypes to select promising parents and families for breeding.

A participatory rural appraisal (PRA) research was conducted involving 180 farmers selected from three major sorghum growing administrative zones. Semi-structured interview and focused group discussion were used for data collection. Results indicated that drought during post-flowering stage was identified by all the respondent farmers as the leading challenge for sorghum production in the three study zones. In addition, *Striga* infestation, damage due to (insects, birds and diseases), limited access to inputs (improved sorghum seeds and inorganic fertilizers) and lack of farmers preferred high yielding sorghum varieties were the principal production limitations recognized by farmers. Through focus group discussion farmers indicated their desire to grow medium-maturing sorghum varieties suitable for April planting and which escape drought in the post-flowering stage.

One hundred ninety-six medium-maturing sorghum genotypes collected from the north eastern Amhara Region were screened for 14 yield and yield related traits under managed stressed conditions. Significant phenotypic variation was observed among genotypes for all measured traits.

Eight medium-maturing sorghum genotypes (E-72457, E-72438, E-72435, E-206214, E-72449, E-75460 and E-75458) with superior agronomic performance were selected and recommended for large-scale production or for further breeding under drought prone sorghum growing agro-ecologies of the country. Conversely, genotypes such as E-72435, E-72438, E-206214, E-72457, E-75454 and E-72449 were the top yielding genotypes and recommended for production or breeding under optimal moisture conditions. Grain yield had significant and positive correlation with yield-related traits assessed under both test conditions. Path coefficient analysis revealed that days to maturity under drought stressed condition and harvest index under non-stressed condition had the highest positive direct effect on grain yield. Principal component analysis showed that the first three principal components (PCs) explained 79.4% and 86.78% of the total variation present among genotypes evaluated under non-stressed and drought-stressed, conditions in that order.

Fifty medium-maturing sorghum genotypes advanced from the screening experiment were evaluated using 39 polymorphic SSR markers to establish genetic structure, diversity and relationships. The SSR analysis showed the presence of considerable genetic diversity and allocated the test genotypes in to three clusters. A population structure analysis with the SSR markers yielded three genetic groups agreeing to the results of cluster and factorial analyses based on phenotypic traits. The presence of genotypes of different origins across clusters, sets and groups indicate similar genetic backgrounds, and evidence of gene flow between administrative Zones where test genotypes were sampled. Fourteen genetically divergent medium-maturing sorghum genotypes (E-72457, E-206214, E-72438, E-75460, E-72435, E-75458, E-72437, E-75452, E-72446, E-74097, E-201444, E-75273, E-211235 and E-200013) were selected for future breeding.

Crosses were performed using a line x tester mating design involving seven lines and seven testers of selected medium-maturing sorghum genotypes.. The 49 F_1 hybrids, 14 parents and a standard hybrid check were evaluated using a triple lattice design with three replications. Results showed the presence of considerable variations amongst test genotypes allowing selection of suitable parents and hybrids for traits of interest. The general combining ability (GCA) effects revealed that lines such as E-75460 and E-72435 and testers E-74097, E-75452, E-72446 and E-201444 were the most promising general combiners for grain yield. The specific combining ability (SCA) effects indicated that five crosses such as E-75460 x E-75273, E-72437 x E-72446, E-72457 x E-72446, E-72435 x E-74097 and E-72457 x E-75452 were superior in grain yields. The cross, E-75460 x E-75273 showed the highest significant positive heterosis for grain yield over the standard check ESH-2. Broad-sense heritability was the highest for plant height (99.77%) followed by harvest index (96.59%) and 1000-

seed weight (94.99%), while narrow-sense heritability values were relatively lower suggesting that dominance gene action was important in controlling the expression of all traits. The selected parents and crosses are recommended for population development and heterosis breeding.

In summary, the results of these studies identified the major sorghum production constraints, indicated the presence of considerable genetic diversity among tested genotypes; identified drought tolerant medium-maturing genotypes with good combining ability for population development and heterosis breeding in the north eastern Amhara Region or similar environments in Ethiopia.

Declaration

I, Solomon Assefa Derese, 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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Solomon Assefa Derese

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

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Prof. Shimelis Hussein (Supervisor)

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Prof. Mark Laing (Co-Supervisor)

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Dedication

This thesis is dedicated to my father (Assefa Derese), my mother (Demekech Shibeshi), my wife (Meseret Gashaw) and children (Tibebe and Belin).

Abbreviations

ACCI	African Center for Crop Improvement
AFLP	Amplified Fragment Length Polymorphism
AGB	Above ground biomass
AGRA	Alliance for a Green Revolution in Africa
AMOVA	Analysis of Molecular Variance was carried out
A_R	Allelic richness
ARARI	Amhara Regional Agricultural Research Institute
ASRP	Average sorghum regional productivity
BBC	British Broadcasting Corporation
BC	Before Christ
BH	Heterobeltiosis
CSA	Central statistical agency
CV	Coefficient of variation
DArT	Diversity Arrays Technology
DF	Degrees of freedom
DF	Days to flowering
DM	Days to maturity
DNA	Deoxyribonucleic acid
DUS	Distinctiveness, uniformity and stability
EBI	Ethiopian Biodiversity Institute
ESH-2	Ethiopian sorghum hybrid two
ESIP	Ethiopian Sorghum Improvement Program
F_1	Filial generation one
FTC	Farmers training center
GCA	General combining ability
G_D	Gene diversity;
GFP	Grain filling period
GS	Growth stage
GY	Grain yield
Ha	Hectare
H_E	Heterozygocity

HI	Harvest index
IBGR	International Plant Genetic Resource
ICRISAT	International Crop Research Institute for the Semi-arid Tropics
IDRC	International Development Research Centre
ISSR	Inter Simple Sequence Repeats
LSD	Least significance difference
MA_F	Major alleles frequency
Max	Maximum
Min	Minimum
N_A	Total number of alleles
NGL	Number of green leaves at harvest
NPGS	Indian National Plant Germplasm System
PCA	Principal component analysis
PCR	Polymerase chain reaction
PCs	Principal components
PE	Panicle exertion
PH	Plant height
PIC	Polymorphic information content
PL	Panicle length
PRA	Participatory rural appraisal
PW	Panicle weight
PY	Panicle yield
RAPD	Random Amplified Polymorphic DNA
RFLP	Restriction Fragment Length Polymorphism
RH	Relative heterosis
SA	South Africa
SAMPL	Selective Amplification of Microsatellite Polymorphic Loci
SARC	Sirinka Agricultural Research Center
SCA	Specific combining ability
SE	Standard error
SH	Standard heterosis
SNP	Single Nucleotide Polymorphism
SSA	Sub-Saharan Africa
SSAP	Sequence Specific Amplification Polymorphism

SSR	Simple Sequence Repeats
SV	Seedling vigor
TSW	Thousand seed weight
USA	United States of America
X^2	chi square
σ^2_A	Additive variance
σ^2_D	Dominance variance
σ^2_E	Environmental variance
σ^2_G	Genetic variance
σ^2_I	Epistasis variance
σ^2_P	Phenotypic variance
H^2	Heritability in broad-sense
h^2	Heritability in narrow-sense

Table of Contents

List of Tables

List of Figures

Introduction to Thesis

Background

Sorghum [*Sorghum bicolor* (L.) Moench; 2n=20] is the fifth most important cereal grain after maize, rice, wheat and barley in the world (FAOSTAT, 2017). It has been cultivated for centuries as a staple food crop in sub-Saharan Africa and Asia. It has a remarkable wide adaptation and tolerates high temperatures, high radiation, high evaporative demand, inadequate and erratic rainfall and soils of poor structure, low fertility and low water holding capacity. It is an important source of food and feed, particularly in the semi-arid regions, including Ethiopia (Duodu et al., 2003; Reddy et al., 2004).

Sorghum is the most important dietary staple cereal crop providing energy, protein, vitamins and minerals for more than 500 million people primarily in the developing countries (Burke et al., 2013; Kumar et al., 2011). The cultivated area is more than 44 million hectares globally with annual grain production of 68 million tons (FAOSTAT, 2017). It grows in more than 90 countries in Africa, America, Asia, Europe and Oceania. USA, Mexico, Nigeria, Sudan, India, Ethiopia, Argentina, China, Brazil and Burkina Faso are the top ten major sorghum producers globally (FAOSTAT, 2017). United States of America is the largest sorghum producer globally. Japan, China, Mexico and South Africa import significant amount of sorghum from the USA (U.S. Grains, 2015; U.S. Grains, 2016).

In sub-Saharan Africa (SSA), sorghum is the foundational staple food for many rural communities, especially in drought prone areas. Sorghum’s grain is processed into flour and consumed in the form of porridge and flat bread (Panguluri and Kumar, 2013). A wide variety of other traditional food products and recipes are prepared from sorghum. Sorghum grain is boiled and consumed and brewed for beer production. Sorghum is a rich source of micronutrients, particularly iron, phosphorus and zinc (Kumar et al., 2011) and starch. A recent study classifies sorghum genotypes as source of vitamin “E” (Cardoso et al., 2015). Sorghum has a similar protein content to that of wheat but higher than maize and rice. Essential amino acid composition of sorghum is comparable to maize or wheat due to the limited content of threonine, arginine and, lysine (FAO, 1995; Henley, 2010). Sorghum’s main storage proteins, the kafirins, are devoid of the essential amino acid lysine. Therefore, the high kafirins content present in a given sorghum variety has a direct negative impact on its nutritional value. Iron content of sorghum is lower than millet but is higher than wheat, maize and rice (FAO, 1995; Henley, 2010). Interestingly, sorghum is considered suitable for people with gluten intolerance due to it's gluten free property (Taylor et al., 2006; Schober et al., 2007; Perazzo et al., 2014).

Sorghum grain is also an important feed source, widely used in Australia and the Americas, while the stover (crop residue after grain harvest) is an important livestock feed in the mixed crop-livestock farming systems prevalent in semi-arid tropics. Sweet stem sorghum with sugar rich juicy stalks is emerging as an important biofuel crop (Reddy et al., 2008).

Ethiopia is the center of origin and diversity of sorghum (Vavilov, 1951) which is huge opportunity to access easily diverse useful genes for future sorghum improvement. The country is the sixth largest sorghum producer after the USA, Mexico, Nigeria, Sudan and India. In Ethiopia about 1.83 million hectares of agricultural lands are devoted to sorghum cultivation with a total production of 4.34 million tons per annum (FAOSTAT, 2017). Sorghum is one of the major food cereals after maize and tef in terms of the total number of growers, area coverage and grain production in Ethiopia (CSA, 2016). Typically, sorghum is used for making the local bread, ‘‘Injera’’, and for the preparation of local beverages, ‘‘tela’’ and ‘‘areki’’. Sorghum stalks are used for animal feed, and for housing and fencing.

Constraints to sorghum production

Sorghum production and productivity in SSA is challenged by biotic, socio-economic and abiotic constraints. Among the biotic constraints the parasitic weed, *Striga hermonthica* and stalk borer (*Chilo partellus*) are the most damaging (Beyene et al., 2016; Wortmann et al., 2006). In Ethiopia optimal production and productivity of the crop has not yet been achieved due to various socio-economic constraints such as poor financial support, lack of farmer preferred variety, lack of improved seed system, poor market linkage, lack of value addition, poor extension service support and lack of storage facility (Alene and Zeller, 2005; Beyene et al., 2016). Drought, poor soil fertility and soil salinity are the most important abiotic constraints affecting sorghum production including in Ethiopia (Waddington et al., 2010; Reynolds et al., 2015; Shrivastava and Kumar, 2015; Beyene et al., 2016). Among the abiotic stresses, recurrent drought is the major cause of yield losses varying from 40% to 60%. Occasionally severe drought stress can cause complete crop loss in sorghum production areas in Ethiopia (Ejeta and Knoll, 2007; Shao et al., 2008).

Drought as a challenge to sorghum production in Ethiopia

Drought refers to inadequate supply of water, including from precipitation and soil-moisture storage capacity, in quantity and distribution during the life cycle of the crop (Blum, 2011). It is a major limiting factor to agriculture and is considered as the most important cause of yield reduction in crop plants by preventing the crop from expressing its full genetic potential (Sanchez et al., 2002). Even though sorghum possesses a relatively better drought tolerance compared to most other crops, drought stress is the primary factor that reduces sorghum productivity worldwide (Xu et al., 2000). The two main types of drought are. metrological and agricultural drought. Meteorological drought is simply defined as shortfall of precipitation over a period of time that happens when dry weather patterns dominate an area whereas agricultural drought refers to circumstances when soil moisture is insufficient and results in the lack crop growth and production. Agriculture can rebound with in a very short period of time depending upon the strength of drought conditions.

In Ethiopia, many sorghum growing areas suffer from recurrent droughts due to shortage and/or uneven distribution of rainfall. In many regions of the country, the rain falls late or stops early, making the crop growing period very short, and this leads to crop failures. The irregular rain pattern, coupled with an age-old, subsistence farming system has made areas of the country vulnerable to drought, leading to severe malnutrition and hunger.

Several attempts have been made to breed for drought tolerant sorghum genotypes that could fit the frequent moisture deficit events in Ethiopia. Research centers have also recommended a number of soil and moisture conservation practices, which include tillage operations, tie-ridging and mulching to reduce the effects of drought. Efforts have also been made to develop early maturing sorghum varieties that are adapted to areas where moisture scarcity is detrimental to sorghum production. More than 51 early maturing sorghum varieties are currently available for use in such environments (ABoA, 2017; SARC, 2017). The impacts of drought in sorghum can be partly mitigated through genetic improvement and deployment of drought tolerant varieties.

This requires exploring the genetic variability present in this species (Rosenow and Dahlberg, 2000).

International, national and regional research centers routinely develop crop varieties without the involvement of end-users; in many cases their new varieties have not been adopted by farmers. The reason is that farmers' preferences and perceptions are rarely taken into consideration during the breeding process (Mekbib, 2007). For successful breeding and increased adoption of new varieties, integrated plant breeding should be adopted in order to develop better varieties, and thereby to increase sorghum productivity in the country. For the rapid improvement of sorghum production, and to enhance the adoption of new sorghum cultivars in north eastern Ethiopia, there is an urgent need to better understand the impact of drought on sorghum production and to establish farmers' preferences and key traits that would be preferred in new sorghum cultivars in the target region.

The ultimate goal of plant breeding is to increase yield through targeting farmers preferred traits. In Ethiopia a number of early maturing sorghum varieties were released however, most of them didn't meet farmer's interest in two main reasons. The first reason is that the released varieties planting time doesn't meet the normal farmers planting period which is April to May annually. The second reason is that farmers grow sorghum for both grain and stalk however, majority of the released varieties were short stature types. In addition to farmers trait preference understanding of the crop's breeding behavior, drought tolerance mechanism and genetic diversity are prerequisite to design a good breeding program. Moreover, use of efficient mating design and application of molecular markers in sorghum breeding is very important in exploiting the available genes through heterosis breeding and population improvement.

Rationale for breeding for drought tolerance

Currently, due to the combined effect of climate change, drought and fast population growth, Ethiopia experiences a critical shortage of food in some regions, resulting in escalating food prices that make food unaffordable for many poor people. Climate change is likely to further affect food production, particularly in regions that have very low yields due to lack of technology .Drought, caused by anthropogenic warming in the Indian and Pacific Oceans, may also reduce

21st century food availability in some parts of Ethiopia by disrupting moisture transports and bringing down dry air over crop growing areas (Chris and Molly, 2009). As a result, producing enough food for the population is becoming a major national priority. Ethiopia being a center of origin for sorghum, there is considerable genetic variability. Landraces have been selected by farmers over many years, and may serve as parental cultivar for developing drought tolerant varieties. This has been evidenced by the identification of post-flowering drought tolerant genotypes in collections from Ethiopia, which have been used by other countries. However, this valuable resource has not been systematically evaluated, documented and used to develop cultivars with improved traits, including drought tolerance, in Ethiopia.

Ethiopian sorghum improvement programs, including regional sorghum improvement programs, primarily depend on dwarf and early maturing exotic materials. However the farmers in the country are still cultivating drought susceptible, late maturing and low yielding local landraces. Given the importance of well adapted sorghum landraces in Ethiopia, a genetic diversity study would be valuable to increase the chances of using new sources of alleles that will improve genetic gain through selection.

In the north eastern Amhara regions of Ethiopia farmers start ploughing their farms after they harvest the previous crop, around the end of January. In the region rain-fed agriculture is the normal practice. A short rainy period commences in April and sorghum growers plant local landraces in mixtures of medium-and long-maturing varieties. For two and half month after planting sorghum often experiences extreme drought in May-June. The main rainy season usually begins in July. During this season sorghum starts to resume growth well with a fast compensatory growth. Medium-maturing local landraces start to boot in the first week of August and complete their grain filling by the end of August. However, there are few of these landraces relative to the total sorghum population and as such, they can be severely affected by birds. Farmers often harvest the stalks of these landraces only to feed their animals; harvesting little or no grain. However, medium-maturing landraces with better biomass and grain yield mature relatively earlier than the late-maturing varieties. Often the late maturing sorghum landraces are affected by post-flowering drought stresses. Therefore, development of sorghum varieties with drought tolerance and medium maturity has significance potential for the farmers of north eastern Ethiopia. In Ethiopia, no improved variety has been released yet that can be planted in April to the first week of June, in line with farmers' needs. Managed drought screening experiments of the study were conducted at Kobo testing site. This is because Kobo is well known drought screening sorghum research testing site for national and regional sorghum research centers with adequate information of weather and soil type information.

Therefore, the study was conducted to document the views of sorghum growers, evaluate genetic diversity of local landraces and evaluate their phenotypic performance, followed by designed crosses between genetically unrelated genotypes, to develop and release drought tolerant medium-maturing sorghum varieties in Ethiopia to meet the farmers' expressed needs.

Research objectives

The overall objective

The overall goal of this study was to contribute to enhancing sorghum production and productivity in Ethiopia with the aim of improving food security of resource poor farmers in drought affected parts of the country, through the breeding of drought tolerant sorghum genotypes with farmer-desired traits.

The specific objectives

The specific objectives of this study were:

1. To determine the impact of drought on sorghum production and productivity over time and space, and to identify farmers' production constraints and coping strategies when dealing with drought in north eastern Ethiopia.
2. To characterise sorghum landraces for drought tolerance and to select farmer-preferred medium-maturing genotypes under managed stress condition.
3. To assess the genetic diversity present among diverse medium-maturing sorghum genotypes based on simple sequence repeat (SSR) markers and phenotypic traits to select unique genotypes for breeding.
4. To determine combining ability, heterosis and heritability of yield and yield-related traits in medium-maturing sorghum genotypes to select promising parents and families for breeding.

Research hypotheses

1. Farmers varietal and trait preferences are different in sorghum growing areas of North-eastern Amhara region of Ethiopia.
2. There exists genetic variability among locally adapted medium-maturing sorghum genotypes for drought tolerance breeding.
3. Sorghum inbred lines and crosses show good combining ability, heterosis and trait heritability to select promising parents and families.

Outline of the thesis

This thesis consists of five distinct chapters in accordance with a number of activities related to the afore-mentioned objectives. Chapters 2-5 are written as discrete research chapters each following the format of a stand-alone research paper. The journal of Crop Science system of referencing is used in the chapters of this thesis, which is the main thesis format adopted by the University of Kwazulu-Natal. There is some unavoidable repetition of references and some introductory information between chapters and references.

Chapters	Titles
-	Introduction to Thesis
1	Review of the Literature
2	A diagnostic survey on the impact of drought on sorghum production, and farmer’s varietal and trait preferences, in the north eastern Ethiopia: implications for breeding.
3	Agro-morphological characterization of sorghum landraces for drought tolerance and selection of farmers-preferred medium-maturity genotypes under managed stress
4	Assessment of the genetic diversity of medium-maturing sorghum genotypes based on simple sequence repeat markers and phenotypic traits
5	Combining ability, heterosis and heritability analyses for yield and yield-related traits in medium-maturing sorghum
6	Overview and implications

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CHAPTER 1

A Review of the Literature

1.1 Introduction

Sorghum (*Sorghum bicolor* (L.) Moench] is predominantly a self-pollinating C4 crop belonging to the family Poaceae. It is believed to have been originated in the Ethiopia-Sudan region of north eastern Africa (Doggett, 1998; FAO, 1995) from where it spread to the rest of Africa, Southeast Asia, India, Australia, and the United States (FAO, 2007). There are five cultivated races of sorghum including *bicolor guinea, caudatum, kafir* and *durra*. Among the five races *durra* is widely grown in Ethiopia (House, 1985). Sorghum is cultivated primarily in the semi-arid regions of Africa, India and the southern plains of the United States (Reddy et al., 2009; Panguluri and Kumar, 2013). In SSA sorghum growers faced biotic and abiotic production constraints year after year however, the most important production constraint in this region is drought. Efforts have been made in different research institutions like NARCs and ICRISAT for the development of drought tolerant and early maturing varieties. It is mainly grown for food, feed, bioenergy and industrial purposes.

1.2 Economic importance of sorghum

Sorghum ranks fifth next to maize, rice, wheat, and barley in total production worldwide. It is the most important dietary staple cereal crop providing energy, protein, vitamins and minerals for more than 500 million people primarily in the developing countries (Burke et al., 2013; Kumar et al., 2011). World cultivated area is more than 44 million hectares producing around 68 million tons of grains annually (FAOSTAT, 2017). It grows in more than 90 countries in Africa, America, Asia, Europe and Oceania (Figure 1.1). USA, Mexico, Nigeria, Sudan, India, Ethiopia, Argentina, China, Brazil and Burkina Faso are the top ten major sorghum producers globally (FAOSTAT, 2017) (Figure 1.2). United States of America is the largest sorghum producer globally mainly as an export commodity crop. Japan, China, Mexico and South Africa import significant amount of sorghum from the USA (U.S. Grains, 2015; U.S. Grains, 2016).

Sorghum is a multi-purpose crop and used in various forms. In sub-Saharan Africa (SSA), sorghum is the foundational staple food for many rural communities, especially in drought prone areas. Sorghum's grain is processed into flour and consumed in the form of porridges (thick or thin) and flat breads (Panguluri and Kumar, 2013). A wide variety of traditional food products and recipes are prepared from sorghum. Sorghum grain is boiled and consumed, brewed for beer production, baked into flatbreads or ground for porridge preparation. The food is a rich source of micronutrients, particularly iron, phosphorus and zinc (Kumar et al., 2011) and starch. A recent study classifies sorghum genotypes as source of vitamin "E" (Cardoso et al., 2015). Sorghum has a similar protein content to that of wheat but higher than maize and rice. Essential amino acid composition of sorghum is comparable to maize or wheat due to the limited content of threonine, arginine and, lysine (FAO, 1995; Henley, 2010). Sorghum's main storage proteins, the kafirins, are devoid of the essential amino acid lysine. Therefore, the high kafirins content present in a given sorghum variety has a direct negative impact on its nutritional value. Iron content of sorghum is lower than millet but is higher than wheat, maize and rice (FAO, 1995; Henley, 2010). Interestingly, sorghum is considered suitable for people with gluten intolerance due to it's gluten free property (Taylor et al., 2006; Schober et al., 2007; Perazzo et al., 2014).

Sorghum grain is also an important feed source, widely used in Australia and the Americas. Sorghum stover (crop residue after grain harvest) is an important livestock feed in the mixed crop-livestock farming systems prevalent in semi-arid tropics. Sweet stem sorghum with sugar rich juicy stalks is emerging as an important biofuel crop (Reddy et al., 2008).

Ethiopia is the center of origin and diversity of sorghum (Vavilov, 1951). The country is the sixth largest sorghum producer after the USA, Mexico, Nigeria, Sudan and India. In Ethiopia about 1.83 million hectares of agricultural lands are devoted to sorghum cultivation with a total production of 4.34 million tons per annum (FAOSTAT, 2017). Sorghum is one of the major food cereals after maize and tef in terms of the total number of growers, area coverage and grain production in Ethiopia (CSA, 2016). Typically, sorghum is used for making the local bread, ‘‘Injera’’, and for the preparation of local beverages, ‘‘tela’’ and ‘‘areki’’. It is also consumed as roasted vegetable and boiled grain. Sorghum stalks are used as feed for animals, and as housing and fencing material.

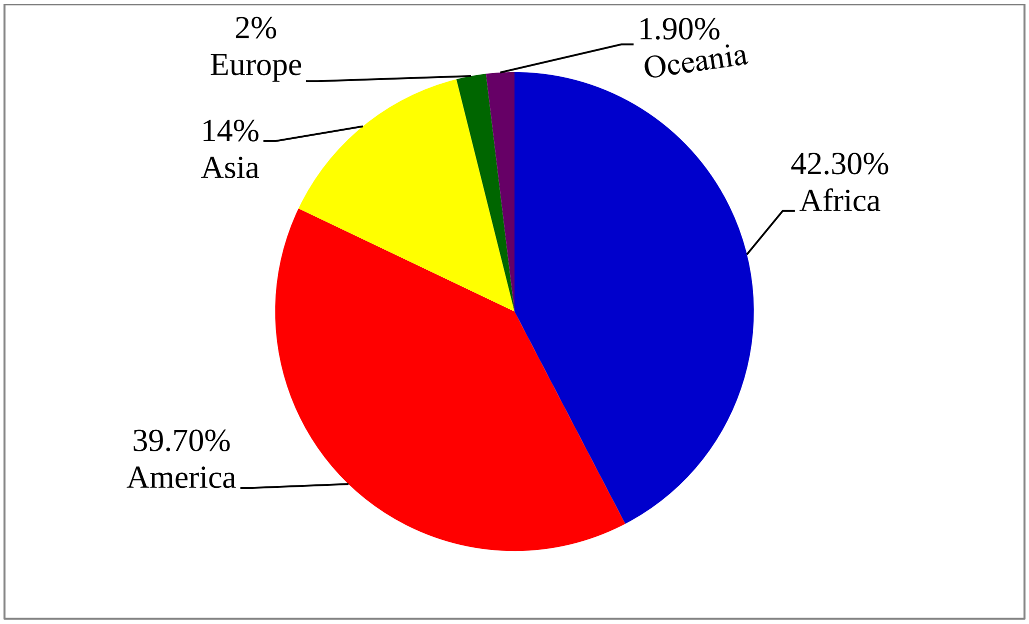

Figure 1.1 Share of sorghum production (%) globally in 2014 (FAOSTAT, 2017)

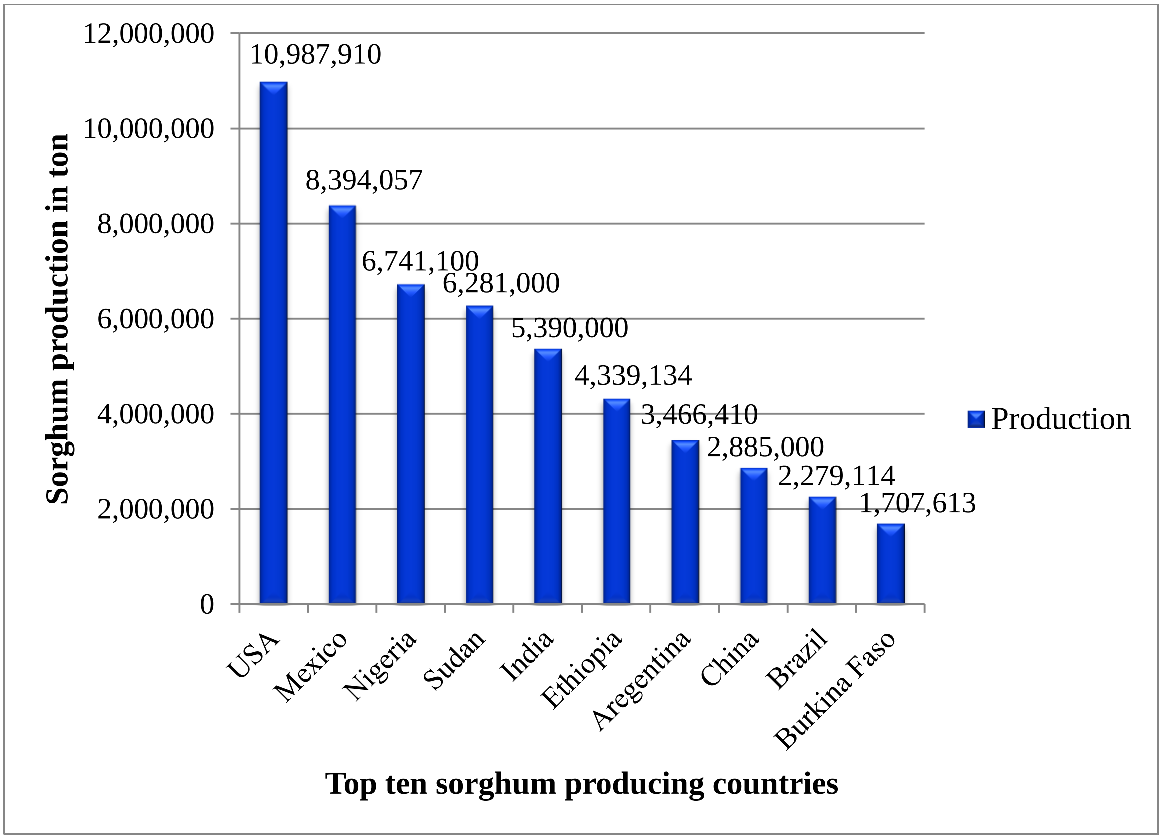

Figure 1.2 Sorghum production (tons) from the top 10 sorghum producing countries in 2014 (FAOSTAT, 2017)

1.3 Constraints to sorghum production and productivity

Sorghum production and productivity in SSA is challenged by abiotic, biotic and socio-economic constraints. Among the biotic constraints *Striga hermonthica* and stalk borer (*Chilo partellus*) are the most damaging pests (Beyene et al., 2016; Wortmann et al., 2006). In Ethiopia optimal production and productivity of the crop has not yet been achieved due to socio-economic constraints such as poor financial support, lack of farmer preferred variety, lack of improved seed system, poor market linkage, lack of value addition, poor extension service support and lack of storage facility (Beyene et al., 2016; Muliokela, 1999). Drought, poor soil fertility and soil salinity are the most important abiotic constraints affecting sorghum production including in Ethiopia (Waddington et al., 2010; Reynolds et al., 2015; Shrivastava and Kumar, 2015; Beyene et al., 2016). Among the abiotic stresses, recurrent drought is the major cause of yield losses varying from 40% to 60%. Occasionally severe drought stress can cause complete crop loss in sorghum production areas in Ethiopia (Shao et al., 2008 (Ejeta and Knoll, 2007).

Sorghum has relatively good adaptation to grow under water scare environments due to its xerophytic features that render efficient drought tolerance mechanism (Landau and Sans, 2012). Despite this feature, under severe moisture stress, sorghum succumbs to terminal drought stress. The reproductive phase of sorghum is the most affected by drought stress leading to reduced biomass production, poor anthesis and seed set (Subudhi et al., 2000; Menezes et al., 2015).

Drought affects molecular, physiological, and morphological functions of sorghum resulting in severe yield loss higher than all other stress factors combined (Farooq et al., 2009; Sakhi et al., 2014). From physiological and agronomic perspectives, drought tolerance is a loosely defined trait related to water use efficiency; but from the perspective of gene discovery, drought tolerance is a complex trait controlled by a large number of interacting genes which are subject to genotype x environment interaction (Blum, 2011).

In Ethiopia, many sorghum growing areas suffer from recurrent droughts due to shortage and/or uneven distribution of rainfall and a lack of supplemental irrigation. In many regions of the country, the rain falls late or stops early, making the crop growing period very short, and this leads to crop failures. The irregular rain pattern, coupled with an age-old subsistence farming system has made areas of the country vulnerable to drought, leading to severe malnutrition and hunger among rural communities who depend on this crop for their livelihoods.

Several attempts have been made to breed for drought tolerant sorghum genotypes that could fit the frequent moisture deficit events in Ethiopia. Research centers have also recommended a number of soil and moisture conservation practices, which include tillage operations, tie-ridging and mulching to reduce the effects of drought. Efforts have also been made to develop early maturing sorghum varieties that are adapted to areas where moisture scarcity is detrimental to sorghum production. More than 51 early maturing sorghum varieties are currently available for use in such environments (ABoA, 2017; SARC, 2017). The impacts caused by drought stress in sorghum can be partly mitigated through genetic improvement and deployment of drought tolerant varieties. This requires exploring the genetic variability present in this species (Rosenow and Dahlberg, 2000).

1.4 Breeding sorghum for drought tolerance

The major objective of plant breeding is generating and selecting for new combinations of genes to produce genotypes with superior trait performances than those of existing genotypes, within the target environment (Chapman et al., 2003). In any breeding program, defining the critical traits to improve grain yield in a given target environment is critical (Fernandez, 1992). Identification of important traits depends on the degree of influence of a trait on yield, expression of the trait at a whole plant level, the nature of the target environment which includes, rainfall amount, distribution, onset and cessation, available soil water, nutrient status of the soil, and diseases, and economic environment. In maize, for example, it has been found that early flowering, crop water use efficiency and early vigour are important traits to breed for improve yield under drought condition (Richards, 1996).

The greater flexibility of sorghum in adapting to diverse climatic conditions has resulted in the evolution of tropical and temperate sorghum varieties. The tropical varieties are characterized by being tall, late maturating with low harvest indices, photoperiod sensitivity and poor population performance. They are generally adapted to low population levels and exhibit little response to improved agricultural practices (fertilization and mechanized harvesting). The temperate sorghum varieties, on the other hand, are characterized by dwarf stems, early maturity, high yields, and less dry matter per plant (Rao et al., 2002). In the early sorghum improvement program, conversions of tropical varieties to temperate varieties were made by substituting two dominant alleles for height and three for maturity for their recessive counterparts. The conversion program started with hybridization of tropical and temperate varieties followed by successive backcrossing (Acquaah, 2007).

The most sorghum breeding programs after the discovery of stable and heritable cytoplasm-nuclear male sterility systems in the crop is exploitation of heterosis by the production of hybrids. This discovery further enables large-scale production of commercial hybrid seed to be commercially viable (Dar et al., 2006). A study of the expression of hybrid vigour in grain sorghum by Doggett (1988), revealed that there was an 84 % increase in number of seed per plant, an 82 % increase in grain weight, and a 12 % increase stover weight in the hybrids relative to the better parent.

Plant breeders have two basic approaches for breeding for drought resistance, direct and indirect breeding. Direct selection for drought is conducted under conditions where stress factors occur uniformly and predictably whereas indirect selection involves selection of genotypes under managed stress environments. However, environmental factors such as temperature and moisture are highly variable from one location to another and hence difficult to predict. As a result, indirect selection breeding is used as a preferred method where selection is made based on based on developmental traits or based on assessment of plant water status and plant function (Ludlow, 1980).

Earlier drought tolerance screening was done under optimal conditions, because the maximum genetic potential of yield can only be realized under optimum conditions. Additionally, it was believed that a high positive correlation exists between performance under optimum and stress conditions (Habyarimana et al., 2004; Tuinstra et al., 1997). However, a high genotype by environment interaction may restrict the expression of the yield potential under drought condition. Although, there is a yield penalty when selecting plants under drought condition in contrast to optimal environmental conditions. Richards (1996) and Tuinstra et al. (1997) suggested that selection under both optimal and a drought condition represents the ideal trial design to select for yield and yield stability, drought tolerance and expression of drought related traits. Hence, drought tolerance and its impact on yield involve interaction between plant water relations and plant physiological functions.

1.5 Mechanisms of drought tolerance

Drought refers to inadequate supply of water, including from precipitation and soil-moisture storage capacity, in quantity and distribution during the life cycle of the crop (Blum, 2011). It is a major limiting factor to agriculture and is considered as the most important cause of yield reduction in crop plants by preventing the crop from expressing its full genetic potential (Sanchez et al., 2002). Even though sorghum possesses relatively better drought tolerance compared to most other crops, drought stress is the primary factor that reduces sorghum productivity worldwide (Xu et al., 2000).

In sorghum excellent sources of tolerance to pre-flowering and post-flowering drought stress have been identified, but high levels of both types of tolerance have not been found in the same genotype (Ejeta, 2007). So far, two sources of stay-green, B-35 and E-36-1, have been identified in the Ethiopian gene pool by ICRISAT and other scientists in SSA, and are now in use in different parts of the world to generate drought tolerance/resistance sorghum varieties (Borrell et al., 2001). The genotypes expressing stay-green trait employ mechanisms to increase availability of soil water during seed fill in drought prone areas. In addition the phenotype of this trait is a persistence of green leaves during and after seed filling stage of the crop in areas where sorghum is challenged by drought.

The response of sorghum genotypes vary with the growth stage at which the drought occurs. Four growth stages in sorghum are considered vulnerable to drought: germination and seedling emergence, post-emergence or early seedling stage, midseason or pre-flowering, and terminal or post-flowering (Panguluri and Kumar, 2013). Variation in these responses has been observed and found to be heritable. Since the phenotypic responses of genotypes differing in drought tolerance can be masked if drought occurs at more than one stage, screening techniques have been developed to identify drought-tolerant genotypes at each of the growth stages, separately. Of the several mechanisms to circumvent drought stress in sorghum, drought escape, drought avoidance and drought tolerance are important and have been well characterized. These mechanisms are briefly described below.

1.5.1 Drought escape

Drought escape is the ability of a plant to complete its life cycle before serious soil and plant water deficits develop (Riboni et al., 2013). This mechanism involves rapid phenological development such as, early flowering, short grain filling period and early maturity, developmental plasticity (variation in duration of growth period depending on the extent of water-deficit) and remobilization of pre-flowering assimilates to grain (Jerotich and Mugendi, 2013). It is mainly demonstrated by desert ephemerals and some short duration dry land crops that have a condensed growth cycle and reach maturity before drought occurs.

1.5.2 Drought avoidance

Drought avoidance is a mechanism for avoiding lower water status in tissues during drought by maintaining cell turgor pressure and cell volume either through aggressive water uptake with an extensive root system or through reduction of water loss from transpiration and other non-stomatal pathways (Chaves et al., 2013). Blum (1979) explained that mechanisms for improving water uptake, shortage of water in plant cells and reducing water loss confer drought avoidance. Drought avoidance is performed by maintenance of turgor through an efficient root system, increased hydraulic conductance and reduction of water loss through reduced epidermal conductance, reduced absorption of radiation by leaf rolling or folding, and reduced evaporation surface (Machado and Paulsen, 2001). Drought avoiding crop plants like sorghum avoid water deficits by maximizing water uptake and minimizing water loss.

1.5.3 Drought tolerance

Drought tolerance is the ability of plants to withstand water deficit while maintaining appropriate physiological activities to stabilize and protect cellular and metabolic integrity at tissue and cellular level (Xiong et al., 2006; Tuinstra et al., 1997). Survival is the ability of the crop to survive drought, irrespective of the yield it produces, while production is the ability of the crop to grow and yield under water stress conditions (Beyene et al., 2015). This is achieved by maintaining sufficient cell turgor to allow metabolism to continue under increasing water deficits. Gunasekera and Berkowitz (1992) indicated that osmotic adjustment enables water uptake to continue under increasing stress in many species and, in some cases, is associated with maintenance of growth and stable yield under drought. At ICRISAT, growth-stage-specific breeding for drought tolerance, which involves alternate seasons of screening in specific drought and well-watered environments, has been used to breed sorghum that can yield well in both high-yield potential environments as well as in drought-prone environments (Reddy et al., 2009).

1.6 Farmer's trait preferences and their drought coping mechanisms

During cultivar development the interest of farmers should be the leading priority in any breeding programs. Farmers' involvement is key during setting breeding goals and problem identification process in plant breeding research. Plant breeders should take into account the interest of farmers with tangible information whether the issue is researchable or not given the available plant breeding facilities and skills. Farmer participation in plant breeding research is based on the principle that participation of end users in the co-production of knowledge generates a higher level of understanding, building up ownership and trust in the information, and increases their capacity and willingness to make use of the technology as per its full package. International, national and regional research centers routinely develop crop varieties without the involvement of end-users; in many cases their new varieties have not been adopted by farmers. The reason is that farmers' preferences and perceptions are rarely taken into consideration during the breeding process (Mekbib, 2007).

Strengthening of farmer's drought coping capacities, together with their preventive measure like irrigation, is an important aspect of drought adaptation and mitigation strategy. This builds resilience to withstand the effects of natural and other hazards. Traditionally, farmers have developed some informal strategies to cope with drought risks by actions taken before or after the risk event occurs. Usually, farmers applied both positive and negative drought coping mechanisms. The positive strategies include changing labour allocations, saving each other from asset disposal, sharing resources amongst relatives and community members, varying cropping practices (crop rotation and intercropping), and conservation tillage that protect soil moisture (Beyene et al., 2016; JGHPD, 2017). Recent experiences have demonstrated that these drought risk management strategies are costly and inefficient because they have important shortfalls resulting in negative implications for economic and social development (Hess et al., 2002, Anderson, 2006). Among the negative drought coping mechanisms the most frequently applied ones are family disintegration, sale of livestock, culling infant animals (lambs and kids) to save core breeding stock and preserve milk for household consumption, school dropout, early marriage and child labour and dependence on food assistance (JGHPD, 2017). Therefore, breeding for farmers-preferred and drought tolerant crop varieties can substantially improve the livelihood of farming community.

1.7 Sources of genetic variation

Genetic diversity is the variation of heritable characteristics present in a population (Swingland, 2001). Mutation is also reported as one of the causes to increase genetic diversity (Yilmaz and Boydak, 2006). The existence of genetic diversity represented in the form of wild species, related species, breeding stocks, mutant lines etc. may serve as the source of desirable alleles and may assist plant breeders in breeding climate resilient varieties (Bhandari et al., 2017).

Genetic diversity is a prerequisite in plant breeding programs. Proper use of genetic diversity within germplasm collection requires a detailed understanding of their characteristics. Characterization of accessions is traditionally based on morphological and agronomic traits, which is of high interest for plant breeders. Molecular markers are complementary tools for diversity analysis of genetic resources. Results of this study revealed the existence of promising phenological and morpho-qualitative traits variation among 50 medium-maturing sorghum genotypes collected from drought prone environments of north-eastern Ethiopia. Use of molecular markers in plant diversity studies is increasingly important for detection of differences in crop populations at the DNA level (Meng et al., 1998).

More than 168,500 sorghum accessions are collected globally (Billot et al., 2013). The large diverse germplasm provides great opportunities for sustainable breeding and prevent the loss of genetic diversity (Javier and Foreward, 1993; Huang, 2004). However, in sorghum growing areas of Africa, due to extreme drought many sorghum accessions have been lost or are under serious risk of genetic erosion, and hence, genetic diversity within primary gene pools has been decreasing (Mohammadi and Prasanna, 2003). This requires targeted selection and crosses to develop breeding populations for drought tolerance and other abiotic or biotic stress tolerance.

Sorghum in Ethiopia is grown under diverse environmental conditions, which includes the eastern and south western highlands of the country, the warmer and mid-elevation terraces of the north, and the hot and dry valleys of the south and west region (Stemler et al., 1977). Ethiopian sorghum collection is reported to be composed of highly genetically diverse germplasm (Cuevas and Prom, 2013). Moreover, farmers in Ethiopia practice seed exchange amongst themselves to use diversity as a tool to overcome the difficult farming system of the region (McGuire, 2002). Both diversity in growing conditions and frequent seed exchange amongst sorghum farmers in Ethiopia may have contributed to increase phenotype and genetic diversity through different selection pressure by nature or farmers (Cuevas and Prom, 2013).

1.8 Molecular markers in genetic diversity analyses

Genetic variation within a species is a fundamental resource in crop improvement programs. A detailed characterization of genetic diversity and understanding of the genetic relationships among accessions are prerequisites for successful exploitation of genetic variation contained in germplasm collections. Molecular markers are identifiable DNA sequences found at specific locations of the genome and transmitted by the standard laws of inheritance from one generation to another. They provide a more robust means of detecting genetic polymorphism, to define the distinctiveness of species and phylogenetic relationships at molecular level. Moreover, DNA markers provide convenient and powerful alternatives since they are not subject to environmental effects and are independent of the developmental stage of the plant. Numerous methods of detecting DNA polymorphism were established over the years, such as: Restriction Fragment Length Polymorphism (RFLP), Amplified Fragment Length Polymorphism (AFLP), Inter Simple Sequence Repeats (ISSR), Random Amplified Polymorphic DNA (RAPD), Selective Amplification of Microsatellite Polymorphic Loci (SAMPL), Sequence Specific Amplification Polymorphism (SSAP), Simple Sequence Repeats (SSR), Single Nucleotide Polymorphism (SNP), Diversity Arrays Technology (DArT) (Karp et al., 1996; Rakoczy-Trojanowska and Bolibok, 2004; Gupta et al., 2008). It is common to use DNA based molecular markers, which are more reliable and robust methods for the characterization of genetic diversity (Amsalu Ayana et al., 2001; Singh et al., 1991).

1.8.1 Simple Sequence Repeat (SSR) markers in sorghum diversity studies

Microsatellites or SSRs are short stretches of DNA sequences occurring as tandem repeats of mono-, di-, tri-, tetra-, penta- and hexa-nucleotides. These short repeats have been found to be abundant and dispersed throughout the genomes of all prokaryotes and eukaryotes analysed (Katti et al., 2001; Toth et al., 2000). SSRs are highly polymorphic due to frequent variation in the number of repeat units. SSR markers are co-dominant and multi-allelic in nature and have been shown to be highly reproducible. The hyper variability of SSRs among related organisms makes them excellent markers for a wide range of applications, including genetic mapping, the molecular tagging of genes, genotype identification, the analysis of genetic diversity, phenotype mapping, marker-trait association and marker assisted selection (Powell et al., 1996; Tautz and Schlotterer, 1994). SSR markers are remained the markers of choice for practical plant breeding, in this case, in sorghum genetic diversity studies. Different scholars used SSR markers for sorghum genetic diversity studies (Beyene et al., 2014; Asfaw et al., 2014; Tesfamichael et al., 2014; Missihoun et al., 2015; Muui et al., 2016; Tesfaye et al., 2016). Chamarthi et al. (2012) used 93 SSR markers for sorghum diversity study of 15 genotypes in relation to shoot fly resistance and found four diverse groups in their factorial analysis.

1.9 Common mating designs in genetic analysis and population development

Mating designs enable to procedure suitable populations. Plant breeders and geneticists use different types of mating designs and arrangements for targeted purpose (Nduwumuremyi et al., 2013). From a breeding point of view the purpose in using the different mating designs is twofold. The first is to furnish the breeder with information on the genetic control of the character under investigation. Second, to generate a breeding population this can be used as a basis for the selection and development of potential varieties. In turn this will enable the breeder to choose an appropriate breeding strategy and to assess the progress that can be expected for a given selection intensity. The common mating designs used in plant breeding are bi-parental mating (Mather and Jinks, 1982), polycross (Tysdal et al., 1942), diallel with four variations (Griffing, 1956), North Carolina Designs I, II and III (Comstock and Robinson, 1952) and line x tester (Kempthorne, 1957). In all mating designs, the individuals are taken randomly and crossed to produce progenies which are related to each other as half-sibs or full-sibs (Nduwumuremyi et al., 2013).

1.10 Combining ability

Combining ability analysis is useful for plant breeders to understand genetic variance and inbred lines important in identifying hybrids for commercial production. Research on combining ability helps plant breeders to select the best parents for development of hybrids or varieties. The concept of general- and specific-combining ability was conceived by Spraque and Tatum (1942) who designated general-combining ability (GCA) as the average performance of a line in hybrid combination, and the term specific-combining ability (SCA) was applied to cases where certain hybrid combinations did relatively better or worse than would be expected on the basis of the average performance of the lines. GCA measures the average performance of an inbred when crossed with a series of other inbreds. GCA indicates the worth of an inbred as a parent of multiple hybrids. Estimates of GCA are useful for choosing a few key inbreds to use as testers. SCA is because of genetic effects specific to a hybrid combination and not accounted for by GCA effects. Henderson and Gowen (1952) attributed that specific combining ability in genetic terms was due to consequences of intra-allelic interaction (dominance) and also due to inter-allelic interaction (epistasis). As a general rule, GCA is the result of additive gene effects, while SCA is the result of non-allelic interactions (Jinks, 1954), is assumed to be a deviation from additivity (Bernardo, 2014), or is attributed primarily to deviations from the additive gene action caused by dominance and epistasis. Massaoudou et al. (2016) crossed 25 F5 recombinant inbred lines with two male sterile lines in line by tester fashion and studied combining ability effects for the 50 F1 hybrids and found Variance due to SCA was higher than that of GCA for all traits except seedling vigor and 1000 seeds weight.

1.11 Heritability

Heritability is the proportion of the phenotypic variance that is genetic in origin which is transferred from parents to their offspring. Heritability can be classified in two types depending on which component of variance is used as numerator i.e. broad-sense and narrow-sense heritability. Broad-sense heritability or genetic determination is the ratio of genotypic variance to the total phenotypic variance whereas narrow-sense heritability is the ratio of additive variance to the total phenotypic variance. Success of breeders in changing the characteristics of a population depends on the degree of correspondence between phenotypic and genotypic values (Singh and Ceccarelli, 1995). Rani and Umakanth (2012) evaluated 30 F_1 crosses of sorghum to assess inherent differences and relationship among crosses. It was observed that grain yield exhibited high heritability coupled with high genetic advance implying additive gene effects.

1.12 Impacts of drought in sorghum production in Ethiopia

Drought and desertification associated with climate are at the core of serious challenges and threats facing sustainable sorghum production in SSA. Drought has adverse impacts on human health, food security, economic activity, physical infrastructure, natural resources and the environment, and national and global security (UNESC, 2007).

In Ethiopia more than 40 periods of drought induced food shortages have been identified in the country (Webb and Braun, 1989). For instance, the country was hardly hit by drought and food shortages from 1964-1966 in Wello and Tigray Provinces; from 1971-1975 in lowlands of Ethiopia; from 1984-1985 in most parts of Ethiopia; and from 2015-2016 in all lowlands of Ethiopia (Webb and Braun, 1989; UNOCHA, 2016).

The 1971-1975 Ethiopian drought driving famine was characterized by considerable geographical discrepancies. Famine in Ethiopia in 1985 was described by the BBC as a "biblical famine" the closest thing to Hell on Earth" (Michael, 1984). During this period, Wollo Province which is the national sorghum production belt suffered uniquely from the droughts. This led to a total collapse in sorghum harvests and many families were significantly affected and displaced (Sen, 1981). Failure in sorghum production directly affected the entitlement of farmers, pastoralists and the market.

Federal and regional research centers are actively involved in developing drought tolerant sorghum varieties. Further, extension agents of the Bureau of Agriculture in each region are involved in technology transfer to the farmers through training and demonstration at farmers training center (FTC). Given the role of sorghum in these farming systems and recurrent drought affecting its production, there is a need for breeding drought tolerant, agronomicallly suitable and medium-maturing sorghum varieties which can be conveniently grown in their planting period (April to May).

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CHAPTER 2

A diagnostic survey on the impact of drought on sorghum production, and farmer's varietal and trait preferences, in the north eastern Ethiopia: implication for breeding

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2.1 Abstract

The yield of sorghum is affected by a wide array of production constraints, notably severe and recurrent drought stress. The objectives of this study were to determine the impact of drought on sorghum production and productivity over time and space, and to identify farmers' production constraints and coping strategies when dealing with drought in north eastern Ethiopia. Purposive sampling was used, by which means 180 farmers who had grown sorghum in 2014 were selected from three major sorghum growing administrative zones. Focus group discussions and individual interviews were held for data collection and analysis. According to the respondents sorghum productivity has declined over time mainly due to recurrent drought stress, *Striga* infestation, damage due to insects, birds and, diseases, a lack of farmers-preferred high yielding varieties, limited policy support, a lack of access to seed of improved varieties, poor sorghum production practices, low level of input, and poor soil fertility. Among the production constraints, drought during post-flowering stage was identified by all the respondent farmers as the leading challenge in the three study zones. Results revealed that farmers were slowly losing their local landrace varieties due to extreme drought conditions over the years. Farmers in the three administrative zones preferred medium-maturing sorghum varieties suitable for April planting and which escape drought in the post-flowering stage. This is the first study on farmers trend and impact of drought on sorghum production in the north eastern Amhara Region of Ethiopia. The main results were the loss of sorghum landraces, and a shift to the growing of medium-maturing varieties. The need for new varieties with drought tolerance and farmers preferred sorghum traits are important considerations in breeding programs to enhance productivity and to ensure the ultimate adoption of improved sorghum cultivars in north eastern Amhara.

Keywords: drought; participatory rural appraisal; farmer; sorghum; trait preference.

2.2 Introduction

Sorghum [*Sorghum bicolor* (L.) Moench] is the fifth most important cereal grain after maize, rice, wheat and barley in the world (FAOSTAT, 2017). It has been cultivated for centuries as a staple food crop in much of sub-Saharan Africa and Asia. It has remarkably wide adaptation and tolerates high temperatures and drought stress. It grows under high radiation, inadequate and erratic rainfall and in soils of poor structure, low fertility and low water holding capacity.

Sorghum is an important source of food and feed, particularly in the arid and semi-arid regions where other cereal crops such as maize and wheat fail to grow (Duodu et al., 2003; Reddy et al., 2004). Considering recent climate changes, sorghum production could reduce the expected food shortages (Abdalla and Gamar, 2011). In developing countries, including Ethiopia, more than 500 million people consume sorghum as their principal food source (Burke et al., 2013). Sorghum is a gluten-free cereal used as a whole grain or processed into flour to provide essential nutrients including carbohydrates, protein, vitamins and minerals, and nutraceuticals such as antioxidants, phenolics and cholesterol-lowering waxes (Taylor et al., 2006; Perazzo et al., 2014).

In Ethiopia a total of 4.34 million tons of sorghum is being produced per annum. The mean yield level in the country is estimated at 2.37 t. ha^{-1}. The crop is the major food cereal after maize and tef in terms of number of growers, area coverage and grain production in the country (CSA, 2016). It is utilized in various forms, such as for making the local bread, ‘‘Injera’’, and for the preparation of local beverages such as, ‘‘tela’’ and ‘‘areki’’. Grain from some sorghum varieties is cooked as a roasted or boiled grain. Sorghum stalks are used as feed for animals, and as housing and fencing material. The crop is highly adapted to the lowland and drier parts of Ethiopia owing to its considerable drought resilience.

Despite its ability to grow in the arid and semi-arid areas of sub-Saharan Africa including in Ethiopia, the yield and quality of sorghum is affected by a wide array of production constraints such as the use of low yielding traditional varieties, which keep its productivity low. Drought, infestations by *Striga hermonthica* and soil salinity are the major stresses that limit sorghum production and productivity in the world (Zhu-Salzman et al., 2004). Among these, drought stress and *Striga* damages are the most important production constraints to sorghum production in Ethiopia (Gebretsadik et al., 2014). Drought is a major constraint in sorghum production worldwide and is considered as the most important cause of yield reduction in crop plants (Sabadin et al., 2012; Besufekad and Bantte, 2013), especially in water-limited areas of the world including parts of eastern and southern Africa. *Striga* infestation is often linked with poor soil fertility, resulting in poor harvests and consequently of hunger (Ejeta, 2007). The impact of *Striga* is more pronounced in areas under moisture and nutrient stresses.

In sorghum, there are two primary types of drought responses including pre-flowering and post-flowering, which are under the control of two different sets of genetic mechanisms. Pre-flowering refers to the stage from panicle differentiation to flowering, while post-flowering refers to the stage between flowering to grain development (GS-3) (Burke et al., 2010). Pre-flowering drought tolerance responses of sorghum includes reductions in panicle size, seed number, and grain yield. Post-flowering drought tolerance encompasses rapid premature senescence, which leads to reductions in seed size, yield loss and stalk lodging (Sanchez et al., 2002; Burke et al., 2010).

Much research effort has been spent trying to understand drought tolerance mechanisms in sorghum in order to breed for drought tolerant genotypes that will tolerate the frequent moisture deficit events in Ethiopia. These studies have recommended a number of soil and moisture conservation practices, which include tillage operations, tie-ridging and mulching to reduce the effects of drought (Teshome et al., 1995). Efforts have also been made to develop early maturing sorghum varieties that are adapted to areas where regular moisture scarcity is detrimental to sorghum production. In Ethiopia, more than 51 early maturing sorghum varieties are currently available for use in such environments (ABoA, 2017; SARC, 2017). However, most of these varieties were not readily adopted by farmers for varied reasons. Firstly, planting dates for these varieties are mismatched with what the farmers are currently using; mid-April to mid-May is the normal sorghum planting time, particularly in north eastern Amhara Region. Secondly, farmers highly expect two most important benefits at the same time from sorghum crop, i.e., grain yield and above ground biomass to their livestock. Thirdly, farmers believe that post-flowering drought recovery capacity of long and medium-maturing sorghum landraces is better than early maturing ones.

Despite the long-term efforts made to breeding for tolerance to drought in sorghum, advances made in developing improved varieties with adequate levels of drought tolerance using indigenous landraces combined with farmers' and market-preferred grain, and above ground biomass traits have been limited. Farmers still prefer to plant local sorghum landraces rather than introduced varieties because local landraces produce larger volumes of biomass for animal fodder, fuel, and construction material in good cropping seasons. Therefore, sorghum breeding programs should ensure that the new varieties satisfy the preferences of the farmers through participatory variety selection to create sustainable adaptation of the released varieties and their production packages. This explains why this breeding study was preceded by a survey using a structured questionnaire to collect information on impact of drought, and on farmer's varietal and trait preferences of sorghum in north eastern Ethiopia. This information was gathered through participatory rural appraisal (PRA).

In Ethiopia sorghum remains a subsistence crop with limited industrial value. It is the third most important cereal next to tef and maize on the basis of area cultivated and production amount (CSA, 2016). In the Oromia Special and North Wello Zones, sorghum is the first major cereal crop in terms of area coverage and amount produced whereas it is the second next to tef in area coverage in the South Wollo Zone (CSA, 2015). Because of its drought tolerance, high biomass production for cattle feed, relatively better productivity during good rainy seasons, and its provision of continuous supply of food starting from mid-September, farmers rely heavily on sorghum cultivation yearly.

In the study zones, April is the ideal sorghum planting time. Farmers start to harvest green heads for food around September or in the 'Meskel' season (coinciding with the celebration of the Finding of the True Cross. At this time sweet stem sorghum varieties reaches the middle of the grain filling stage, at this point the stems can be chewed as an important food source ("Gulbet"). Farmers often grew a mixture of varieties (locally referred to as 'Wajera') so that in some areas medium maturing local landraces of grain and sweet sorghum could be ready for family consumption before September 11. It was believed that eating sweet sorghum stalks before September 11 would increase the likelihood of catching malaria. Some stands of the sweet sorghum varieties were left in sorghum fields up to grain physiological maturity to be used for porridge preparation and as a seed source in the coming production year. Heads of sorghum at grain filling are roasted and eaten, which is locally termed as ‘mashella eshet’, ‘tibese’ or ‘lemete’. These are the most common food types around September and October when sorghum reaches the soft dough stage. Depending on the maturity period farmers have access to “mashela eshet” until harvest.

Participatory rural appraisal is one of the most effective and popular way to gather information in rural areas. The basic concept of PRA is to learn from rural communities. It is a bottom-up approach developed in the early 1990s and stands on the principle that local communities are creative, capable and can do their own investigations, analysis and planning (Chambers, 1992). Therefore, the objectives of this study were to determine the impact of drought on sorghum production and productivity over time and space, and to identify farmers’ production constraints and coping strategies when dealing with drought in north eastern Ethiopia.

2.3 Materials and methods

2.3.1 Description of the study areas

The study was carried out in the north-eastern Amhara Regional State of Ethiopia in three selected major sorghum growing administrative zones namely, North Wello, South Wello and Oromiya Special Zones. The study areas represent semi-arid to arid lowland agro-ecologies known for their sorghum production. The geographical descriptions of the study zones are shown in Figure 2.1 and their typical agro-ecological characteristics are summarized in Table 2.1.

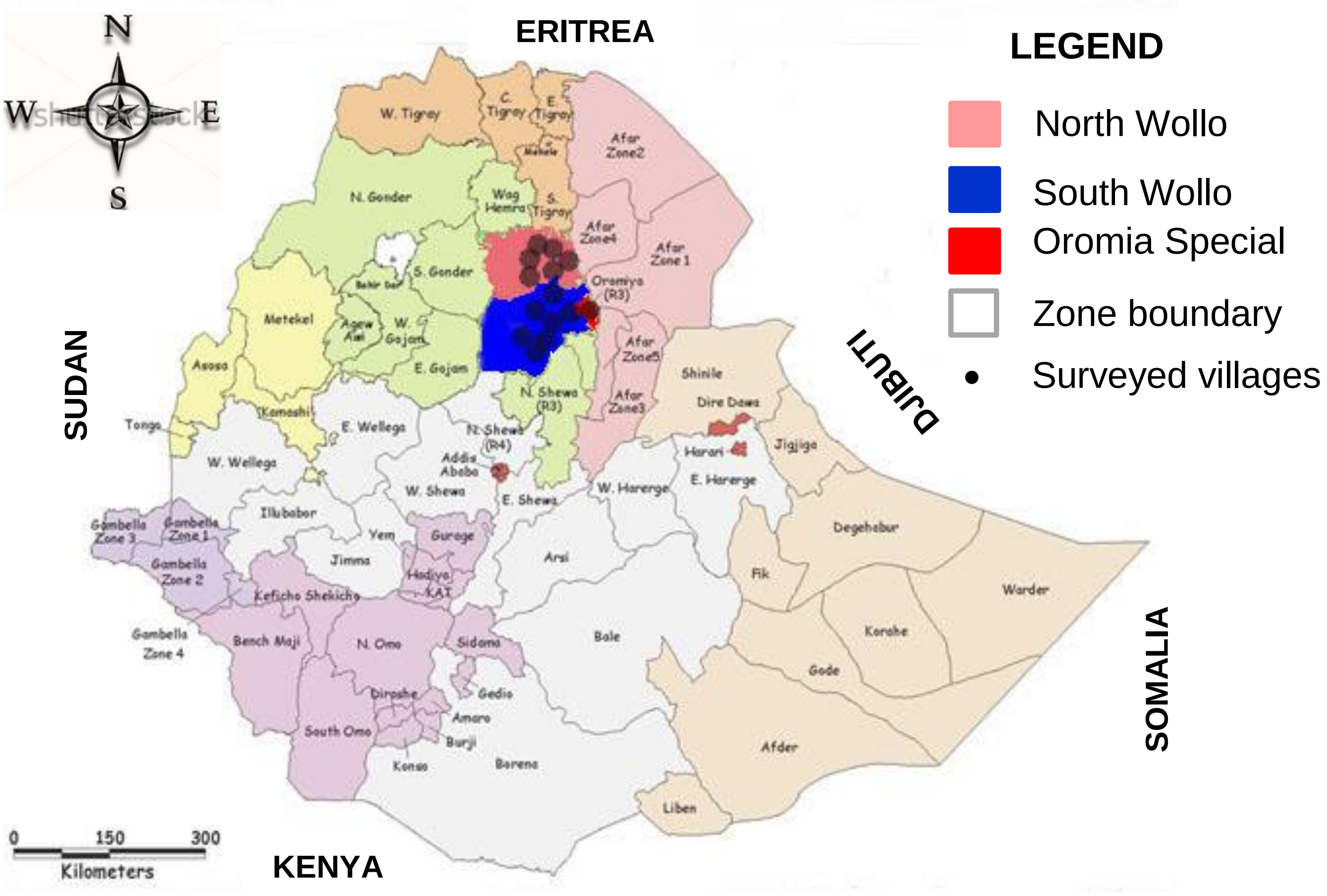

Figure 2.1 Map of Ethiopia showing the study zones

Table 2.1 Major agro-ecological characteristics of the study zones

Study zone	Agro-ecology	Altitude (masl)	Geographic position	Annual rainfall (mm)	Temperature (°C)	
					Min	Max
North Wollo	Semi-arid	1450-2400	11°49′50.49″N 39°35′39.94″E	700-1000	19	34
South Wollo	Semi-arid	1600-2700	11°08′00.36″N 39°37′58.32″E	800-1250	16	31
Oromia Special	Semi-arid	1400-2100	10°42′58.64″N 39°52′04.61″E	750-1300	21	33

Key: masl= meters above sea level

The priority objective of farmers in the study areas is to secure an adequate family food supply throughout the year. Therefore, farmers in these areas practice mixed crop and livestock farming, which is the predominant source of farmers' livelihoods. Sorghum and tef are the major food crops in terms of the area they are planted and volume of production obtained (CSA, 2016). The second priority is to earn cash incomes for household expenditures such as farm inputs, school fees, taxes and medical costs. This is also achieved through the production of cash crops such as sesame, noug, soybean, pepper, and in years of crop failure through the sale of livestock. The study sites are the major production and diversity belt for sorghum in the country. Sorghum, the main food source, is made into “injera”, which is the preferred dish in the area. Sometimes sorghum is prepared in the form of porridge, roasted “kolo”, cooked “nifro” or locally brewed “tella”.

In the study site, tef is the preferred food crop. However, farmers give greater importance to sorghum and expect to harvest more grain and biomass than from tef. Sorghum is also harvested for its green-head as a food source in the immature stage, for roasted grains when tef is still in its vegetative stage, and the food supply is short.

2.3.2 Sampling method

Purposive sampling was employed to include the major sorghum growing agro-ecologies and zones for the study. According to the Ethiopian administrative classification a zone is a large administrative unit below region. From each administrative zone one woreda was selected. A zone is composed of a number of woredas, while a woreda is an administrative level that is equivalent to a district and composed of a number of kebeles. A kebele or neighbourhood association is the smallest unit of local government. From each woreda two kebeles known for experiencing recurrent droughts were purposely selected. The target woredas and kebeles were chosen on the basis of sorghum area coverage, production, consumption and prior information on the intensity, duration and spatial coverage of drought with the assistance of zone and woreda agriculture office. Overall, the survey was conducted in six kebeles selected from three woredas. A total of 180 farmers that cultivated sorghum during 2014/15 cropping season participated in the study. In each kebele, 30 sorghum growing men and women farmers were selected and interviewed with the participation of kebele level developmental agents and three researchers (a Socio-Economist, an Agronomist and a Plant Breeder) drawn from Sirinka Agricultural Research Center. The survey was conducted between December 2014 and January 2015 when farmers were harvesting their sorghum.

2.3.3 Data collection and analysis

Data were collected through individual interviews, observations made by transect walks across selected kebeles, and focus group discussions with farmers. Semi-structured questionnaires were used to collect information on cropping systems, the impact of drought and other production constraints, drought coping mechanisms, farmer's varietal and trait preferences, sorghum utilization, seed sources and planting periods. Drought tolerant sorghum landraces widely used by farmers were identified and collected with their local names. In each kebele, discussions were held among selected elders, and their experiences and interests were recorded. Additional information was recorded through personal observations made during transect walks through each of the sampled kebeles. During the transect walks observations were made on crop lands where sorghum had been planted during the growing season. Observations were also made on the impact of a recent drought, maturity period, uses of sorghum, landrace diversity and cultural practices such as weeding and row planting.

Both qualitative and quantitative data were collected through questionnaires. Data were coded and subjected to analysis using the SPSS statistical package version 16.0 (SPSS, 2007). The processes of qualitative data analysis included identifying common observations, concepts, ideas, and issues related to cropping systems, as well as elements and indicators of drought. Quantitative data that was collected from primary sources were subjected to statistical summaries such as means and chi-square analysis. Chi-square test was used for testing relationships between categorical variables included in this study. It is used to determine whether there is a significant association between the two variables. Sorghum productivity data was subjected to a one tailed t-test using the SAS statistical software package version 9.3 (SAS, 2011). A one tailed t-test was conducted using the mean grain yield of surveyed zones during the 2015 cropping season.

For t-test analysis used to test the significance of two means so that the surveyed sorghum productivity mean for each region was compared with its respective zonal mean sourced from CSA, 2015 data. In addition, the overall surveyed mean across the three zones was also compared with the mean of the country sorghum productivity sourced from CSA, 2015 data.

2.4 Results and discussion

2.4.1 Demographic descriptions and socioeconomic aspects

A total of 180 smallholder farmers (60 per administrative zone) who had planted sorghum during the 2014 main cropping season were interviewed. The respondents' gender, family size, age, education background and number of farm animals owned are summarized in Table 2.2. The percentage of male farmers was higher than female farmers in the surveyed zones except in the South Wello Zone. The Oromia Special Zone had a higher percentage (80%) of interviewed male farmers than the North Wello Zone. The South Wello Zone had the lowest percentage (46.7%) of interviewed male farmers. The South Wello Zone had the highest percentage of female sorghum growers (53.3%) while Oromia Special Zone had the lowest percentage (20%) followed by North Wello Zone (28.3%). There were statistically significant gender differences ($P \leq 0.05$, $X^2=16.118$, df=2) across the three sampled administrative zones. Despite the above gender imbalance during the interview, female farmers were purposely included in the focus group discussion to collect reliable information on the food making quality of sorghum varieties.

In all the surveyed zones except the South Wello Zone most of the interviewed sorghum growers had family sizes of less than five. The North Wello Zone had the most interviewed farmers with a family sizes of less than five (58.3%) followed by Oromia Special Zone (53.3%). Of all the respondents, 37.0% had a family size between 5 to 6. Only a limited number of interviewee had a family size greater than seven, with the most (11.7%) being in the Oromia Special Zone. Focus group discussions revealed that family size has a vital role in the rural farming systems of the three surveyed zones. Adult males not too old to work provide the bulk of family labour, together with boys of > 9 years old, who often help with field activities. Married women, particularly those with children > 9 years old, are mostly responsible in house work, to fetch water, to nurture children, to collect firewood and to sell grain in small quantities in the local markets. In addition, women actively participate during sorghum planting and harvesting activities which are the most labour intensive activities. Sorghum planting periods are very critical in the three surveyed zones of north eastern Amhara. The time of planting should be carefully scheduled due to: 1) unpredicted falls of first rain; 2) the necessity of planting as large area as shortly as possible with the onset of rain; and 3) to escape seeding late rains for drought management. The farming system forces farmers to undertake intensive field activities with whole family working from sunrise to sunset. In female headed households, it is normal to see women working in the fields. Relatively large farmland owners mobilise extra labour through working groups (teams) of neighbours, commonly known as “Debo” or “Wonfel”. At the critical stages of a busy agricultural season, team work helps to keep the morale of the farmers. It is also an effective means in time management. A Debo is a team of people working together to support family relatives or intimate friends who have a labour shortage at the stages of planting, weeding or harvesting. A Wonfel is a relatively a small group of people working cooperatively at a village level to complete the tasks of planting, weeding, harvesting and threshing. Each Wonfel member receives these services in rotation on a scheduled timeframe.

The North Wello Zone had the highest percentage (46.7%) of respondents aged less than 45 years, while South Wello had the lowest percentage (36.7%) proceeded by Oromia Special Zone (45%). South Wello had the highest percentage (58.3%) of respondents aged between 45 to 65 years. More (23.3%) respondents aged above 65 years old were interviewed in North Wello with fewer interviewed in Oromia Special Zone (10%) and the least in South Wello (5%). A majority (44.4%) of respondents were between 45 to 65 years of age. Inclusion of 12.8% of respondents aged more than 65 years accessed their long term knowledge of sorghum diversity and sorghum cultivation trends.

The South Wello Zone had the most illiterate farmers (45%). In the same zone 31.7% of the respondents are able to read and write. The Oromia Special Zone had fewest illiterate farmers (36.7%) followed by the North Wello Zone (38.3%). Education has an indispensable effect on the lives of rural farming community. The focus group discussion revealed that farmers who are able to read and write acted as positive role models for others around them. A more highly educated community may also lead to more active participation in all developmental activities, and in particular in resource management.

Livestock rearing is an integral part of the farming systems of the north eastern Amhara. Local breeds of cattle, sheep, goat, donkey, camel and chicken are reared by households. Cattle graze in community pastures and farm borders while goats and sheep range freely over domestic sites and scrublands. The Oromia Special Zone had the highest percentage (38.3%) of respondents who had less than 4 farm animals, while South Wello had the lowest percentage (28.4%) followed by the North Wello Zone (31.7%). The South Wello Zone had the highest percentage

(48.4%) of respondents who kept between 4 to 7 farm animals per household while the North Wello Zone had the lowest percentage (35%), followed by Oromia Special Zone (38.3%). The North Wello Zone had the highest percentage (33.3%) of respondents who had more than 8 farm animals per household while in South Wello and Oromia Special Zones this was 23.3% of respondents. Experienced farmers in the focus group discussions pointed out that the ownership of cattle was directly related to the availability of forage for them. The commonly used animal feed residues were tef straw, weeds collected from farm fields and sorghum stalks. Farm animals, particularly oxen, are the main source of draft power in the lowland sorghum growing agro-ecologies of north eastern Amhara. From focus group discussions, it was learned that traditional plowing with oxen is the most common way of land preparation, therefore most of the surveyed farmers owned at least a pair of oxen. A few farmers across the three zones had one ox. These farmers pair with another single ox owner in the village (locally referred to as ‘mekenajo’) to cultivate their lands based on mutual agreements.

A survey previously conducted in South Wello, North Shewa and Metekel administrative zones in 2011 the mean farm size of each interviewed household was 2.34 ha^{-1} (Gebretsadik et al., 2014). This finding concurs with the present study, where in the South Wello Zone the mean farm size was 1.44 ha (Amelework et al., 2016). Similarly, the mean farm size in the Oromia Special Zone was 2.0ha^{-1}.

Table 2.2 Proportion of respondents aggregated by sex, family size, age, education level and farm animals owned across the three study zones(N=180) in the north eastern Ethiopia

Variables	**Zone**			**Total**
	North Wollo	**South Wollo**	**Oromia Special**	
Sex				
Male	71.7	46.7	80.0	66.11
Female	28.3	53.3	20.0	33.89
Family size (number of individuals)				
<5	58.3	45.0	53.3	52.2
5-6	33.3	45.0	35.0	37.0
>7	8.3	10.0	11.7	10.0
Significance	*df= 4*	X^2= *2.641* [a]		*P-value =0.620*
Age (years)				
<45	46.7	36.7	45.0	42.8
45-65	30.0	58.3	45.0	44.4
>65	23.3	5.0	10.0	12.8
Significance	*df= 4*	X^2=*14.665* [a]		*P-value = 0.005*
Education level				
Illiterate	33.3	35.0	31.7	33.30
Read and write	25.0	33.3	31.7	30.00
Grade 3-6	20.0	10.0	25.0	18.30
Grade 7-8	13.3	16.7	8.3	12.8
Grade 10 or 12 complete	8.3	5.0	3.3	5.60
Significance	*df= 8*	X^2= *7.748*[a] ,		*P-value = 0.458*
Number of farm animals owned				
<8	16.7	35.0	18.3	23.30
9-11	30.0	45.0	23.3	32.80
>12	53.3	20.0	58.3	43.90
Significance	*df= 4*	X^2= *21.668*[a]	*P-value =0.000*	

2.4.2 Cropping system

Crop production was the leading livelihood activities of all households in the surveyed areas. The predominant cropping practice was sole cropping. Transect walks across the six selected kebeles showed that crop rotation is only limited to few crops. Almost all agricultural fields were predominantly covered by sorghum and tef. The main crop production period occurs during summer (‘meher’) season during the months of April to December. In some areas double cropping is a common farming practice as a result of effective rainfall in the months of January, February and March, which is commonly known as the spring (‘belg’) season. Overall, in the study areas farmers relay on their sorghum and tef crops. They are not practicing crop rotation much due to unpredictable rainfall conditions which are inadequate to support other crops. Crop rotation enhances efficient resource utilization, minimizes weather risks, and reduces insect pest and disease prevalence (Cothern et al., 2000). It is reported that a sorghum crop yields 6 tons per hectare by taking up about 105 kg nitrogen, 15 kg each potassium and phosphorus from the soil (Hulse, 1980). In the north eastern Amhara recurrent drought conditions minimize farmers' crop choice option.

The mean area cultivated per crop depended on the total land holding, and the priority that each farmer attaches to a crop, the number of crops cultivated per household and the agro-climatic conditions of the area. Annual crops are grown for household subsistence. Sorghum and tef are the staple foods grown during the main cropping season. These two crops constituted 54.6%, 61.8% and 94.1% of the total area devoted to cereal production in South Wello, North Wello and Oromia Special Zones, respectively (CSA, 2015). In addition, chickpea, barley, haricot bean, soybean, mung bean, sesame and maize were also grown with smaller land allocations. Sorghum is known to have a relatively long growing period. Consequently, it was usually the first to be planted as a main season crop in the north eastern part of Amhara. It was planted between mid-April to the first week of May annually for a harvest during November and December. During the main cropping season, time of sorghum planting varied from place to place, with most planting done in April, depending on the start of the main rains in a given location. The method of planting of all crops was hand broadcasting and often a given field was planted at one time. Farmers have their own experience of seed rate that may be adjusted based on soil fertility, moisture content of the soil, planting time and variety used. Focus group discussions indicated that the onset of 'belg' rain appeared to be shifting towards the 'meher' season, perhaps due to climate change. This has left the farmers to grow only one crop of sorghum reducing production and productivity.

Crop weeds are not a major problem in the study areas, given that most farmers owned smaller landholdings and weeds were removed by family labour. However, the parasitic weed *Striga hermonthica* was reported to be a production constraint. Households in the surveyed zones have excess labour relative to the land they have. As such, weeding was done at least twice. Farmers weeded until resemble no weeds left, or the numbers of weeds were trivial. In some cases farmers left weeds with the current crop so that it could be used as animal feed using a cut and carry method.

2.5 Importance of sorghum

The three surveyed zones are drought prone areas characterized by semi-arid and arid environmental conditions. The areas experienced erratic rainfall with poor distribution. Early cessations of rainfall and high temperatures were common scenarios across the three zones. This made sorghum the best potential crop across the study areas. Sorghum is a C_4 plant predominantly grown in environments subjected to high temperatures and water limitation (Edwards et al., 2004).

Respondents were asked to estimate their sorghum yields per unit area during the 2015 cropping season. Table 2.3 summarises their responses, showing the significant differences ($P \leq 0.05$) of sorghum productivity across zones. The mean yield reported in Oromia Special Zone was 4.5 t ha^{-1}, which was the best performance than the overall mean of 3.6 t ha^{-1}. In the North Wollo Zone the mean sorghum yield was the lowest (2.8 t ha^{-1}) (Table 2.3). The national mean yield of sorghum is 2.37 t ha^{-1}(CSA, 2015). In general sorghum productivity assessed in the three administrative zones were positive relative to the zonal and country yield levels.

Table 2.3 Significance tests of surveyed sorghum productivity across the study zones and mean sorghum reference productivity ASRP of the year 2015, N=North Wello Zone, S= South Wello , O= Oromia Special Zone and E=Ethiopia

Zone	Mean	ASRP	t-value	P-value
North Wello	2.83 (0.17)	1.8	6.0	0.0001
South Wello	3.55 (0.21)	2.3	5.8	0.0001
Oromia Special	4.49 (0.22)	2.4	9.3	0.0001
All Zones	3.62 (0.13)	2.4	9.6	0.0001

Table 2.4 summarises the results of the focus group discussions held in the study areas during November and December 2014. After harvest, sorghum grain was usually used to make of injera (flat bread), qollo (roasted grain), nifro (boiled), chibeto (kitta or chapatti mixed with noug or sesame), kitta (chapatti), porridge, soup and tella (local beer). Women farmers who participated in the focus group discussion explained that they made sorghum injera daily to increase its

palatability. Typically, sorghum injera has a dry texture with a lower palatability one or two days after cooking than tef injera. Eating of sorghum as chapatti with milk was common in the lowlands of the north eastern Amhara.

A highly significant number (68.3%) of interviewed farmers indicated that they mixed their sorghum landraces during planting to improve the food making quality of sorghum. Further, farmers planted mixtures of different maturity groups to reduce resource competition because the reproductive stage of sorghum, in the flowering, heading and grain filling stages, the crop enters into a high resource intake situation for its source-sink balance. Farmers also practiced mixing of different sorghum maturity groups to have food access for an extended period of time. They grew also different sorghum landraces in one season on a single farm for the preparation of different foods from sorghum. During focus group discussion women farmers explained that sorghum landraces such as Chobye, Jameyo, Degalete and Zengada are very good for the preparation of porridge, injera, tela and soup, respectively. As shown Table 2.4 there was a statistically highly significant difference ($P \leq 0.05$) among farmers reason for mixing sorghum landraces during planting.

Table 2.4 Summary of farmers' reasons for mixed plantings of sorghum landraces

Reasons	1st	2nd	3rd	4th	Total
To reduce resource competition among different maturity groups.	31.7	68.3	0.0	0.0	100.0
To improve food making quality	68.3	30.0	1.7	0.0	100.0
To have a continuous supply of food based on maturity	0.0	1.7	46.7	51.7	100.0
To have sorghum grains for beer, injera and porridge making in one season	0.0	0.0	51.7	48.3	100.0
Significance	df=9		X^2=799.2	P-value=0.000	

Sorghum had a special economic, cultural and psychological significance in the livelihoods of rural households of the surveyed zones. In these areas maize does not perform well due to regular drought conditions. The three most important uses of sorghum were to prepare pure sorghum injera, sorghum chapattis and mixed sorghum and tef injera, which were reported by 38.3%, 35% and 26.1% of respondents, respectively (Table 2.5).

Table 2.5 A summary of cross tabulation analysis on sorghum utilization by farmers across the three study zones

Utilization	1st	2nd	3rd	4th	5th	Total
Injera (pure sorghum)	38.3	51.1	10.6	0.0	0.0	100.0
Injera mixed with tef	26.1	26.1	45.0	2.8	0.0	100.0
Porridge	0.0	0.0	9.4	47.8	42.8	100.0
Alcoholic drink	0.6	0.0	5.6	37.2	56.7	100.0
Chapatti	35.0	24.4	28.3	11.7	0.6	100.0
Significance	df =16		X^2 =825.546[a]		P-value = 0. 000	

Sorghum was indicted as a crop that provide food needs at time when the majority of households had exhausted their previous year grain stores. A farmer growing tef has to wait until the crop is harvested and threshed at ground before it can be consumed. Sorghum also provides feed for cattle starting from early in June (a stage of early cultivation to reduce the plant population, locally referred as ‘shilshalo’) until harvest. Leaves, chaffs, and unproductive tillers are the main animal feed sourced from sorghum. Table 2.6 summarises the main reasons why farmers grew to grow sorghum year after year. The main reasons were the availability of rainfall in April, and the drought tolerance of the crop. These were ranked first and second (57.8%) and (41.7%), respectively. Limited crop options ranked third (42.8%) followed by the good productivity of the crop (38.9%). The good productivity of sorghum also ranked fourth (55%) followed by limited crop option (42.8%) in area cultivated (Table 2.6). Good biomass productivity and extended family size ranked fifth with 55% and 41.7%, respectively.

Table 2.6 Percentage and count of farmers of the reasons why they would like to grow sorghum year after year in the three study zones

Reason for cultivating sorghum	Rank of reasons						Total
Rank	1st	2nd	3rd	4th	5th	6th	
Drought tolerance	41.7	45.6	12.8	0.0	0.0	0.0	100.0
Good gain yield	0.6	0.6	38.9	55.0	1.1	3.9	100.0
Good harvestable biomass	0.0	0.6	0.0	1.1	55.0	43.3	100.0
Availability of rainfall in April	57.8	41.7	0.6	0.0	0.0	0.0	100.0
Extended family size	0.0	0.0	8.9	2.2	41.7	47.2	100.0
Limited crop option	0.0	7.8	42.8	45.6	1.7	2.2	100.0
Significance	*df=25*		X^2=1785.433[a]			*P-value =0.000*	

2.6 Other crops grown in the study zones

Table 2.7 summarises other crops grown next to sorghum in the surveyed zones. These included tef, maize, chickpea, sesame, soybean, mung bean and barley in decreasing order of importance. Tef (33.3%), maize (25.6-27.8%) and chickpea (15.6-20%) were cultivated widely in the three zones. Barley production was not widely practiced in the North Wello and Oromia Special Zones because of the high temperatures and low altitude being unsuitable for the crop. Due to limited farm size and low productivity, the amount of sorghum grain available to sell was small. However, sesame, mung bean and chickpea were cultivated largely to sell. Farmers sell their produce in local markets after they meet the family needs. Focus group discussions revealed that grain and oil crops (e.g. noug) were sold in December–February to buy clothing, to pay debts, school fees and transport fees, and to purchase house supplies (e.g. pepper, coffee and spices) and for payments for various social events. The South Wello Zone had the highest percentage (27.8%) of respondents who had grown maize, while the North Wello Zone had the lowest percentage (25.6%) of respondents next to Oromia Special Zone (26.7%). There was statistical significant difference among crops grown across the three administrative zones.

Table 2.7 Other crops grown in the three study zones during 2015

Zone	Sesame	Tef	Soybean	Chickpea	Maize	Barley	Mung bean	Total
North Wello	11.1	33.3	7.8	18.3	25.6	0.0	3.9	100.0
Oromia Special	11.1	33.3	6.7	20.0	26.7	0.0	2.2	100.0
South Wello	2.8	33.3	7.2	15.6	27.8	7.8	5.6	100.0
Significance	df=12			X^2=41.902[a]			P-value =0.000	

2.7 Trend of sorghum cultivation

East African countries including Ethiopia, Kenya, Burundi, Rwanda and Tanzania experienced about 15% rainfall variability from 1979 to 2005, resulting in followed by drastic losses in food production and increased food insecurity (Funk et al., 2008; Lobel et al., 2008). In north eastern Ethiopia, the erratic rainfall impacted on traditional sorghum farming, although drought is a common challenge for the lowland farming communities of Ethiopia. The region experienced a severe drought during 2015, which caused major social and economic impacts. As a result of increased climatic changes, areas that previously cultivated faba bean, lentil and barley are shifting to sorghum, mung bean, soybean and lowland oil crops. Sorghum has become the most important crop because of its ability to grow under arid and semi-arid conditions. Among farmers interviewed, 78.3% in the North Wello Zone, 73.3% in South Wello and 71.7% in Oromia Special Zone explained that cultivation of sorghum was increasing despite its variable productivity. Respondents from Oromia Special Zone (28.3%), North Wello (21.7%) and south Wello (26.7%) perceived that the state of sorghum cultivation was constant (Table 2.8).

Table 2.8 Farmers perceptions of changes in sorghum production

Zone	Constant	Increasing	Total
North Wello	21.7	78.3	100.0
Oromia Special	28.3	71.7	100.0
South Wello	26.7	73.3	100.0
Significance	df=2	X^2=0.759[a]	P-value =0.684

Sorghum cultivation increased from time to time in the study areas (Table 2.9). This was mainly in the area coverage by replacing crops like tef, chickpea, maize, soybean, mung bean and sesame in north Wello and Oromia Special Zones in the order of decrease of replacement percentage. The highest percentage (33.3%) of respondents across the three zones perceived that sorghum cultivation increased through minimized farm size allocated to tef. It was noted that sorghum has been largely grown under higher altitude areas such as in south Wello Zone of Ancharo Kebele. Chickpea, maize and mung bean were replaced by sorghum almost in a similar fashion across the three zones. Table 2.9 showed a similar trend of sorghum cultivation replacing other crops showing non-significant ($P \leq 0.05$) differences. A greater number of interviewed farmers allocated their plots for sorghum production instead of tef, soybean, chickpea, and maize crops.

Table 2.9 Crops replaced by sorghum across the three study zones

Zone	Tef	Sesame	Soybean	Barley	Chickpea	Maize	Mung bean	Total
South Wello	33.3	2.8	13.5	0.0	27.0	17.7	5.7	100.0
Oromia Special	33.3	2.3	13.2	0.0	27.1	18.6	5.4	100.0
South Wello	33.3	0.8	10.6	4.5	27.3	18.9	4.5	100.0
Significance	df= 12			X^2=14.638[a]			P-value = 0.262	

2.8 Constraints to sorghum production

In Ethiopia about 1.83 million hectares of land is devoted to sorghum production every year. About 4.34 million tons of grain is produced with mean productivity of 2.37 t ha^{-1} per annum exclusively by about 5 million smallholder farmers (CSA, 2016). During the past two decades production area and total production of sorghum have increased considerably. However, productivity per unit area stagnated due to biotic and abiotic production stresses and socio-economic factors. Table 2.10 summarises the most important constraints that affected sorghum production in the study areas. Sorghum production is challenged by various constraints associated with the harsh growing environment where other crops are unable to perform well and other socio-economic aspects (Wortmann et al., 2006).

The most important production constraints affecting sorghum production include poor stand establishment, drought stress, unavailability and unaffordability of improved production packages, low yield potential of local landraces, a lack of an improved seed system, a lack of farmer preferred improved varieties, poor soil fertility and a lack of attention by policy makers. The most important biotic stresses of sorghum include insect pests such as stalk borer (*Chilo partellus*), sorghum shoot fly (*Atherigona soccata*) and sorghum chaffers (*Pachnoda spp.*), diseases such as anthracnose (*Colletotricum graminicola*), leaf blight (*Exserohilum tiorcicum*), and sorghum panicle diseases especially head smut (*Sphacelotheca peiliana*), grain mold (*Aspergillus Sp.*) and red billed quelea (*Quelea quelea*) bird and *Striga* (*Striga hermonthica*) weed (Wortmann et al., 2006; Gebretsadik et al., 2014; Beyene et al., 2016).

In the present study the most important production constraints described by interviewed farmers were drought, *Striga* and a lack of improved cultivars with farmers-preferred traits, followed by the cost of production inputs (fertilizers etc), poor stand establishment and poor soil fertility. These were rated as moderate to severe production constraints (Table 2.10). Most of farmers (71.4%) considered that insects, birds, limited use of production packages and lack of attention by policy makers were relatively less severe sorghum production constraints. Focus group discussants in the North Wello Zone of Kobo Woreda revealed that the effect of head smut disease was severe, whereas stalk borer was the main challenge of farmers in Oromia Special Zone, occurring after the May rainfall, i.e., before the sorghum plants reached knee height. These production stresses, coupled with high temperatures and drought, hamper growth, development and final yields of sorghum (Prasad et al., 2008; Hammer et al., 2010; Nguyen et al., 2013; Singh et al., 2015).

Overall, farmers rated drought as the most challenging sorghum production constraint reported by 44.8% and 29.1% of respondents as being a very severe and moderately severe constraint, respectively. *Striga* infestation was reported by 23% of interviewed farmers in the study areas. Gebretsadik et al. (2014) reported that in North Wello and Metekel Zones *Striga* was the first biotic constraint to sorghum production.

Table 2.10 Farmers' ratings of the severity of the primary abiotic and biotic sorghum production constraints across the three study zones of the north eastern Amhara, Ethiopia during 2015

Abiotic and biotic constraints	Highly severe	Moderately severe	Less severe	Total
Drought	44.8	29.1	0.0	34.4
Striga	23.0	0.0	0.0	11.1
Lack of farmer-preferred improved varieties	12.6	5.1	0.0	8.3
Low yield potential of local landraces	5.7	11.4	0.0	7.8
Lack of policy attention to the crop	4.6	3.8	7.1	4.4
Lack of improved seed system	3.4	8.9	0.0	5.6
Insect pests	2.3	5.1	35.7	6.1
Birds	2.3	3.8	28.6	5.0
Diseases	1.1	6.3	0.0	3.3
Limited access and affordability of production packages	0.0	11.4	28.6	7.2
Poor soil fertility	0.0	10.1	0.0	4.4
Poor stand establishment	0.0	5.1	0.0	2.2
Significance	df = 22	X^2 = 115.452[a]		P-value = 0.000

2.9 Impact of drought

Drought is a constant problem of crop and livestock production in Ethiopia. It is especially important in the lowland and mid-altitude regions of the country. Severe droughts now occur frequently. In the north eastern Amhara Region of Ethiopia, crop production is mainly rainfall dependent. Use of irrigation is confined to small area which are adjacent to main rivers. Where irrigation is available, farmers grow high value crops such as tomato, onion, green maize, cabbage, carrot, lettuce and tropical fruit to earn cash.

In the north eastern Amhara region drought has historically caused multidimensional economic, social, and environmental disruption. Poor crop production and productivity, the absence of agriculture based industries, reduced employment in agriculture, increased costs of transport for water and food, and strains on financial institutions are typically among the major drought induced economic problems. Drought causes negative social impacts leading to shifting settlements, disintegration of extended families, social losses, change in social values, disruption of sociocultural institutions, disturbance of inter-caste relations, and conflicts are water and other resources among communities. The most severe socio-economic impacts of drought have been the loss of crop and livestock genetic resources, increased prevalence of diseases and insect pests, poor crop performance, high levels of livestock mortality, forced sale of land and sale of household and personal assets and water insecurity. During severe drought conditions, loss of crop diversity, removal of vegetation, overgrazing, wind erosion, increased areas of abandoned and barren lands, and over-exploitation of ground water are among the most negative bio-physical impacts of drought.

Some crops that were common in the past have become rare as a result of high temperatures coupled with regular severe droughts. Focus group discussions revealed that farmers' crop choices were thus apparently made on the basis of ecological potential, historical antecedents, and the relative economic and social pay-off of different options. Farmers in the study area indicated that sorghum diversity had been drastically affected by drought. The farmers reported that several replanting (two to three times) in the year of drought exhausted their seed stock of valuable local sorghum varieties. Drought also had highly significant effects on the composition of natural vegetation, structure and function (Allen et al., 2010). It also adversely affects photosynthesis and increases species mortality by creating conditions conducive to the increase of plant insect pests and diseases, leading extensive plant mortality, endangering the survival of plant species and accelerating the loss of biodiversity (Wang et al., 2010). In the three surveyed zones in North eastern Amhara Region farmers were able to identify local sorghum landraces lost as a result of the adverse effect of drought (Table 2.11). According to Lanta et al. (2012) extreme conditions of drought and high temperatures aggravate the extinction of species.

Table 2.11 Names of farmers' sorghum varieties lost as a result of severe drought conditions in the north eastern Amhara Region of Ethiopia.

Zone	Name of local sorghum varieties lost due to drought
North Wello	Abola, Kuchibeye Jameyo, Arate Afa Chibete Tekureta, Chobye, Workeye Zengada, Kolebo Rayo, Melete Degalet, Tati, Jeru, Marute
South Wello	Keteto, Gorade, Marute, Gurendo, Achier jamo Nech jeru, Keye Wogene, Tengele, Marute
Oromia Special	Jarse, Marchuke

2.9.1 Drought adaptation and mitigation mechanisms

There were highly significant differences ($P \leq 0.05$) on the ranking of major drought adaption and mitigation practices used by farmers in the lowland sorghum agro-ecologies of north eastern Amhara Region (Table 2.12). To reduce the effects of drought, farmers apply various drought mitigation and adaptation strategies. Most interviewed farmers (69.2%) indicated that planting of medium-maturing sorghum landraces such as Jameyo, Jegurete and Cherekit was their first way of avoiding drought stress. Growing medium maturity sorghum varieties was considered to be the most successful drought coping strategy in the study areas. The listed sorghum landraces have the capability of adapting to late planting with relatively early maturity when compared to long cycle sorghum landraces that are usually affected by both pre-flowering and post-flowering drought stress. All interviewed farmers indicated that they cultivated a mixture of sorghum landraces with different maturity periods in a single field as a second option in order to achieve a reasonable yield. Repeated field ploughing before sorghum planting to increase water holding capacity of the soil and diversion of flood waters into sorghum fields time of heavy rainfall events were the most important drought mitigation mechanisms reported by 64.3 % and 58.9% of interviewed farmers, respectively (Table 2.12). These methods increase moisture in the soil to cope with the uneven rainfall rates in the season planting early maturing sorghum varieties is the fourth drought mitigation option reported by 82.2% of respondent farmers while crop rotation, particularly alternate cultivation of sorghum with tef was regarded a fifth option that was practiced by a significant percentage of respondent farmers (79.2%). Growing sorghum with a reduced plant population during periods of moisture stress was among the drought mitigation mechanisms adopted to ensure maximum productivity of the remaining plants with compensatory yield gains per unit area. Reduced plant population is perceived to be associated with big panicle size and consequently providing better yield in drought prone areas of the north eastern Amhara Region.

Table 2.12 Drought adaptation and mitigation mechanisms used by farmers at three study sites of the north eastern Amhara Region of Ethiopia during 2015

Drought coping mechanisms	Percentage of respondents who ranked a coping strategy				
	1st	2nd	3rd	4th	Total
Growing early-maturing improved sorghum varieties	0.0	0.0	19.8	80.2	100.0
Growing medium-maturing local sorghum landraces	69.2	30.8	0.0	0.0	100.0
Replacing sorghum with other crops	0.0	0.0	79.2	20.8	100.0
Diverting flood waters into sorghum fields	41.1	58.9	0.0	0.0	100.0
Reducing plant populations	0.0	20.0	80.0	0.0	100.0
Repeating ploughing of the soil before planting	0.0	64.3	35.7	0.0	100.0
Mixing varied maturity sorghum landraces	0.0	100.0	0.0	0.0	100.0
Regular weeding	0.0	0.0	9.1	90.9	100.0
Significance	df=21	X^2=1075.848[a]		P-value = 0.000	

2.10 Farmers-preferred traits in sorghum varieties

Knowledge of farmers preferred traits in sorghum varieties and the prevailing climatic conditions of the growing areas are among the overriding prerequisites for launching a breeding program, and to ensure the adoption of these improved varieties. In the study areas, sorghum traits preferred by farmers included high grain and biomass yields, good food making quality, medium-maturity, drought tolerance, *Striga* tolerance, good market price for the grain and adaptability. All respondent farmers preferred high yielding local sorghum landraces as their first choice. During the study period, 49.7% and 44.3% of respondent farmers chose to grow drought tolerant and medium-maturing sorghum landraces, next to high yielding varieties. Farmers perceived that medium-maturity period helped the crop to withstand post-flowering drought problems. The second farmers preferred traits included food making quality, medium-maturity and drought resistance as expressed by 100%, 55.7% and 42.3% respondents, in that order. Other farmers preferred traits included adaptability, good biomass yield and tolerant to *Striga* which were rated as their third choice with 100%, 53.9% and 47%, respectively. Respondents listed some traits like good market price, tolerant to *Striga* and good biomass as their fourth preferred traits showing statistically significant difference among traits chosen under the fourth category.

Table 2.13 Farmers preferred traits in sorghum in north eastern Amhara, Ethiopia.

Farmers-preferred traits	Percentage of respondents who ranked a preferred-trait				
	1st	2nd	3rd	4th	Total
Drought tolerance	49.7	42.3	8.1	0.0	100.0
Good food making quality	0.0	100.0	0.0	0.0	100.0
Medium- maturity	44.3	55.7	0.0	0.0	100.0
High yield	100.0	0.0	0.0	0.0	100.0
Tolerant to *Striga*	0.0	2.0	47.0	51.0	100.0
Good market price	0.0	0.0	0.0	100.0	100.0
Best adaptability	0.0	0.0	100.0	0.0	100.0
Good biomass	5.1	0.0	53.9	41.0	100.0
Significance	df= 21	X^2=834.822[a]		P-value=0.000	

7. Sorghum planting time and farmers preferred maturity groups

In the North Wello Zone 71.7% of interviewees preferred medium-maturing sorghum varieties followed by early maturity and long maturity types with 18.3% and 10.0%, respectively. Number of farmers who preferred long maturing sorghum varieties was the highest in the South Wello Zone (35%) and lowest in the North Wello Zone (10%). North Wello Zone had the most of farmers (18.3%) who preferred early maturity types, while the South Wello Zone had the least farmers (10%) next to Oromia Special Zone (16.7%). In general, the result showed statistically significant differences among the maturity groups preferred by farmers across the three study zones.

The South Wello Zone had the most farmers (90%) who usually planted sorghum from April to the first week of May, depending on the onset of rain fall. The Oromia Special Zone had the most farmers (21.7%) planting from the third week of June to July. This showed that the rainfall from April to May every year was not sufficient to support sorghum crop in the Oromia Special Zone. There was non-statistical difference ($P \leq 0.05$) in percentage of farmers practicing sorghum planting among the three study zones but there were a slight variation of sorghum planting times among the three zones.

Table 2.14 A summary of farmers- preferences (%) on maturity group and planting dates across the three study zones of the north eastern Amhara Region of Ethiopia.

Administrative Zone	Maturity group				Planting time		
	Early maturity	Medium maturity	Long maturity	Total	April to first week of May	End of June to July	Total
North Wello	18.3	71.7	10.0	100.0	81.7	18.3	100.0
South Wello	10.0	55.0	35.0	100.0	90.0	10.0	100.0
Oromia Special	16.7	50.0	33.3	100.0	78.3	21.7	100.0
Significance	df=4 X^2=13.157^a		P-value = 0.011		df=2 X^2=3.120^a	P-value = 0.625	

2.11 Conclusions

The study indicated that productivity of sorghum was challenged by recurrent droughts, *Striga* infestation, insects, birds, diseases, a lack of varieties with farmers-preferred traits and high yield potential, limited policy support, a lack of improved seed system, poor sorghum production practices and application of crop input and poor soil fertility, in a decreasing order of importance. Among the listed sorghum production constraints, severe drought in the post-flowering stage was identified by most interviewed farmers as the leading constraint across the three study zones. Focus group discussions held in each kebele revealed that farmers' had lost numerous valuable local landrace varieties due to extreme drought conditions over the years. It is concluded that a significant number of interviewed farmers preferred to grow medium-maturing sorghum varieties which can be sown at the normal planting time but which would escape post-flowering drought. Sorghum breeding program should be directed at developing farmers' ideal sorghum varieties with high yield, adequate level of drought tolerance and *Striga* tolerance and tall plants with high biomass.

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CHAPTER 3

Agro-morphological characterization of sorghum landraces for drought tolerance and selection of farmers-preferred medium-maturity genotypes under managed stress

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3.1 Abstract

Quantifying the genetic variation among sorghum genotypes in phenological, yield and yield related traits contributing towards drought tolerance is vital for ultimate breeding and conservation. The aim of this study was to characterise sorghum landraces for drought tolerance and to select farmer-preferred medium-maturing genotypes under managed stress condition. The study was conducted using 196 sorghum accessions using a lattice square design with two replications. Sampled genotypes were evaluated at Kobo site of the Sirinka Agricultural Research Center in 2014/2015 in Ethiopia. Data collected from 14 traits were subjected to analysis of variance, correlation and path analysis and principal component analysis (PCA). The results showed significant genotypic differences ($p<0.05$). Medium-maturing sorghum genotypes such as E-72457, E-72438, E-72435, E-206214, E-72449, E-75460 and E-75458 with superior agronomic performance were selecte and recommended for large-scale production or for further breeding under drought prone sorghum growing agro-ecologies of the country. Conversely, genotypes such as E-72435, E-72438, E-206214, E-72457,E-75454 and E-72449 are the top yielding collections and recommended for production or breeding under optimal moisture conditions. Grain yield had significant and positive correlation with yield-related traits assessed under both test conditions. Path coefficient analysis revealed that days to maturity under drought stressed condition and harvest index under non-stressed condition had the highest positive direct effect on grain yield. PCA showed that the first three principal components (PCs) explained 79.4% and 86.78% of the total variation present among genotypes evaluated under non-stressed and drought-stressed, conditions in that order. Overall, the study found marked genetic diversity among the tested genotypes and selected suitable medium-maturing farmers-preferred accessions for effective breeding emphasising drought tolerance and medium maturity.

Keywords: agro-morphological traits, drought tolerance, principal component analysis, sorghum, medium-maturity, grain yield.

3.2 Introduction

Drought is related to limited water availability and lack of rains during main production seasons or for an extended period of time. The severity and frequent occurrence of drought has become a global challenge. Drought is expected to heavily influence global food production in the coming years (Godfray and Garnett, 2014; Magrin et al., 2014). Therefore, there is need to develop drought tolerant and adapted crop genetic resources including sorghum to enhance production and productivity under drought stress condition.

Drought stress affects the molecular, physiological, and morphological mechanisms of the plant, resulting in yield losses higher than all other production constraints combined (Farooq et al., 2009; Sakhi et al., 2014). From physiological and agronomic perspectives, drought tolerance is a loosely defined trait related to water use efficiency; but from the perspective of gene discovery, drought tolerance is a complex trait due to the large number of genes involved, interactions among genes, and genotype by environment interactions (Blum, 2011). Sorghum has strong ability to cope with many types of stresses, including heat, drought, salinity and flood (Ejeta and Knoll, 2007). However, in arid and semi-arid regions, occurrence of post-flowering drought on sorghum may result in premature plant death, stalk collapse and lodging, and a significant reduction in seed size; each of these can result in decreased yield (Rosenow et al., 1996; Tolk et al., 2013; Borrell et al., 2014). Drought stress occurring either at pre-or post-flowering can significantly decrease grain yield. Traits that may be associated with pre-flowering drought tolerance include improved panicle exsertion (Ayeneh et al., 2002) and being stay-green under drought condition (Rajcan and Tollenaar, 1999; Borrell et al., 2000). Longer grain filling duration, and increased individual seed weight are associated with post-flowering drought tolerance (Tuinstra et al., 1997; Borrell et al., 2000; Harris et al., 2007).

In Ethiopia, many sorghum growing areas are vulnerable to recurrent droughts due to shortage and/or uneven distribution of rainfall. In sorghum producing regions, the rain falls late or stops early, making the crop growing period very short, and this leads to crop failures. The irregular rain pattern, coupled with an age-old, subsistence farming system has made areas of the country vulnerable to drought, leading to severe malnutrition and hunger.

Several *Striga* resistant and drought tolerant sorghum varieties have been developed since the inception of the Ethiopian Sorghum Research program in 1957 at the then Alemaya University of Agriculture (now Haramaya University). During 1973 the Ethiopian Sorghum Improvement Program (ESIP) was established with the support of International Development Research Centre (IDRC) of Canada (Yemane and Lee-Smith, 1984). Unfortunately, majority of the varieties developed were not widely adopted in the country since they did not meet the needs and preferences of farmers and consumers. In the country, most farmers are still preferring to grow indigenous sorghum landraces for their biomass yield rather than improved grain yield *per se*. Farmers in this region are still cultivating drought-susceptible, long maturing and low yielding local landraces. Development of sorghum varieties with drought tolerance and medium-maturity would have significant value in the farming system of north eastern Ethiopia. Evaluating the response of genotypes under various environmental conditions is very crucial in determining the tolerance and susceptibility level of test genotypes. Loss of economical yield is the concern of plant breeding researchers and they hence capitalize on yield performance under stress conditions. Thus, drought indices that provide a measure of drought based on loss of yield under drought conditions in comparison to normal conditions have been used for screening drought-tolerant genotypes. Plant breeders have used different selection methods to evaluate genetic differences of genotypes in drought tolerance. Drought resistance has been defined by Hall (1993) as the relative yield performance of a genotype compared to other genotypes exposed to the same drought stress condition. Drought susceptibility of a genotype is often measured as a function of the reduction in yield under drought stress, whilst the values are confounded with the differential yield potential of genotypes (Ramirez-Vallejo and Kelly, 1998). Several evaluation criteria have been proposed to select genotypes based on their performance under stress and non–stress conditions (Mitra, 2001). Rosielle and Hamblin (1981) defined stress tolerance (TOL) as the differences in yield between stress and irrigated environments and mean productivity (MP) as the average yield of genotypes under stress and non-stress conditions. The geometric mean productivity (GMP) is often used by breeders interested in relative performance, since drought stress can vary in severity in field environments over years (Fernandez, 1992). Stress tolerance index (STI) has been identified as a useful tool for determining high yield and stress tolerance potential of genotypes (Fernandez, 1992). Fischer and Maurer, 1978) suggested the stress susceptibility index (SSI) for measurement of yield stability that evaluated the changes in both potential and actual yields in variable environments. The yield index (YI) suggested by Gavuzzi

et al. (1997) and the yield stability index (YSI) were proposed by Bouslama and Schapaugh (1984) in order to evaluate the stability of genotypes in both stress and non-stress conditions.
Low Stress Susceptibility Index value indicates that yield variations of a given genotype is less under stressed condition than under non-stressed condition and is a result of higher stability of that genotype. Therefore, the objective of this study was to characterise sorghum landraces for drought tolerance and to select farmer-preferred medium-maturing genotypes under managed stress condition for breeding.

3.3 Material and methods

3.3.1 Study sites

The study was conducted at Kobo research site of Sirinka Agricultural Research Center in north eastern Ethiopia. Kobo is located at 12°8′41.21″N latitude and 39°38′40.50″E longitude at an altitude of 1480 m.a.s.l. in North Wello Zone. It is found some 570 Km away from Addis Ababa. The long term average annual rainfall at Kobo is 833 mm and the mean maximum and minimum air temperatures in the area are 27.2 and 14.1^{o}C, respectively. The area has unimodal rainfall pattern. The main rainy season is from June to September. The major crops grown in the study area include tef (*Eragrostis tef*) and sorghum (*Sorghum bicolor*).

3.3.2 Plant materials

The study used a total of 196 sorghum accessions. The details of plant materials are presented in Table 3.1 along with their original collection areas. All sorghum accessions used in the study were kindly supplied by Ethiopian Biodiversity Institute (EBI). These accessions were originally collected from three administrative zones of the Amhara Regional State namely from North Wollo, South Wollo and Oromiya Special Zones. From the total 196 sorghum accessions 83 accessions were collected from three woredas (Gubalafto, Raya Kobo and Habru) of North Wollo administrative zone, 71 from three woredas (Ambasel, Kalu and Tehuledere) of South Wollo and the remaining 42 were collected from three woredas (Kemise Zuria, Harbu and Jille Timuga) of Oromiya Special Zone. The accessions were evaluated, both under drought stressed and non-stressed conditions.

Table 3.1 Population, collection zones, number and name of 196 sorghum genotypes used in this study

Collection area		**No of genotypes**	**Genotype name**
Zone [a]	**Woreda [b]**		
South Wollo	Ambasel	29	E-72435, E-206100, E-200070, E-71382, E-211236, E-72477, E-75454, E-72443, E-72439, E-202507, E-69213, E-69214, E-69215, E-69216, E-69217, E-69246, E-69247, E-69248, E-69250, E-69251, E-69252, E-70774, E-71082, E-71160, E-71245, E-212637, E-212638, E-212639 and E-212641
	Kalu	19	E-72457, E-72449, E-75458, E-206213, E-75452, E-74097, E-210973, E-212642, E-212643, E-212644, E-212646, E-213353, E-214837, E-214840, E-214841, E-214842, E-214843, E-214845 and E-214846
	Tehuledere	23	E-75460, E-75453, E-75457, E-214848, E-214849, E-214852, E-21484, E-214855, E-214856, E-215725, E-215726, E-217703, E-226055, E-226056, E-226057, E-226058, E-228108, E-228109, E-228113, E-228115, E-228116, E-228251 and E-228252
North Wollo	Guba Lafto	26	E-72444, E-210952, E-211239, E-201444, E-72445, E-72475, E-75274, E-75272, E-228253, E-228254, E-229887, E-229898, E-236216, E-236217, E-239144, E-239145, E-239146, E-239147, E-239152, E-239154, E-239158, E-239160, E-239161, E-239163, E-239164 and E-239167
	Habru	23	E-20006, E-201319, E-72620, E-239169, E-239170, E-239173, E-239175, E-239176, E-239177, E-239179, E-239183, E-239184, E-239185, E-239186, E-239187, E-239188, E-239191, E-239192, E-239193, E-239195, E-239196, E-239197 and E-239198
	Raya Kobo	34	E-72438, E-206214, E-212636, E-206215, E-72446, E-201318, E-210953, E-206112, E-72437, E-211240, E-211235, E-210972, E-210951, E-210971, E-75273, E-202508, E-243645, E-243646, E-243647, E-243648, E-243650, E-243651, E-243652, E-243653, E-243654, E-243655, E-243656, E-243657, E-243658, E-243659, E-243660, E-163, E-146 and E-141
Oromiya Special	Kemise Zuria	11	E-239201, E-239202, E-239203, E-239204, E-239205, E-239206, E-239207, E-239208, E-239217, E-239218 and E-239221
	Harbu	18	E-239225, E-239230, E-239231, E-239232, E-239233, E-239238, E-239240, E-239241, E-239242, E-239243, E-239244, E-239245, E-239246, E-239248, E-239250, E-242036, E-242037 and E-242039
	Jille Timuga	13	E-211237, E-200013, E-72476, E-242040, E-242046, E-242047, E-242048, E-242049, E-242050, E-242051, E-242052, E-242053 and E-242054
Total		196	

[a] A zone is a large administrative unit below a regional state and composed of a number of Woredas.

[b] A Woreda is an administrative level which is equivalent to a district and composed of a number of Kebeles.

3.3.3 Experimental design and field establishment

One hundred ninety-six lowland sorghum accessions randomly drawn from the gene bank collections were sown under managed stress condition. Genotypes planted under rainfed condition experience moisture stress at pre-flowering and post-flowering growth stages of the crop. For non-stressed experiment, supplementary irrigation was applied every 10 days from planting to grain filling stage. Supplementary irrigation was applied to ensure normal crop growth and development.

The study was conducted in 2014/2015 main cropping season using a lattice square design with 14 blocks and 14 incomplete blocks with two replications. Fourteen entries were assigned in each incomplete block. Figure 3.1 displays performance of sorghum genotypes planted for drought screening experiment under managed stress condition. Seeds were manually drilled in to two rows of 3m long with inter-row spacing of 0.75m intra-row spacing of 0.20m with two replications. The total harvestable plot area was 4.5m^2. Each replication fitted in an area of 21m x 61.5m. All plots were fertilized with 100 kg ha^{-1} DAP and 25 kg ha^{-1} urea at the time of planting and additional 25 kg ha^{-1} urea was applied when plants reached a height of 60cm after thinning. Weeds were removed manually as they appeared.

Figure 3.1 Partial view of screening trial under irrigation condition at Kobo

3.3.4 Data collection

The following data were collected: seedling vigor (SV), days to flowering (DF), grain filling period (GFP), days to maturity (DM), plant height (PH) and number of green leaves at harvest (NGL). At maturity, grain yield and major yield components including panicle length (PL), panicle exertion (PE), panicle weight (PW), panicle yield (PY), thousand seed weight (TSW), above ground biomass (AGB) and harvest index (HI) were recorded in all testing conditions. Traits were recorded following IBGR/ICRISAT sorghum descriptors (IBGR and ICRISAT 1993). Seedling vigor was assessed at the time of thinning approximately 25 days after emergency, with a scale of 1 to 5. Well vigor genotypes were rated 1 and poorly vigor genotypes were rated 5. Days to flowering and days to maturity were recorded on plot basis. Days to flowering was measured as the number of days from planting to when approximately 50% of the plants in a plot reached half bloom stage. Days to maturity was recorded as the number of days from planting to when seeds on 50% of the plants in a plot showed black layer from seeds at the base of the panicle. Grain fill duration was measured as the number of days between days to flowering and days to maturity. Plant height was measured as the average height of the plant from the ground to the tip of the panicle at maturity. Panicle exertion was measured as the average exertion of the panicle from flag leaf’s blade to the base of the lowest panicle branch at maturity. Number of green leaves were measured by counting the number of green leaves at maturity. Panicle length was measured as the average length of the panicle from the lower panicle branch to the tip of the panicle at maturity and panicle width was measured as the average width of the panicle at its widest section. Thousand seed weight was recorded as the weight of one thousand kernels sampled from bulk seeds from all heads in each plot. Panicle yield was measured as the weight of the seed threshed from individual panicles and panicle weight was measured as the weight of the un-threshed head. Above ground dry matter was measured as the average weight of the above ground plant part including the grain at maturity and harvest index was estimated as a ratio of mean grain yield to mean yield of above ground dry matter. The average of measurements taken from 10 plants in each plot was used in the analysis. Grain yield was recorded as the total weight of the grain harvested from each plot. Data on grain yield, PY, TKW and PW was adjusted to 12.5% moisture for data analysis.

3.3.5 Data analysis

Data were subjected to statistical analysis using GENSTAT software version 16 (Payne, 2013) variance components and mean trait performance of accessions were calculated. The Pearson's correlation coefficients (r) were calculated to describe the relationship between grain yield and other traits. Path coefficient analysis was estimated according to the method suggested by Dewey and Lu (1959). Cluster analysis was performed to estimate values and dendrogram constructed to visualize the relationship among the 196 sorghum genotypes tested under stressed and non-stressed conditions based on the Neighbour-Joining method. Principal component analysis (PCA) were performed using the genotypic trait means to partition the performance of accessions under non-stressed and drought- stressed conditions. Genotypic and phenotypic coefficient of variation and genetic advance as per cent of the mean grain yield were estimated using Singh and Chaudhary (1979).

3.4 Result and discussion

3.4.1 Variation in agro-morphological characteristics

There were highly significant ($P<0.01$) differences among genotypes for all traits evaluated under drought-stressed condition (Table 3.2). Likewise, the analysis of variance for genotypes evaluated under non-stressed condition were highly significant ($P<0.01$) for all measured traits. Both results indicated that the genotypes were divergent showing substantial variation in phenological and yield-related traits useful for sorghum breeding. Coefficient of variation (CV%) for all traits evaluated under both stressed and non-stressed conditions were relatively low and comparable except for number of green leaf counted under stressed condition (Table 3. 2).

Table 3.2 Mean square values and significance tests for grain yield and yield related traits of 196 sorghum accessions tested under managed stress condition at Kobo site in 2014/2015

	Drought-stressed		Non-stressed	
Traits	Genotypes (df=195)	CV(%)	Genotypes (df=195)	CV(%)
SV	3.05080**	7.4	2.66958**	7.3
DF	223.733**	2.7	188.89**	4.1
GFD	47.357**	5.3	88.69**	4.4
DM	249.526**	1.6	199.534**	1.3
PH	179.805**	1.3	282.971**	1.2
PE	19.625**	12.6	35.0873**	8.7
NGL	15.639**	22	27.979**	12.2
PL	217.54**	7.7	220.927**	3.9
PW	1931.37**	3.7	2192.115**	1.5
TSW	107.448**	3.7	124.26**	5
PY	1161.566**	2	1117.264**	2.2
GY	0.89052**	2.6	2.282072**	3.1
ADM	65.9336**	2.2	50.5658**	2.4
HI	19.9018**	5	23.8562**	10.2

Key: SV= seedling vigor; DF=days to flowering; DM= days to maturity; GFD= days to grain filling period; PH= plant height; PE= panicle exertion; NGL= number of green leaf at physiological maturity; PL= panicle length; PW= panicle weight; TSW= thousand seed weight; PY= panicle yield; GY= grain yield; ADM= above ground dry matter; HI= harvest index; df=degree of freedom, **= indicates highly significant difference at $P \leq 0.01$ and CV= coefficient of variation.

3.4.2 Variation in phenological traits under drought-stressed and non-stressed conditions.

The mean performance of fourteen top yielding and five low yielding genotypes evaluated under irrigation condition is presented in Table 3.3. The mean performance of genotypes for DF, GFD and DM were 111, 45.33 and 156.51 days respectively. The ranges were 65 to 129 days for DF, 30 to 73 days for GFD, and 114 to 170 days for DM (Table 3.4). Fast seedling establishment of genotypes under non-stressed condition will shorten the days for flowering, grain filling period and days to maturity whereas slow seedling establishment of genotypes will require more time to reach stage of flowering, maturity and will experience extended grain filling period. Significant genotypic effects were recorded influencing PH in both environments. Long plant height has vital role in the acceptance of a variety by farmers in the study areas. In the current study accessions with the highest plant height scored relatively low grain yield. The mean plant height values were 196.76 and 189.97cm for accessions evaluated under non-stressed and stressed conditions, respectively. For accessions evaluated under non-stressed condition PH ranged from 124 to 227 cm, whereas it ranged from 157 to 225 cm under stressed condition (Tables 3.3 and 3.4). The genotypes tested under both environments also showed significant differences with regards to number of green leaf at physiological maturity. The overall performance of the tested sorghum genotypes indicated that stay-green score at physiological maturity ranged from 5 to 24 and 4 to 24 under non-stressed and stressed conditions, respectively. Among the fourteen top yielding genotypes evaluated, genotype E-72435 recorded stay-green score of 22.75 and 16.32 under non-stressed and stressed conditions, respectively.

The mean performance of fourteen top yielding and five low yielding genotypes evaluated under stressed condition is presented in Table 3.4. The mean performance of genotypes for DE, DF, GFD and DM were 8.14, 87.70, 45.99 and 133.69 days respectively and the ranges were 4 to 8 days for DE, 65 to 127 days for DF, 31 to 60 days for GFD, and 106 to 173 days for DM (Table 3.3). Seedling vigor of genotypes evaluated under stressed condition is summarized in Table 3.4. Number of green leaf counted at physiological maturity has significant role in drought tolerance evaluations in sorghum. In the current study sorghum accessions with relatively higher green leaf number exhibited higher yield levels (Tables 3.3 and 3.4).

3.4.3 Variation in yield and yield related traits under drought-stressed and non-stressed conditions

The variation among genotypes was highly significant ($P<0.001$) for all yield and yield related traits evaluated under non-stressed as well as stressed conditions. Significant genotypic effects were recorded for panicle exertion, panicle length, panicle width, thousand seed weight, panicle yield, grain yield, above ground dry matter and harvest index under both test conditions. The mean performances of sorghum genotypes were significantly reduced for panicle exertion, panicle length, panicle width and grain yield under drought stressed condition. Panicle exertion ranged from 5 to 25 cm under non-stressed and stressed condition. Performance of genotypes for panicle length ranged from 22 to 66 cm with a mean of 39.93 cm under non-stressed condition. Whereas the range under stressed condition was 20 to 65 cm with a mean of 35.63cm. Panicle width also varied among genotypes evaluated in both environments ranging from 98.18 to 231.25 g with the mean value of 159.65 g under irrigation whereas the range was 97.58 to 224.52 g with a mean of 151.39 g under stressed condition. Thousand seed weight and panicle yield also significantly varied among genotypes evaluated under both test conditions (Tables 3.3 and 3.4).

As indicated on Tables 3.3 and 3.4 the overall mean grain yields of genotypes were 5.84 and 4.08 t ha^{-1} in the non-stressed and drought stressed conditions, respectively. Percentage yield reduction due to drought stress was estimated at 30.14% (1.76 t ha^{-1}). The current study also indicated that the genotype designated as E-72435 ranked first and third in grain yield levels under non-stressed and stressed conditions, providing mean grain yield of 3.17 and 2.48 t ha^{-1} in that order. The yield reduction of this genotypes was 36.12% due to drought stress. However, this genotype performed well even under drought stressed condition when compared to the current released cultivars in the country which are reported to be providing a national mean grain yield of 2.4 t ha^{-1}. Therefore, these selections are useful for direct production or for breeding of sorghum cultivars with medium-maturity under areas of the country where erratic and poor distribution of rainfall is the common phenomenon.

Table 3.3 indicates that genotype E-72435 yielded the highest (6.70 t ha^{-1}) among 196 sorghum genotypes tested under non-stressed condition followed by genotype E-72438, E-206214, E-72457, E-75454 and E-72449 in decreasing order of productivity. Under stressed condition genotype E-72457 provided maximum grain yield (4.38 t ha^{-1}) followed by genotype E-72438, E-72435, E-206214, E-72449 and E-75460 in decreasing order of productivity. Therefore, the above medium-maturing sorghum genotypes had better grain yield performance which is above the overall mean grain yield of all entries (Table 3.3). These are potential genotypes ideal for large scale-production or breeding to boost the national average sorghum productivity and to minimize food insecurity.

The high yielding capacity of the above genotypes were associated with their drought tolerance capacity and their reduced physiologically maturity where they matured within four to five months before the onset of post-flowering drought. Therefore, these genotypes are recognized as medium-maturing sorghum types. This suggests that sorghum has the highest pre-flowering drought resistant capability. Drought tolerance capacity of genotypes dramatically reduced during flowering and post-flowering period (Table 3.3). The overall performance of a variety depends on the plant integral activity during the pre-stress, the stress periods and the recovery phases (Vassileva et al., 2011). In general, Tables 3.3 and 3.4 showed varied yield performance of sorghum genotypes under stressed and non-stressed conditions. Therefore, the following genotypes: E-72457, E-72438, E-72435, E-206214, E-72449, E-75460, E-75458, E-206100 and E-75453 were systematically selected to advance breeding of medium-maturing and high yielding sorghum genotypes.

It can be concluded that the above listed genotypes are very important for future sorghum breeding program as a source of useful genes for the development of drought tolerance, medium-maturing and high yielding sorghum varieties which can be adapted in drought prone areas of north eastern Amhara and similar agro-ecologies of the country.

Table 3.3 Mean performance of the top yielding14 and low yielding 5 sorghum genotypes when evaluated under non-stressed condition at Kobo site in 2014/2015

Accessions	SV (scale)	DF (days)	DM (days)	GFD (days)	PH (cm)	PE (cm)	NGL (#)	PL (cm)	PW (cm)	TSW (gm)	PY (gm)	GY (t ha^{-1})	ADM (t ha^{-1})	HI (%)
Top yielding accessions														
E-72435	1.00	70.79	133.18	62.39	164.71	23.43	22.75	60.39	215.82	50.27	169.91	6.70	34.06	18.17
E-72438	1.07	73.29	138.54	65.25	183.86	21.54	19.57	55.96	213.81	52.62	166.49	6.68	36.13	16.98
E-206214	0.96	72.57	131.64	59.07	184.29	19.93	17.50	64.39	221.20	53.44	165.11	6.65	36.72	17.34
E-72457	0.96	83.71	129.54	45.82	179.36	22.07	20.07	50.79	220.14	49.26	167.93	6.11	31.81	19.83
E-75454	1.07	71.75	130.50	58.75	193.11	19.68	21.07	56.18	209.57	44.96	165.36	6.02	35.17	15.91
E-72449	1.04	67.21	118.79	51.57	177.00	21.54	20.18	62.46	229.23	53.87	166.20	6.01	38.44	13.84
E-206100	0.89	68.29	124.82	56.54	184.29	16.68	22.64	63.64	223.06	55.19	162.76	5.91	42.83	12.69
E-201319	1.07	70.00	123.86	53.86	184.50	19.39	20.43	62.93	215.81	47.15	164.44	5.85	40.51	12.21
E-75453	1.18	68.96	127.43	58.46	184.79	14.43	18.21	63.25	214.45	46.16	165.72	5.79	32.65	18.40
E-75460	1.04	79.64	130.71	51.07	179.82	24.39	18.64	51.21	226.44	53.43	164.44	5.43	27.06	19.25
E-200013	1.54	71.82	129.46	57.64	184.14	15.46	18.07	58.32	219.20	43.91	154.15	5.19	30.54	16.93
E-75458	1.64	76.39	124.18	47.79	182.93	22.25	19.82	37.93	204.33	44.40	163.18	5.18	28.59	19.04
E-71382	1.21	70.14	131.82	61.68	184.54	15.36	19.00	61.82	204.68	43.21	164.23	5.13	27.63	18.37
E-72446	1.96	69.89	122.57	52.68	185.32	16.04	19.75	52.50	192.76	42.29	147.00	5.11	35.63	12.27
mean	**1.19**	**72.46**	**128.36**	**55.90**	**182.33**	**19.44**	**19.84**	**57.27**	**215.04**	**48.58**	**163.35**	**5.84**	**34.13**	**16.52**
Low yielding accessions														
E-243656	4.96	88.00	141.71	53.39	211.79	5.93	10.54	31.68	113.31	24.74	83.13	1.58	37.31	4.05
E-239243	4.79	126.89	159.07	32.18	206.14	5.39	10.82	22.89	114.39	26.64	92.38	1.58	43.63	3.69
E-243657	4.93	128.11	165.75	37.64	216.54	5.71	7.96	30.29	126.50	23.48	90.78	1.55	44.36	3.30
E-243659	5.00	123.36	164.86	41.50	214.68	5.54	8.18	23.46	124.32	20.45	76.72	1.38	43.97	3.06
E-163	5.00	88.86	151.14	61.96	217.25	6.11	7.64	27.00	98.54	20.56	76.92	1.32	44.47	3.18
Mean	**4.94**	**111**	**156.51**	**45.33**	**213.28**	**5.74**	**9.03**	**27.06**	**115.41**	**23.17**	**83.99**	**1.48**	**42.75**	**3.46**
Grand Mean	**3.58**	**83.11**	**137.57**	**54.58**	**196.76**	**10.45**	**12.96**	**39.93**	**159.65**	**34.04**	**119.76**	**3.17**	**36.67**	**8.48**
Minimum	**1.00**	**65.00**	**114.00**	**30.00**	**124.00**	**5.00**	**5.00**	**22.00**	**98.18**	**18.56**	**74.98**	**1.29**	**24.84**	**2.93**
Maximum	**5.00**	**129.00**	**170.00**	**73.00**	**227.00**	**25.00**	**24.00**	**66.00**	**231.25**	**65.38**	**171.39**	**6.81**	**46.02**	**21.00**
LSD$_{0.05}$	**0.55**	**7.21**	**3.84**	**5.03**	**5.05**	**1.92**	**3.34**	**3.30**	**4.96**	**3.60**	**5.55**	**0.21**	**1.88**	**1.83**

Table 3.4 Mean performance of the top yielding14 and low yielding 5 sorghum genotypes when evaluated under stressed condition at Kobo site in 2014/2015

Accession	SV (scale)	DF (days)	DM (days)	GFD (days)	PH (cm)	PE (cm)	NGL (#)	PL (cm)	PW (cm)	TSW (gm)	PY (gm)	GY (t ha^{-1})	ADM (t ha^{-1})	HI (%)
Top yielding accessions														
E-72457	1.11	80.57	43.29	123.86	173.18	16.75	14.21	47.32	212.12	46.79	160.67	4.38	23.79	18.64
E-72438	1.00	77.00	53.54	130.54	173.25	13.04	11.89	44.89	200.07	49.42	164.16	4.36	29.29	14.93
E-72435	1.11	72.96	55.21	128.18	158.11	18.00	16.32	54.46	209.91	46.57	169.04	4.28	28.40	15.04
E-206214	0.96	78.46	51.21	129.68	177.18	18.18	13.54	63.00	219.32	48.36	165.52	4.20	25.46	16.50
E-72449	0.68	71.36	36.57	107.93	170.68	20.57	12.25	63.00	221.24	49.52	163.75	4.18	36.96	11.35
E-75460	1.07	87.68	36.07	123.75	173.93	24.32	16.00	34.11	216.22	47.38	162.95	4.11	23.89	17.20
E-75458	1.61	78.82	42.25	121.07	174.96	18.25	14.93	38.07	201.11	41.38	160.23	4.05	22.41	18.25
E-72437	2.11	92.57	42.86	135.43	176.93	12.43	13.82	46.11	209.28	46.79	159.67	3.98	34.44	11.60
E-72444	1.00	105.11	48.54	153.64	177.46	15.46	16.04	26.75	136.97	30.07	158.93	3.97	41.03	9.57
E-206100	1.25	68.82	47.86	116.68	175.43	12.04	14.61	60.07	209.43	45.13	158.48	3.96	40.32	9.85
E-20006	0.96	67.93	42.18	110.11	175.50	16.86	10.75	59.25	204.35	44.50	154.32	3.93	35.79	11.06
E-200070	1.07	95.32	52.25	147.57	177.50	14.93	11.29	60.07	207.80	45.37	158.12	3.93	41.03	9.54
E-75453	1.46	75.29	48.86	124.14	177.71	15.43	13.46	55.93	197.56	39.07	156.24	3.90	21.46	18.19
E-75457	2.04	72.21	46.61	118.82	175.86	14.61	9.89	49.43	191.67	45.31	156.18	3.88	33.96	11.41
Mean	**1.24**	**80.29**	**46.24**	**126.53**	**174.12**	**16.49**	**13.50**	**50.18**	**202.65**	**44.69**	**160.59**	**4.08**	**31.30**	**13.80**
	Low yielding accessions													
E-243659	4.79	102.68	49.18	151.86	209.57	5.54	6.36	22.25	114.30	19.35	75.27	1.45	40.82	3.66
E-243660	4.89	98.39	51.71	150.11	219.54	5.93	6.71	27.61	119.52	20.45	75.26	1.42	41.43	3.39
E-163	5.07	92.36	49.39	141.75	209.50	7.25	6.18	28.96	96.78	18.97	79.14	1.40	40.54	3.50
E-146	5.04	88.68	41.50	130.18	224.32	5.54	6.36	39.25	160.19	31.71	72.77	1.32	30.90	4.22
E-141	4.93	104.57	55.54	160.11	218.25	7.50	6.82	24.61	105.04	20.57	74.08	1.28	41.59	3.06
Mean	**4.943**	**97.336**	**49.46**	**146.8**	**216.2**	**6.3502**	**6.4856**	**28.536**	**119.2**	**22.21**	**75.304**	**1.374**	**39.054**	**3.566**
Grand mean	**4.09**	**87.70**	**45.99**	**133.69**	**189.97**	**8.68**	**8.85**	**35.63**	**151.39**	**30.23**	**112.33**	**2.48**	**33.46**	**7.84**
Minimum	**1.00**	**65.00**	**31.00**	**106.00**	**157.00**	**5.00**	**4.00**	**20.00**	**97.58**	**12.58**	**71.72**	**1.27**	**19.48**	**3.08**
Maximum	**5.00**	**127.00**	**60.00**	**173.00**	**225.00**	**25.00**	**24.00**	**65.00**	**224.52**	**50.42**	**169.52**	**4.47**	**43.38**	**20.69**
LSD (0.05)	**0.64**	**4.91**	**5.19**	**4.42**	**5.11**	**2.31**	**4.10**	**5.77**	**11.66**	**2.38**	**4.66**	**0.14**	**1.54**	**0.83**

3.5 Clustering of sorghum genotypes for yield and yield related traits under drought-stressed and non-stressed conditions

The genotypes evaluated under drought stressed and non-stressed conditions were grouped into five and six clusters, respectively based on their yield and yield related characters (Tables 3.5 and 3.6). Under drought stressed condition, the analysis grouped the 196 test sorghum genotypes in to five clusters of 1 to 81 genotypes (Table 3.5). In increasing order, Cluster II had 1 genotype, Cluster I (29), Cluster IV (35), Cluster III (50) and ClusterV (81). Conversely, the cluster analysis grouped the 196 sorghum genotypes evaluated under non-stressed condition in to six clusters. Clusters I, II, III, IV, V and VI consisted 91, 26, 29, 48, 1 and 1 genotypes, respectively. Under both test conditions majority of the clusters comprised diverse genotypes sourced from the three zones except Cluster II under drought stressed condition and Clusters V and VI under non-stressed condition which all had one genotype each collected from North Wollo.

As summarized in Table 3.5, Cluster I consisted of 29 genotypes of which 7 were selected high yielding types (Table 3.4). Grain yield and days to maturity in this group ranged from 2.94 to 4.36 t ha^{-1} and 107.93 to 136 days, respectively. Cluster I, III and V were dominated by genotypes collected from North Wollo Zone 16, 20 and 37, respectively. Cluster II consisted of only one high yielding genotype (E-72444) which yielded 3.97 t ha^{-1}. Cluster III was the second largest cluster consisting of 50 genotypes which were very poor in their agronomic performance and relatively late maturing. In this group grain yield and days to maturity ranged from 1.28 to 2.94 t ha^{-1} and 117.64 to 163.61 days, respectively. For instance, genotypes E-243660, E-141 and 243659 were the bottom low yielding genotypes clustered under this group. Cluster IV consisted of 35 genotypes of which 6 were selected high yielding ones (Table 3.4). Majority of the genotypes in this cluster had very good agronomic performance next to Cluster I with yield of 3.13 t ha^{-1} and 126.32 days to maturity. The largest cluster, Cluster V, consisted of 81 genotypes which were intermediate performing ones with mean yield of 2.12 t ha^{-1} and 136.79 days to maturity. Majority of the genotypes in this cluster were collected from North Wollo Zone (37) followed by South Wollo zone (23). Among the bottom low yielding genotypes E-163 and E-146 were grouped in this cluster. Thus, genotypes grouped under Cluster I and Cluster IV are important for breeding due to their divergent nature and better agronomic performance. The clustering pattern of genotypes was different under stressed and non- stressed conditions.

Table 3.6 indicated the clustering pattern of genotypes evaluated under non-stressed condition. The clustering pattern was more discriminating than under stressed condition. Cluster I comprised of 92 genotypes which were low yielding with mean grain yield and mean days to maturity of 2.55 t ha^{-1} and 139 days, respectively. Cluster II accommodated 26 genotypes which were the second agronomically better performing ones. In this cluster, grain yield and days to maturity ranged from 2.88 to 6.11 t ha^{-1} and 117.71 to 158.82 days, respectively. Cluster III made up of 28 genotypes which were agronomically the top performing ones. Of the total 14 selected high yielding genotypes presented in Table 3.3, 11 of them were grouped under this cluster. In this cluster gran yield and days to maturity ranged from 3.38 to 6.70 t ha^{-1} and 114.79 to 138.75 days, respectively. There were 48 genotypes belonged to Cluster IV which were agronomically intermediate performing ones. In this cluster grain yield ranged from 1.64 to 4.67 t ha^{-1} with mean grain yield of 2.73 t ha^{-1}. Genotypes, E-243651 and E-141 were placed separately under Clusters V and VI, respectively.

Genotypes collected from North Wollo, South Wollo and Oromiya Special Zones appeared together across clusters. Also, genotypes from the same Zone were distributed across different clusters, indicating variation among genotypes within a given Zone. Distribution pattern of all the genotypes into five and six clusters under stressed and non-stressed conditions, respectively showed the presence of considerable phenotypic differences among the genotypes for most of the traits under consideration. Thus, cluster analysis pattern proved that geographical diversity need not necessarily be related to phenotypic performance. In both conditions, the overlapping of the clustering patterns of the sorghum genotypes hinted lack of strong genotype differentiation, which could mean the presence of gene flow among genotypes.

Overall, the cluster analysis confirmed the presence of variation among genotypes. Besides, the genotypes evaluated under stressed test condition were grouped in Cluster I which were also known for their drought tolerance and high yielding potential. Thus among the clusters presented those clusters which contain drought tolerant, medium-maturing and high yielding genotypes are important for the good by good crossing for future sorghum breeding program.

Table 3.5 Genetic classification of 196 sorghum genotypes evaluated under drought stressed condition showing main clusters based on cluster analysis using group linkage method

Population	Collection zone	I	II	III	IV	V	Total
Genotypes	South Wollo	12	-	13	23	23	71
	North Wollo	16	1	20	10	37	84
	Oromiya Special	1	-	17	2	21	41
Total		29	1	50	35	81	196

Table 3.6 Genetic classification of 196 sorghum genotypes evaluated under non-stressed condition showing main clusters based on cluster analysis using group linkage method

Population	Collection zone	I	II	III	IV	V	VI	Total
Genotypes	South Wollo	32	14	12	13	-	-	71
	North Wollo	39	10	16	16	1	1	83
	Oromiya Special	20	2	1	19	-	-	42
Total		91	26	29	48	1	1	196

3.6 Correlation among traits

The Pearson correlation coefficients among yield and its contributing traits of 196 sorghum genotypes evaluated under non-stressed and stressed conditions are shown in Table 3.7. Grain yield exhibited significant ($P \leq 0.01$) positive association with grain filling duration (r=0.15) panicle exertion (0.90), number of green leaf (0.85), panicle length (0.77), panicle width (0.83), thousand seed weight (0.85), panicle yield (0.91) and harvest index (0.90). However, grain yield showed negative and significant associations with seedling vigor, days to flowering, days to maturity, plant height and above ground dry matter under non-stressed condition.

Under moisture stressed conditions, grain yield had significant and positive correlation with panicle exertion (0.87), number of green leaf (0.81), panicle length (0.76), panicle width (0.88), thousand seed weight (0.92), panicle yield (0.98), harvest index (0.87) whilst exhibiting negative significant correlation with seedling vigor, days to flowering, plant height and above ground dry matter. Information regarding the degree of correlation among various yield and yield related traits is important for selection of desirable genotypes with desirable traits (Ali et al., 2009). Aruna and Audilakshm (2008) emphasized on the importance of yield and yield related traits in the development of high yielding cultivars in sorghum. Generally, the results of correlation analysis presented in Table 3.7 revealed that the genotypes with early vigor, early flowering and early maturity produced more grain yield and scored higher harvest index showing significantly negative correlation.

Above ground dry matter yield was significantly and positively correlated with seedling vigor, days to flowering, days to maturity, grain filling period and plant height, and negatively correlated with the remaining traits under both non-stressed and stressed conditions. Harvest index had significant and negative association with seedling vigor, days to flowering, days to maturity, plant height and above ground dry matter (Table 3.7). Makanda et al. (2010) observed that the grain yield 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 increases. Warkad et al. (2010) revealed that only one character, 1000 seed weight showed highly significant association with grain yield per plant at both genotypic and phenotypic level and among the yield components themselves; days to 50% flowering showed highly significant positive association with days to maturity, plant height, dry fodder weight per plant and number of leaves per plant. planttt

Table 3.7 Correlations coefficients showing pair-wise associations of 15 yield and yield related traits of 196 sorghum genotypes tested under drought stressed (S) and non-stressed (N) conditions.

Traits	ENV	SV	DF	DM	GFD	PH	PE	NGL	PL	PW	TSW	PY	GY	ADM	HI
SV	N	**1.00**													
	S	**1.00**													
DF	N	0.54**	**1.00**												
	S	0.53**	**1.00**												
DM	N	0.45**	0.73**	**1.00**											
	S	-0.06**	-0.09**	**1.00**											
GFD	N	-0.12ns	-0.30**	0.41**	**1.00**										
	S	0.46 ns	0.89ns	0.37**	**1.00**										
PH	N	0.64 **	0.42**	0.40**	-0.02ns	**1.00**									
	S	0.72**	0.56**	0.04**	0.54**	**1.00**									
PE	N	-0.84**	-0.48**	-0.41**	0.10ns	-0.61**	**1.00**								
	S	-0.86**	-0.44**	-0.09**	-0.45ns	-0.71**	**1.00**								
NGL	N	-0.77**	-0.49**	-0.42**	0.11ns	-0.58**	0.82**	**1.00**							
	S	-0.78**	-0.42**	0.00**	-0.39ns	-0.71**	0.79**	**1.00**							
PL	N	-0.74**	-0.64**	-0.62**	-0.02ns	-0.55**	0.68**	0.66**	**1.00**						
	S	-0.75**	-0.64**	-0.06**	-0.63ns	-0.66**	0.67**	0.60**	**1.00**						
PW	N	-0.81**	-0.61**	-0.58**	0.03ns	-0.66**	0.78**	0.77**	0.80**	**1.00**					
	S	-0.79**	-0.65**	-0.08**	-0.64ns	-0.83**	0.76**	0.74**	0.80**	**1.00**					
TSW	N	-0.80**	-0.59**	-0.52**	0.09ns	-0.68**	0.77**	0.75**	0.75**	0.89**	**1.00**				
	S	-0.83**	-0.60**	-0.02**	-0.57ns	-0.87**	0.80**	0.73**	0.77**	0.95**	**1.00**				
PY	N	-0.87**	-0.58**	-0.51**	0.09ns	-0.76**	0.84**	0.83**	0.77**	0.88**	0.89**	**1.00**			
	S	-0.89**	-0.57**	0.02**	-0.52ns	-0.91**	0.83**	0.81**	0.76**	0.91**	0.94**	**1.00**			
GY	N	-0.92**	-0.56**	-0.44**	0.15*	-0.66**	0.90**	0.85**	0.77**	0.83**	0.85**	0.91**	**1.00**		
	S	-0.91**	-0.55**	0.00**	-0.51ns	-0.90**	0.87**	0.81**	0.76**	0.88**	0.92**	0.98**	**1.00**		
ADM	N	0.23**	0.45**	0.65**	0.29**	0.30**	-0.30**	-0.23**	-0.35**	-0.36**	-0.32**	-0.34**	-0.23**	**1.00**	
	S	0.27**	0.54**	0.33**	0.65**	0.39**	-0.34**	-0.36**	-0.33**	-0.45**	-0.40**	-0.37**	-0.35**	**1.00**	
HI	N	-0.83**	-0.59**	-0.58**	0.01ns	-0.65**	0.86**	0.79**	0.76**	0.82**	0.81**	0.88**	0.90**	-0.58**	**1.00**
	S	-0.78**	-0.58**	-0.11**	-0.60ns	-0.79**	0.80**	0.76**	0.67**	0.82**	0.82**	0.86**	0.87**	-0.72**	**1.00**

3.7 Path coefficient analysis

Path coefficient analysis partitions the total correlation coefficient into direct and indirect effects and measures the relative importance of the causal factors individually. In the present study grain yield was considered as dependent variable and other traits were considered as independent variables. Table 3.8 presents partitioning of yield and yield components into direct and indirect effect of 14 quantitative traits of sorghum evaluated under stressed and non-stressed conditions. The result revealed that days to maturity exhibited the highest positive direct effect (6.578) on grain yield followed by panicle yield (0.455), harvest index (0.440), above ground dry matter (0.257), thousand seed weight (0.104) and panicle exertion (0.061) for the experiment conducted under stress condition, while harvest index (0.599) showed low but positive direct effect on grain followed by above ground dry matter (0.289), panicle exertion (0.130), panicle yield (0.428), thousand seed weight (0.091), panicle length (0.057), number of green leaf at physiological maturity (0.045) and days to maturity (0.013) for the experiment conducted under non-stressed condition. Therefore, selection of these traits under both test environments will provide good responses to grain yield improvement. Hence, days to maturity, panicle yield, harvest index, above ground dry matter, thousand seed weight and panicle exertion are important traits useful in sorghum selection programs to improving grain yield under drought stressed and non-stressed conditions. Iyengar et al. (2001), Shanmugasundaram and Subrananian (1990) and Patil and Thombre (1995) reported 1000 seed weight and panicle length, respectively, as important traits influencing grain yield of sorghum.

In this study seedling vigor, days to maturity, grain filling duration, plant height and panicle width exhibited direct negative effect on grain yield under both stressed and non-stressed conditions. Number of green leaf and panicle length also showed negative direct effect on grain yield for the experiment conducted under stressed condition (Table 3.8). Therefore, direct selection for these traits may not enhance grain yield.

Table 3.8 Direct path coefficients (diagonal and bold faced scripts) and indirect path coefficients (off diagonal) of 14 yield and yield related traits of 196 sorghum genotypes evaluated under non-stressed and drought stressed conditions

Traits	ENV	SV	DF	GFD	DM	PH	PE	NGL	PL	PW	TSW	PY	ADM	HI	rg GY
SV	N	**-0.180**	-0.013	-0.015	-0.002	-0.008	-0.109	-0.035	-0.042	0.078	-0.073	-0.087	0.068	-0.499	-0.906
	S	**-0.082**	-3.269	0.192	3.051	-0.066	-0.053	0.005	0.006	0.073	-0.086	-0.403	0.069	-0.343	-0.906
DF	N	-0.098	**-0.023**	-0.025	-0.004	-0.005	-0.063	-0.022	-0.036	0.059	-0.054	-0.058	0.130	-0.356	-0.547
	S	-0.043	**-6.184**	0.260	5.872	-0.051	-0.027	0.003	0.005	0.060	-0.062	-0.260	0.138	-0.257	-0.547
GFD	N	-0.080	-0.017	**-0.034**	0.005	-0.005	-0.053	-0.019	-0.035	0.056	-0.048	-0.051	0.188	-0.346	-0.001
	S	0.005	0.532	**-3.029**	2.451	-0.004	-0.005	0.000	0.000	0.007	-0.002	0.011	0.084	-0.051	-0.001
DM	N	0.022	0.007	-0.014	**0.013**	0.000	0.012	0.005	-0.001	-0.003	0.008	0.009	0.084	0.005	-0.510
	S	-0.038	-5.520	-1.128	**6.578**	-0.049	-0.027	0.003	0.005	0.059	-0.059	-0.237	0.167	-0.262	-0.510
PH	N	-0.115	-0.010	-0.014	0.000	**-0.012**	-0.080	-0.026	-0.032	0.064	-0.062	-0.076	0.086	-0.386	-0.896
	S	-0.059	-3.435	-0.131	3.533	**-0.092**	-0.044	0.005	0.005	0.077	-0.090	-0.416	0.100	-0.347	-0.896
PE	N	0.151	0.011	0.014	0.001	0.007	**0.130**	0.037	0.039	-0.075	0.070	0.084	-0.086	0.513	0.870
	S	0.071	2.719	0.259	-2.948	0.065	**0.061**	-0.005	-0.005	-0.071	0.083	0.378	-0.087	0.351	0.870
NGL	N	0.139	0.012	0.014	0.001	0.007	0.107	**0.045**	0.038	-0.074	0.069	0.083	-0.067	0.472	0.812
	S	0.064	2.626	-0.012	-2.591	0.065	0.048	**-0.006**	-0.005	-0.068	0.076	0.369	-0.091	0.337	0.812
PL	N	0.134	0.015	0.021	0.000	0.007	0.089	0.030	**0.057**	-0.077	0.069	0.077	-0.101	0.453	0.757
	S	0.062	3.974	0.184	-4.119	0.060	0.041	-0.004	**-0.008**	-0.074	0.080	0.347	-0.084	0.296	0.757
PW	N	0.146	0.014	0.020	0.000	0.008	0.102	0.034	0.046	**-0.096**	0.081	0.088	-0.104	0.493	0.884
	S	0.065	4.022	0.229	-4.211	0.076	0.047	-0.005	-0.006	**-0.092**	0.098	0.413	-0.115	0.360	0.884
TSW	N	0.145	0.014	0.018	0.001	0.008	0.100	0.034	0.043	-0.086	**0.091**	0.089	-0.092	0.486	0.924
	S	0.068	3.712	0.052	-3.729	0.079	0.049	-0.005	-0.006	-0.088	**0.104**	0.428	-0.103	0.363	0.924
PY	N	0.156	0.014	0.018	0.001	0.009	0.110	0.037	0.044	-0.085	0.081	**0.100**	-0.097	0.524	0.980
	S	0.073	3.527	-0.073	-3.423	0.084	0.051	-0.005	-0.006	-0.084	0.097	**0.455**	-0.094	0.378	0.980
ADM	N	-0.042	-0.010	-0.022	0.004	-0.004	-0.039	-0.010	-0.020	0.035	-0.029	-0.034	**0.289**	-0.345	-0.350
	S	-0.022	-3.316	-0.992	4.261	-0.035	-0.021	0.002	0.003	0.041	-0.042	-0.167	**0.257**	-0.318	-0.350
HI	N	0.150	0.014	0.020	0.000	0.008	0.112	0.035	0.043	-0.079	0.074	0.088	-0.166	**0.599**	0.869
	S	0.064	3.607	0.348	-3.916	0.072	0.049	-0.005	-0.005	-0.076	0.085	0.391	-0.186	**0.440**	0.869

SV= seedling vigor; DF=days to flowering; DM= days to maturity; GFD= days to grain filling period; PH= plant height; PE= panicle exertion; NGL= number of green leaf at physiological maturity; PL= panicle length; PW= panicle weight; TSW= thousand seed weight; PY= panicle yield; GY= grain yield; ADM= above ground dry matter; HI= harvest index; ENV=testing conditions, where N and S denote non-stressed and stressed conditions, rg GY =, respectively and

3.8 Principal component analysis of yield and yield related traits

Through principal component analysis (PCA), the relative contribution of traits towards the variation in the 196 sorghum genotypes were estimated and presented in Table 3.9. The analysis showed that the first three principal components (PCs) explained majority of the total variation of traits of sorghum genotypes evaluated under non-stressed and stressed conditions. The three PCs with Eigen values ≥ 1.1 and 1.2 contributed 79.41% and 86.78% of the total variability amongst the sorghum genotypes evaluated for various yield and yield related traits under non-stressed and stressed conditions, respectively. The percentage contributions of the first three principal components to the gross genetic variation obtained in the current study were 79.41% and 86.78% under non-stressed and stressed conditions, respectively. These results were in agreement to the reports of Mujaju and Chakuya, (2008) and Ali et al. (2011) who explored various agro-morphological traits in sorghum using PCA. PC_1 contributed to 60.26% and 66% of the variation amongst the genotypes investigated under non-stressed and stressed conditions, respectively. The variation in PC_1 was explained by majority of the traits examined except above ground dry matter, days to emergency and grain filling duration in decreasing order of contribution under non-stressed condition, while above ground dry matter and days to maturity contributed less in stressed conditions. In both experiments, traits such as seedling vigor, days to flowering, days to maturity, plant height and above ground dry matter showed negative association to this component (Table 3.9).

PC_2, on the other hand, contributed to 11.86% and 12.45% of the total variation amongst test genotypes evaluated under non-stressed and stressed conditions, respectively (Table 3.9). The variation in PC_2 is mainly contributed by grain filling duration, above ground dry matter, days to maturity and grain yield in non-stressed condition. Relatively higher variation was observed in PC_2 under stressed condition contributed by grain filling duration, days to emergency and above ground dry matter. Except seedling vigor, plant height and panicle length other traits showed positive association with PC_2 under both test conditions.

Furthermore, PC3 contributed to 7.3% and 8.33% of the total variation in the genotypes which was mainly resulted from grain filling duration, days to flowering and days to emergency under non-stressed condition, and days to maturity, days to flowering and days to emergency under stressed condition (Table 3.9). Majority of the test traits showed positive association with PC3. Moreover, the principal components analysis also showed that the variation in the genotypes cannot be explained on the basis of few characters. This, in turn, implied that a number of traits were involved in explaining the gross variance among the genotypes. In order of diminishing importance, the explanation of greater proportion of the entire phenotypic diversity involved were panicle traits (*i.e.* its panicle width and panicle exsertion), yield related traits (1000 seed weight and biomass) and plant phenology (plant height, days to flowering and maturity). This further confirmed the previous results that also described the importance of these traits in contributing towards the overall diversity of the sorghum germplasm landraces (Ayana and Bekele 1999).

Table 3.9 Principal component analysis for grain yield and yield related traits evaluated under drought stressed and non-stressed conditions at Kobo site in 2014/2015

Traits	Non-stressed			Stressed		
	PC1†	PC2	PC3	PC1	PC2	PC3
SV	-0.899	-0.195	-0.073	-0.876	-0.296	0.049
DF	-0.699	0.120	0.541	-0.746	0.519	0.405
DM	-0.644	0.656	0.236	-0.067	0.374	-0.855
GFD	0.057	0.771	-0.394	-0.725	0.653	-0.010
PH	-0.739	-0.028	-0.185	-0.877	-0.152	-0.043
PE	0.882	0.165	0.154	0.847	0.286	0.161
NGL	0.855	0.185	0.112	0.808	0.297	0.105
PL	0.851	-0.094	-0.017	0.832	-0.013	-0.094
PW	0.923	0.006	0.045	0.937	0.059	0.014
TSW	0.910	0.081	0.051	0.934	0.162	0.003
PY	0.951	0.104	0.102	0.947	0.255	0.002
GY	0.937	0.221	0.113	0.943	0.277	0.036
ADM	-0.447	0.675	0.274	-0.544	0.557	-0.316
HI	0.936	-0.073	0.019	0.910	0.000	0.196
Eigen value	9.04	1.78	1.1	9.9	1.87	1.25
% total variance	60.26	11.86	7.3	66	12.45	8.33
Cumulative variance %	60.26	72.12	79.4	66	78.45	86.78

Key: SV= seedling vigor; DF=days to flowering; DM= days to maturity; GFD= days to grain filling period; PH= plant height; PE= panicle exertion; NGL= number of green leaf at physiological maturity; PL= panicle length; PW= panicle weight; TSW= thousand seed weight; PY= panicle yield; GY= grain yield; ADM= above ground dry matter; HI= harvest index and PC=principal component.

3.9 Conclusions

The current study successfully selected drought tolerant medium-maturing sorghum from landrace collections of Ethiopia. The following medium-maturing sorghum genotypes were selected: E-72457, E-72438, E-72435, E-206214, E-72449, E-75460 and E-75458. These are better performing selections and can be recommended for wide-area production or breeding under drought prone agro-ecologies of the country.

Similarly, genotypes such as E-72435, E-72438, E-206214, E-72457, E-75454 and E-72449 are selected as the top yielding entries and recommended for large-scale production or breeding in areas where potential rainfall prevails. Overall, the present study found marked genetic diversity among the tested genotypes and selected suitable medium-maturing farmer preferred accessions for effective breeding emphasising drought tolerance and medium-maturity.

Given Ethiopia is the center of origin and diversity of sorghum we have great opportunity in accessing important genes through continuous testing of the diverse genotypes for the development of farmer preferred, drought tolerant, medium-maturing and high yielding sorghum varieties which can adapt the current drought situation.

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CHAPTER 4

Assessment of the genetic diversity of medium-maturing sorghum genotypes based on simple sequence repeat markers and phenotypic traits

4.1 Abstract

Sorghum having evolved across a wide range of environments in Africa exhibits a great range of genetic diversity and possesses desirable attributes including tolerance to abiotic and biotic stresses. The aim of this study was to assess the genetic diversity present among diverse medium-maturing sorghum genotypes based on simple sequence repeat (SSR) markers and phenotypic traits to select unique genotypes for breeding. Fifty medium-maturing sorghum genotypes were evaluated using 39 SSR markers to establish genetic structure, diversity and relationships. Based on phenotypic traits the genotypes were clustered into three groups. The SSR analysis showed the presence of considerable genetic diversity. The number of alleles per locus varied from 2 to 18 with a mean of 7.15, while the polymorphic information content ranged from 0.24 to 0.89 with a mean of 0.601. A population structure analysis with the SSR markers yielded three genetic groups agreeing to the results of cluster and factorial analyses based on phenotypic traits. The two marker types complement each other. The presence of genotypes of different origins across clusters, sets and groups indicate similar genetic backgrounds, and evidence of gene flow between administrative Zones where test genotypes were sampled. Partitioning of the total genetic variation indicated 61.85% and 37.24% of the variations explained by among individuals within populations and within individuals, respectively. Fourteen genetically divergent medium-maturing sorghum genotypes (E-72457, E-206214, E-72438, E-75460, E-72435, E-75458, E-72437, E-75452, E-72446, E-74097, E-201444, E-75273, E-211235 and E-200013) were selected for future breeding. It is concluded that molecular markers along with important agronomic traits could be used for conservation and breeding programs of sorghum.

Keywords: Ethiopia; genetic diversity; Sorghum bicolor; SSR markers.

4.2 Introduction

Sorghum [*Sorghum bicolor* (L.) Moench) is the fifth most important cereal crop in the world after wheat, rice, maize and barley. It is a C_4 crop with the ability to produce high biomass. It is widely cultivated in semi-arid tropics where growing conditions are harsh for other domesticated crops such as maize (Dogget, 1988; Rooney, 2004; Gnansounou et al., 2005). Sorghum is a multipurpose crop of great economic importance for its uses and products including animal feed, unleavened breads, cakes, wallboard, starch, dextrose, brooms, ethanol, high quality wax and alcoholic beverages (Murray et al., 2009; Kiber et al., 2013; Houx et al., 2013). Sorghum is considered as a pillar of food security in sub-Saharan Africa and Asia (Bhosale et al., 2011).

It is believed that sorghum has been first domesticated in Ethiopia and neighboring countries such as Sudan and Somalia commencing around 4000-3000BC (Dogget, 1988; Dillon et al., 2007). Sorghum has high genetic diversity in eastern African regions mainly in Sudan and Ethiopia (Gebrekidan, 1982). Globally, about 168,500 accessions of sorghum germplasm are conserved mainly in the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Indian National Plant Germplasm System (NPGS), United States, Ethiopia, Sudan, South Africa, India and China having larger number of breeding program (Rosenow and Dahlberg, 2000; Billot et al., 2013).

In Ethiopia, sorghum is the third most important staple cereal crop after tef and maize (CSA, 2016). The crop is grown in the majority of the country's agro-ecology by subsistence farmers for multiple uses mainly for food, feed and alcoholic beverages. Despite being an excellent food security crop, sorghum productivity has remained low with an estimated national mean yield of 2.3 t ha^{-1}(CSA, 2016) due to various production constraints, mainly drought and socio-economic constraints. Sorghum productivity in Ethiopia can be improved through effective breeding program using well-characterized and genetically unique and locally adapted medium-maturing sorghum germplasm.

Genetic variation within a species is a fundamental resource in crop improvement programs. A detailed and systematic characterization of genetic diversity and understanding of the genetic relationships among germplasms are prerequisite for successful exploitation of genetic variation contained in germplasm collections for breeding and for efficient gene bank management. Characterization and identification of promising inbred lines is useful for strategic breeding, for planning crosses and conservation (Geleta et al., 2006; Perumal et al., 2007).Geleta and Labuschagne (2005) underlined the importance of using molecular markers as an additional tool for varietal description. The genetic control of morphological traits is polygenic and their expression depends on environmental factors. Molecular markers are invaluable tools for understanding the genetic make-up of agricultural crops. Molecular markers occur in greater numbers and can be distinguished without relying on the complete development of the plant and their expression is not affected by the environment (Jeya Prakash et al., 2006; Tabbasam et al., 2006; Mehmood et al., 2008; Abu Assar et al., 2009).

Morphological and agronomical traits and biochemical markers are widely used to assess intra species genetic variation. But these marker systems are influenced by environmental factors (Abdi et al., 2002; Fufa et al., 2005). Sorghum breeding programmes in Ethiopia mainly establish genetic relationships through morphological traits and physiological indices with limited use of molecular markers. However, morphological traits are influenced by the environment and thus genetic characterization and evaluations require complementary molecular markers.

DNA based markers provide convenient and powerful alternative for genetic analysis. Numerous methods of detecting DNA polymorphism were established over the years, such as: Restriction Fragment Length Polymorphism (RFLP), Amplified Fragment Length Polymorphism (AFLP), Inter Simple Sequence Repeats (ISSR), Random Amplified Polymorphic DNA (RAPD), Selective Amplification of Microsatellite Polymorphic Loci (SAMPL), Sequence Specific Amplification Polymorphism (SSAP), Simple Sequence Repeats (SSR), Single Nucleotide Polymorphism (SNP), Diversity Arrays Technology (DArT) (Karp et al., 1996; Rakoczy-Trojanowska and Bolibok, 2004; Gupta et al., 2008).

With the advent of molecular fingerprinting labor-intensive and time-consuming phenotyping procedures were replaced allowing for sampling of only relatively limited numbers of accessions and loci. The recent advances in high throughput genotyping technologies, such as fluorescence-based SSR detection on automated sequencers and highly parallel SNP genotyping assays, along with the establishment of high throughput DNA isolation protocols (Bashalkhanov and Rajora, 2008) enabled extensive characterizations of whole germplasm collections (Upadhyaya et al., 2008; Lv et al., 2012; Emanuelli et al., 2013). In consequence molecular markers became an indispensable tool of assessing genetic diversity that supplements morphological evaluations.

Over the years, the application of molecular markers have played a significant role in the conservation and use of sorghum genetic resources (Aldrich and Doebley, 1992; Whitkus et al., 1992; Rami et al., 1998; Deu et al., 2006; Wang et al., 2006; Morris et al., 2013) and also in many aspects of sorghum improvement programs ranging from identification of diverse lines, to mapping of genomic regions controlling desirable traits and their use in marker-assisted breeding. Simple sequence repeat (SSR) markers are the preferred marker system for many sorghum genomics and molecular breeding applications (Caniato et al., 2007; Ali et al., 2008; Deu et al., 2008; Muraya et al., 2011), especially in developing countries (Sharma et al., 2010) where SNP genotyping applications are extremely rare.

Limited genetic diversity assessment studies have been done by sorghum breeders in Ethiopia using molecular markers. Menkir et al. (1997) studied the genetic diversity of sorghum collected from different parts of Ethiopia using random amplified polymorphic DNA (RAPD) markers. Ayana et al. (2000) did diversity study on sorghum collected from western part of Ethiopia using the same marker system. Geleta et al. (2006) used SSR and AFLP markers for genetic diversity analysis of sorghum sampled from the eastern regions of Ethiopia.

Simple Sequence Repeats (SSR) or Sequence Tagged Sites (STS) or microsatellite markers are short repetitive sequences which help in identifying the polymorphism based on Polymerase Chain Reaction (Gupta et al., 1996; Powell et al., 1996). Here sequence specific primers are used instead of random primers. Thus the repeatability and reliability are more in this case. These are powerful tools for genotype differentiation, genetic diversity analysis, purity evaluation of seeds, mapping studies and marker assisted selection. Simple Sequence Repeats (SSR) markers have been exploited to assess potential recent population bottleneck in wild sorghum (Muraya et al., 2010).

To date, no known past genetic diversity studies exhaustively characterized medium-maturing sorghum which adapted to the lowlands of north eastern part of Ethiopia where drought stress largely limits the productivity of sorghum. Hence, further genetic diversity studies that fully included medium-maturing sorghum genotypes collected from drought prone harsh environments are crucial for effective breeding. Therefore, the aim of the present study was to assess the genetic diversity and interrelationships among and within medium-maturing sorghum genotypes collected from drought-prone lowland areas of north-eastern Ethiopia, using phenotypic traits and SSR markers.

4.3 Materials and methods

4.3.1 Plant materials, phenological and morpho-qualitative data recording

The study used 50 genetically diverse medium sorghum genotypes. The 50 sorghum genotypes were advanced from the previous screening experiment of this study (Chapter three). The genotypes were selected on the basis of their contrast phenotypic performance such as drought tolerance, high yielding and medium-maturity, when evaluated under managed stressed condition and based on their phenological and morpho-qualitative distinctiveness. The selected sorghum germplasm represented three Administrative Zones of North eastern Ethiopia (North Wello, South Wello and Oromiya Special) which are major sorghum growing areas. A total of 19 genotypes were selected from North Wello, 20 from South Wello and 11 from Oromiya Special Zone.

Genotypes were planted in 2016 main cropping season under rain-fed condition at Kobo testing site in Ethiopia. Genotypes were planted in single row of three meter long for further phenological data recording. Row to row and plant to plant distances were 0.75 m and 0.25 m, respectively. Fertilizer was added at the rate of 100 kg ha^{-1} DAP and 50 kg ha^{-1} urea. At the time of sowing 100 kg ha^{-1} DAP and 25 kg ha^{-1} urea was applied and the remaining 25 kg ha^{-1} urea added at 60 cm plant height stage of the crop after thinning. Weeding at different stages of the crop was done manually. From each genotypes planted, five plants were randomly selected to record phenological and morpho-qualitative traits. Three phenological traits were assessed such as flowering date measured as the duration in days from planting to 50% of the plants within a plot; days to maturity recorded as the time from emergence until the grains from the main shoot reached to the black layer stage and plant height measured as the distance from the base of the plant to the tip of the panicle. In addition, seven morpho-qualitative traits were recorded. These were presence or absence of awns, glum colour, seed colour, head shape, leaf orientation, midrib colour and leaf colour (Table 4.1).

Table 4.1 List of sorghum genotypes used for morphological and genetic diversity analysis

Genotypes	Zone	Woreda	DF	DM	PH	AW	GC	SC	HS	LO	MC	LC
E-72457	South Wello	Kalu	80.57	123.86	173.18	Absence	White	White	Elliptical	Erect	White	Dark green
E-72438	North Wello	Raya Kobo	77.00	130.54	173.25	Absence	White	Light yellow	Oblong	Dropping	Green	Green
E-72435	South Wello	Ambasel	72.96	128.18	158.11	Absence	Grey	Orange	Round	Erect	Yellow	Dark green
E-206214	North Wello	Raya Kobo	78.46	129.68	177.18	Absence	Black	White	Semi loose	Erect	White	Green
E-72449	South Wello	Kalu	71.36	107.93	170.68	Absence	White	White	Loose	Erect	Purple	Dark green
E-75460	South Wello	Twuledere	87.68	123.75	173.93	Present	Purple	White	Semi loose	Dropping	White	Green
E-75458	South Wello	Kalu	78.82	121.07	174.96	Absence	Red	Orange	Semi loose	Erect	Green	Dark green
E-72437	Oromiya Special	Kemise Zuria	92.57	135.43	176.93	Absence	White	White	Elliptical	Dropping	White	Green
E-72444	North Wello	Guba Lafto	105.11	153.64	177.46	Absence	White	White	Semi loose	Erect	Yellow	Green
E-206100	South Wello	Ambasel	68.82	116.68	175.43	Present	Grey	Orange	Oblong	Erect	White	Dark green
E-20006	North Wello	Habru	67.93	110.11	175.50	Present	White	White	Semi loose	Erect	Yellow	Dark green
E-200070	South Wello	Ambasel	95.32	147.57	177.50	Absence	Dark Brown	White	Elliptical	Erect	Green	Light green
E-75453	South Wello	Twuledere	75.29	124.14	177.71	Absence	White	Red	Round	Dropping	White	Green
E-75457	South Wello	Twuledere	72.21	118.82	175.86	Absence	White	White	Semi loose	Erect	Green	Dark green
E-71382	South Wello	Ambasel	74.61	125.07	178.64	Present	Brown	White	Elliptical	Erect	White	Green
E-212636	North Wello	Raya Kobo	83.54	124.57	175.57	Present	Purple	Orange	Round	Erect	Green	Dark green
E-211240	Oromiya Special	Kemise Zuria	74.71	118.68	179.00	Present	Black	White	Semi loose	Erect	White	Green
E-211236	South Wello	Ambasel	74.11	121.11	181.57	Absence	White	White	Elliptical	Erect	Green	Light green
E-72477	South Wello	Ambasel	80.00	124.75	177.18	Present	White	White	Elliptical	Erect	White	Green
E-211235	Oromiya Special	Kemise Zuria	86.07	127.39	179.25	Absence	Brown	Orange	Round	Erect	Green	Dark green
E-75454	South Wello	Ambasel	77.93	128.86	177.25	Present	White	White	Round	Erect	Green	Green
E-206215	North Wello	Raya Kobo	88.14	124.57	178.79	Present	Grey	White	Round	Erect	Yellow	Green
E-72443	South Wello	Ambasel	82.32	128.82	178.68	Absence	Brown	White	Oblong	Erect	Green	Dark green
E-201319	North Wello	Habru	71.57	118.82	180.04	Absence	White	Light yellow	Round	Erect	Green	Green
E-72439	South Wello	Ambasel	77.50	136.00	179.57	Absence	White	White	Oblong	Dropping	Green	Light green
E-210972	Oromiya Special	Kemise Zuria	81.39	120.86	176.50	Absence	Dark Brown	Red	Semi loose	Erect	White	Green
E-210952	North Wello	Guba Lafto	75.75	127.54	179.07	Present	White	White	Elliptical	Erect	Green	Dark green
E-211237	Oromiya Special	Jille Timuga	79.36	129.18	179.04	Absence	Grey	Light yellow	Loose	Erect	Purple	Green
E-210951	Oromiya Special	Kemise Zuria	82.50	128.75	180.43	Absence	White	White	Elliptical	Erect	Yellow	Dark green
E-211239	North Wello	Guba Lafto	72.00	114.14	183.18	Present	Red	Brown	Semi loose	Dropping	Green	Green
E-210971	Oromiya Special	Kemise Zuria	72.25	113.36	176.96	Present	White	White	Semi loose	Erect	Yellow	Dark green

Table 4.1. Continued

Genotypes	Zone	Woreda	DF	DM	PH	AW	GC	SC	HS	LO	MC	LC
E-201444	North Wello	Guba Lafto	76.71	123.68	179.50	Absence	Dark Brown	Pink	Round	Erect	Green	Green
E-200013	Oromiya Special	Jille Timuga	72.29	122.32	178.96	Absence	Red	White	Semi loose	Erect	Yellow	Green
E-206213	South Wello	Kalu	76.89	123.07	179.00	Absence	Grey	Red	Round	Erect	Purple	Green
E-72445	North Wello	Guba Lafto	72.54	114.18	179.21	Absence	White	White	Semi loose	Erect	White	Green
E-75273	Oromiya Special	Kemise Zuria	76.61	121.57	177.50	Absence	Red	Light yellow	Loose	Erect	White	Dark green
E-72620	North Wello	Habru	77.32	122.11	178.75	Absence	Purple	White	Semi loose	Erect	Yellow	Green
E-72475	North Wello	Guba Lafto	79.18	128.00	180.57	Absence	White	White	Semi loose	Dropping	White	Dark green
E-75274	North Wello	Guba Lafto	103.61	159.04	178.82	Present	Dark Brown	Pink	Round	Erect	Green	Green
E-72476	Oromiya Special	Jille Timuga	79.68	128.57	180.50	Absence	White	White	Oblong	Erect	White	Green
E-75452	South Wello	Kalu	88.00	130.54	181.54	Absence	Red	White	Semi loose	Erect	White	Green
E-75272	North Wello	Guba Lafto	77.25	126.39	180.93	Absence	White	Brown	Oblong	Erect	Yellow	Dark green
E-74097	South Wello	Kalu	69.18	116.89	180.21	Present	Grey	White	Semi loose	Erect	White	Green
E-72446	North Wello	Raya Kobo	72.43	116.39	181.43	Present	White	Pink	Round	Erect	Purple	Dark green
E-202507	South Wello	Ambasel	82.07	126.68	178.89	Absence	White	White	Semi loose	Erect	White	Green
E-201318	North Wello	Raya Kobo	74.79	115.43	183.57	Absence	Red	White	Loose	Erect	White	Green
E-202508	Oromiya Special	Kemise Zuria	73.71	119.39	181.57	Present	White	Red	Loose	Erect	Yellow	Green
E-210973	South Wello	Kalu	67.43	110.32	180.93	Absence	Dark Brown	White	Semi loose	Erect	White	Green
E-210953	North Wello	Raya Kobo	91.25	138.07	183.93	Absence	White	White	Semi loose	Erect	Green	Light green
E-206112	North Wello	Raya Kobo	76.21	122.21	183.50	Present	Purple	Pink	Round	Erect	White	Light green
Mean			**78.90**	**124.97**	**178.15**							

DF=days to flowering; DM=days to maturity; PH=plant height; AW=awns; GC=glum colour; SC=seed colour; HS=head shape; LO=leaf orientation; MC=midrib colour and LC=leaf colour

4.3.2 DNA extraction

Twenty seeds of each genotype were packed in to plastic bag and sent to University of Kwazulu-Natal, South Africa and grown at the facility of African Center Crop Improvement (ACCI). Fifty seeds of each genotype were grown in the tunnel in small plastic pots and were watered till the length of the seedlings was around 10 to 15 cm. Two-week-old leaves were collected and used for DNA extraction. Genomic DNA from each of the genotypes was extracted from a bulk of 15 plants using a cetyltrimethylammonium bromide (CTAB) procedure (Saghai-Maroof et al., 1984).

4.3.3 Polymerase chain reaction (PCR) and SSR genotyping

Equal amounts of DNA from each plant representing each accession were pooled into one sample. DNA purity and concentration were also checked and evaluated. Thirty-nine simple sequence repeat (SSR) markers were used for genotyping (Table 4.2). All the markers used were part of a sorghum SSR kit (Billot et al., 2012) (http://sorghum.cirad.fr/SSR_kit), which provides reasonable coverage across the sorghum nuclear genome. DNA prepared from bulk of 15 seedlings of each sample was used for PCR reactions. The parameters set for PCR amplification conditions were followed as described by Folkertsma et al. (2005) and the PCR and SSR assay was carried out at INCOTEC Pvt.Ltd, Pietermaritzburg, South Africa. PCR conditions were optimized for each of the 39 SSR markers and PCR reactions were set up in 5µl volumes. Each PCR reaction contained 2 to 4 pmol of primer, 1 to 4 mM $MgCl_2$, 0.1 to 0.2 mM dNTP, 0.1 to 0.125 U Amplitaq Gold Polymerase (Applied Biosystems, Johannesburg, SA) and 1X PCR buffer (Applied Biosystems, Johannesburg, SA). Temperature cycling was carried out using the Gene-Amp PCR System 9600 (Applied Biosystems, Johannesburg, SA) and touch-down PCR amplification: one 15 min denaturation cycle, followed first by ten cycles of 94°C for 10 sec, 61°C for 20 sec (ramp of 1°C per cycle) and 72°C for 30 sec, then by 35 cycles of 94°C for 10 sec, 54°C for 20 sec and 72°C for 30 sec. After completion of the 35 cycles, a final extension of 20 min at 72°C was included based on their expected implicon size and the dye. PCR products were fluorescently labelled and separated by capillary electrophoresis on an ABI 3130xI automatic sequencer (Applied Biosystems, Johannesburg, SA) and the analysis was performed using GeneMapper software Version 4.1. (Applied Biosystems, Johannesburg, SA). Product size was scored in base pairs based on the relative migration of the internal size standard. Information generated from GeneMapper Software (Applied Biosystems, Johannesburg, SA) was then used to determine the genetic diversity parameters.

4.4 Data analysis

4.4.1 Phenological and morpho-qualitative data analysis

The phenological and morpho-qualitative traits such as days to flowering, days to maturity, plant height, presence or absence of awns, glum colour, seed colour, head shape, leaf orientation, midrib colour and leaf colour, were assigned numerical ratings following the DUS (distinctiveness, uniformity and stability) ratings developed by the National Research Centre for Sorghum (Reddy et al., 2006) to facilitate statistical analysis. Neighbour-joining tree using Gower's Distance Matrix was done in order to determine the affinity of genotypes and clustering them based on phonological and morpho-qualitative traits data. Pair-wise genetic dissimilarity values based on the Gower's distance (Gower, 1985; Gower and Legendre, 1986) were calculated using morphological data (SAS 9.3). The dissimilarity indices obtained were used to perform principal coordinate analyses using DARwin v5.0 (Perrier and Jacquemoud-Collet, 2006). The tree was plotted using hierarchical clustering following Ward's minimum variance method (Ward, 1963) with a bootstrapping value of 10000. Mantel's test (Mantel, 1967) with 1000 permutations was performed to determine the significance of correlation between dissimilarity matrices derived from SSR data and from phenotypic traits associated with disease resistance using DARwin v5.0.

4.4.2 SSR data analysis

4.4.2.1 Genetic parameters

Genomic data were subjected to various measures of genetic diversity of within and among genotypes. PowerMarker v.3.25 (Liu and Muse, 2005) was used to calculate the numbers of common alleles with frequencies of at least 5%, the total numbers of alleles, allelic richness and polymorphic information content (PIC) values (Botstein et al., 1980; Smith et al., 2000) and gene diversity. PIC which provided an estimation of the discriminatory power of a locus by taking in to account not only the amount of alleles expressed but also the relative frequency of each allele (Botstein et al.,1980; Smith et al., 2000). PIC values were calculated as per the formula developed by Anderson et al. (1993), which assumes homologous alleles. The values of PIC were calculated according to the algorithm: $PIC = 1 - \sum P_{ij}^2$ where Pij is the frequency of the j^{th} allele of the i^{th} locus; PIC values ranged from 0 (monomorphic locus) to 1 (very highly discriminative). DARwin v.5.0 (Perrier and Jacquemoud-Collet, 2006) was used to display a graphical genetic relationship (factorial and cluster analyses for diversity structure). The factorial analysis was performed using Rogers-Tanimoto dissimilarity index and the cluster was obtained using the “Neighbor-Joining” method.

4.4.2.2 Cluster analysis

Genetic relationships within and among the genotypes collected from the three administrative Zones was evaluated with a neighbour-joining algorithm. The program GGT 2.0 (Van Berloo, 2008) was used to calculate the Euclidian distances between bulked samples, and the matrix of the genetic distance was used to create a UPGMA dendrogram. Bootstrap analysis was performed for node construction using 10,000 bootstrap values.

4.4.2.3 Analysis of molecular variance

An analysis of molecular variance (AMOVA) was performed to explain the genetic variation. Its estimation is based on genetic distance within individuals and takes account of information released by all studied markers. AMOVA was performed by using Arlequin v.3.1 (Excoffier et al., 2005).

4.4.2.4 Genetic structure analysis

The Bayesian genotypic clustering approach of STRUCTURE 2.3.4 (Pritchard et al., 2000) was used to validate the population structure among the genotypes. An admixture model with independent allele frequencies, without prior population information, was used for simulation. This model assumes that the genome of each individual is a mixture of genes originating from K unknown ancestral populations. For joint inference of the population substructure, the model was run for 20 replicate analyses for each K value ranging from 1 to 10, with a burn-in period of 106 and Markov Chain Monte Carlo (MCMC) steps of 106 iterations (Bouchet et al., 2012). Graphical representation of population assignments from STRUCTURE were produced (Figure 4.4) from the program DISTRUCT (Rosenberg, 2002).

4.4.2.5 Factor analysis

Factor analysis technique reduces data into smaller meaningful groups based on their inter-correlations or shared variance. It is based on the assumption that correlated variables measure a similar factor or trait. It is used to describe the covariance relationships among many variables in terms of few underlying random quantities called factors. The main goal of factor analysis is to explain as much variance as possible in a data set by using the smallest number of factors and the smallest amount of items or variables within each factor. For interpretation of analysis, the factors with Eigen values greater than 1.0 are considered.

4.5 Results and discussion

4.5.1 Phenological and morpho-qualitative traits

As indicated in Figure 4.1, the test genotypes were clustered into three clusters, two of them divided into various subgroups. The largest cluster, Cluster I, composed of five sub-clusters containing 32 genotypes within which were 15, 11 and 6 genotypes from South Wello, North Wello and Oromiya Special Zones, respectively. This Cluster mainly consisted of high yielder sorghum genotypes selected from the previous chapter (Chapter 3) such as E-72457, E-72438, E-72435 and E-72449. The first sub-cluster of Cluster I, contained five genotypes representing the three collection sites with two genotype except South Wello. The second sub-cluster contained two genotypes only from South Wello. The third, fourth and fifth sub-clusters contained 4, 8, and 13 genotypes, respectively. Cluster II, the second largest cluster comprised four sub-clusters. This cluster contained argonomically better performing genotypes such as E-206214 and E-75460. The four sub-clusters of Cluster II contained 3, 2, 3 and 5 genotypes, respectively. Cluster III comprised of five genotypes of which 80% of them were collected from North Wello. In general, the phenological and morpho-qualitative traits did not distinctly group genotypes according to their geographic origin/area of collection, materials from the different area tended to cluster together within each group, indicating that their geographic origin didn’t play a role in the selection of germplasm used.

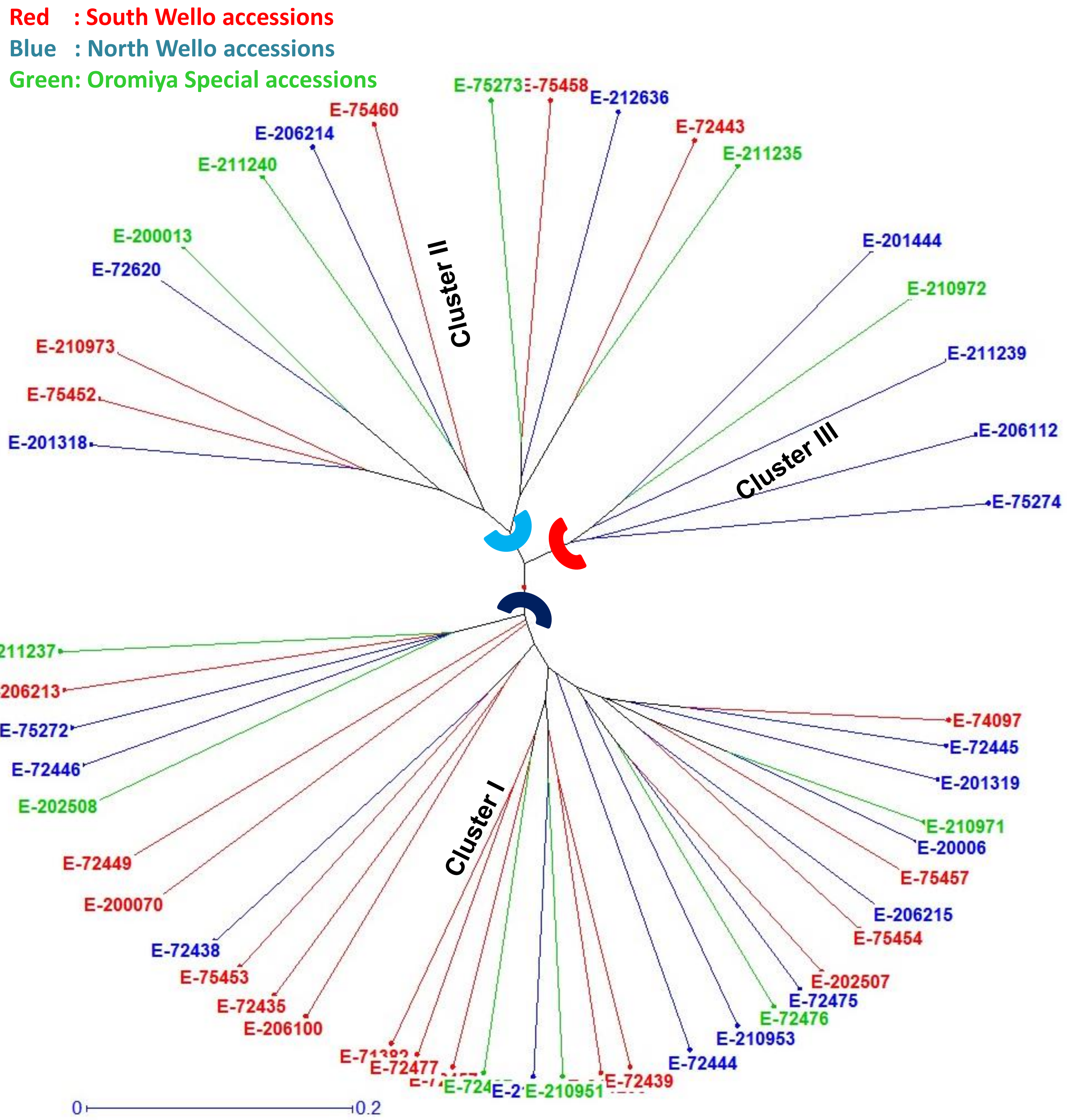

Figure 4.1 Morphological diversity analysis of 50 medium maturing sorghum genotypes based on Gower’s distance matrics

4.5.2 Polymorphism of SSR markers

Summary on genetic parameters are presented in Table 4.2. Numbers, PIC and heterozygosity fragments amplified by each SSR marker are listed in Table 4.2. Results showed that 100% of the markers used in this study were polymorphic and a total of 279 alleles were generated. Majority of the SSRs generated 2 to 9 alleles; six markers generated 12 to 14 alleles and the remaining three markers generated 11 to 18 alleles with a mean of 7.15 alleles per locus. Major allele frequency ranged from 0.174 to 0.880 with a mean of 0.48. The observed allele sizes ranged from 93 (msbCIR238) to 312 base pairs (gpsb123). The two accessions with the lowest PIC values in the loci of mSbCIR246 and mSbCIR300 were E-72437 and E-72444, respectively. The accessions with the highest PIC values in the loci of Xgap206 and Xtxp265 were E-20006 and E-75454, respectively. Gene diversity is defined as the probability that two randomly chosen alleles from the population are different. It varied from 0.253 (E-75458) to 0.894 (E-210972), with a mean of 0.64. Heterozygosity values of the 39 polymorphic SSR markers ranged from 0.00 (E-72438, E-72444) to 0.98 (E-72439) with a mean of 0.24, suggesting that each detected a single genetic locus and that each of the sorghum genotypes used was reasonably inbred and homogeneous.

Table 4.2 Genetic parameters estimated using 39 polymorphic SSR loci screened across 50 sorghum genotypes

Marker	Motif type	MA_F	N_A	Size	A_R	G_D	H_E	PIC
gpsb067	(GT)10	0.38	7	188-202	1.00	0.74	0.00	0.71
gpsb123	(CA)7+(GA)5	0.38	4	305-312	0 .96	0.67	0.00	0.60
mSbCIR223	(AC)6	0.74	4	127-138	0.94	0.42	0.17	0.38
mSbCIR238	(AC)26	0.28	12	93-135	0.90	0.84	0.20	0.82
mSbCIR240	(TG)9	0.28	15	126-187	0.98	0.86	0.31	0.84
mSbCIR246	(CA)7.5	0.84	2	113-119	0.98	0.27	0.12	0.24
mSbCIR248	(GT)7.5	0.70	3	113-115	0.98	0.45	0.16	0.39
mSbCIR262	(CATG)3.25	0.54	3	231-235	0.94	0.58	0.11	0.51
mSbCIR276	(AC)9	0.58	3	246-250	0.96	0.55	0.19	0.47
mSbCIR283	(CT)8 (GT)8.5	0.37	12	133-166	1.00	0.79	0.42	0.77
mSbCIR286	(AC)9	0.40	8	127-156	0.96	0.76	0.31	0.73
mSbCIR300	(GT)9	0.86	5	122-129	1.00	0.25	0.20	0.24
mSbCIR306	(GT)7	0.70	3	140-144	0.98	0.46	0.02	0.41
mSbCIR329	(AC)8.5	0.38	7	128-134	0.98	0.74	0.27	0.70
Xgap72	(AG)16	0.31	7	205-217	0.98	0.78	0.39	0.75
Xgap206	(AC)13/(AG)20	0.17	18	120-140	0.98	0.89	0.63	0.89
Xgap84	(AG)14	0.44	13	203-225	0.98	0.77	0.22	0.75
Xisep0310	(CCAAT)4	0.52	4	195-227	1.00	0.59	0.24	0.51
SbAGB02	(AG)35	0.50	11	113-145	0.98	0.70	0.27	0.68
Xcup02	(GCA)6	0.39	5	216-218	1.00	0.68	0.26	0.61
Xcup14	(AG)10	0.45	3	226-230	0.96	0.59	0.35	0.51
Xcup53	(TTTA)5	0.42	5	201-219	0.98	0.67	0.18	0.60
Xcup61	(CAG)7	0.54	2	216-218	0.96	0.50	0.13	0.37
Xcup63	(GGATGC)4	0.77	2	158-164	0.98	0.36	0.06	0.29
Xtxp010	(CT)14	0.42	7	155-170	1.00	0.74	0.20	0.71
Xtxp012	(CT)22	0.34	13	184-224	0.98	0.82	0.37	0.80
Xtxp015	(TC)16	0.46	8	233-247	0.70	0.73	0.31	0.70
Xtxp021	(AG)18	0.54	8	185-200	1.00	0.67	0.10	0.65
Xtxp040	(GGA)7	0.52	4	150-160	0.96	0.57	0.15	0.48
Xtxp057	(GT)21	0.41	9	260-283	0.98	0.76	0.20	0.73
Xtxp114	(AGG)8	0.41	4	235-253	0.92	0.64	0.98	0.57
Xtxp136	(GCA)5	0.71	3	255-258	0.96	0.42	0.21	0.34
Xtxp141	(GA)23	0.30	9	169-189	0.98	0.81	0.22	0.78
Xtxp145	(AG)22	0.43	14	231-263	0.96	0.78	0.52	0.77
Xtxp265	(GAA)19	0.24	14	224-273	0.98	0.87	0.29	0.86
Xtxp273	(TTG)20	0.50	9	231-256	0.96	0.67	0.23	0.63
Xtxp278	(TTG)12	0.85	3	264-276	0.96	0.26	0.13	0.24
Xtxp320	(AAG)20	0.33	8	281-305	0.92	0.78	0.09	0.74
Xtxp321	GT)4+(AT)6+(CT)2	0.50	8	212-226	1.00	0.69	0.14	0.65
Mean		0.48	7.15	188-205	0.96	0.64	0.24	0.60

MA_F = major alleles frequency; N_A=total number of alleles; A_R = allelic richness; G_D = gene diversity; H_E=heterozygocity and PIC= polymorphic information content

4.5.3 Genetic diversity revealed through cluster analysis

The cluster analysis based on Neighbor-Joining method grouped and displayed the 50 sorghum genotypes into three main clusters (Figure 4.2). The dendrogram provided a basic overview of diversity analysis among sorghum genotypes. No clustering according to area of collection could be observed in the dendrogram. Group I could be considered as an outlier as it contained only one genotype (E-212636). Group II composed of five sub-groups and mainly contained drought tolerant and high yielding genotypes such as E-72457, E-72438, E-206214, E-75460, E-72449 and E-72435. Genotypes in Group III exhibited moderate yielding potential under drought condition when compared to Group II genotypes.

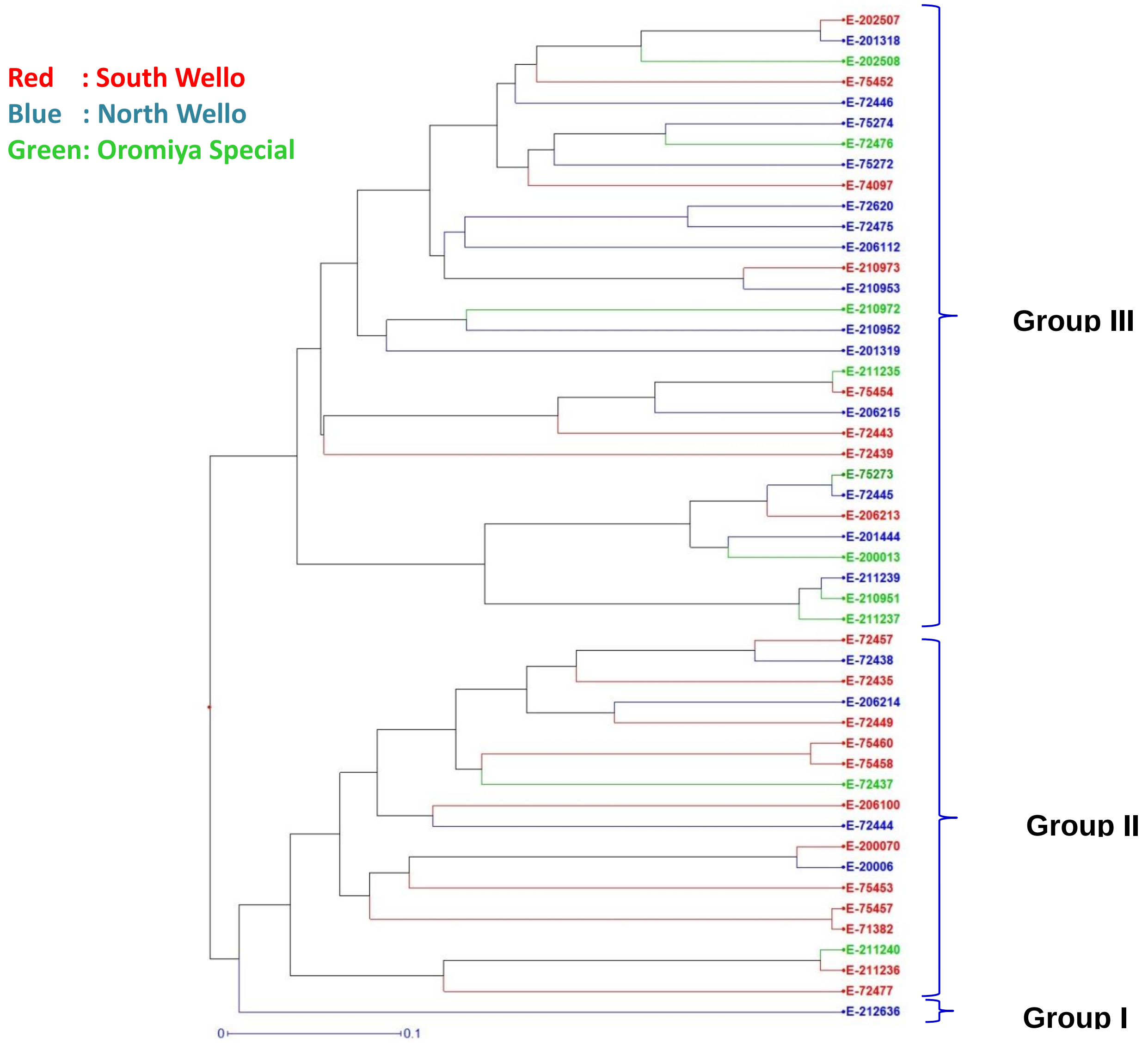

Figure 4.2 Dendrogram illustrating the genetic diversity of 50 sorghum genotypes with 39 SSR markers using "Neighbor Joining" method

4.5.4 Genetic diversity through principal component analysis

Factorial analysis of 50 sorghum genotypes was performed based on Rogers-Tanimoto dissimilarity index. The two first principal components (PC) accounted for 38.29% of the total variation with PC1 accounting to 25.08% and PC2 to 13.21%. Three major sets are displayed (Figure 4.3). The samples used in the present study were more diverse in terms of their genetic distinctiveness than that of their area of collection. Set I contained 4, 3 and 5 genotypes collected from North Wello, South Wello and Oromiya Special Zones, respectively. Genotype E-72437, better performing genotype under drought condition was also presented in Set-I. Twenty-two genotypes were presented in Set-II. This set comprised of mainly drought tolerant and high yielding genotypes (E-72457, E75457, E-20006, E-206100, E-206214, E-72435, E-75458 and E-75460). Set-III composed of 16 genotypes of which four were drought tolerant high yielding genotypes (E72449, E-200070, E-72444 and E-75453).

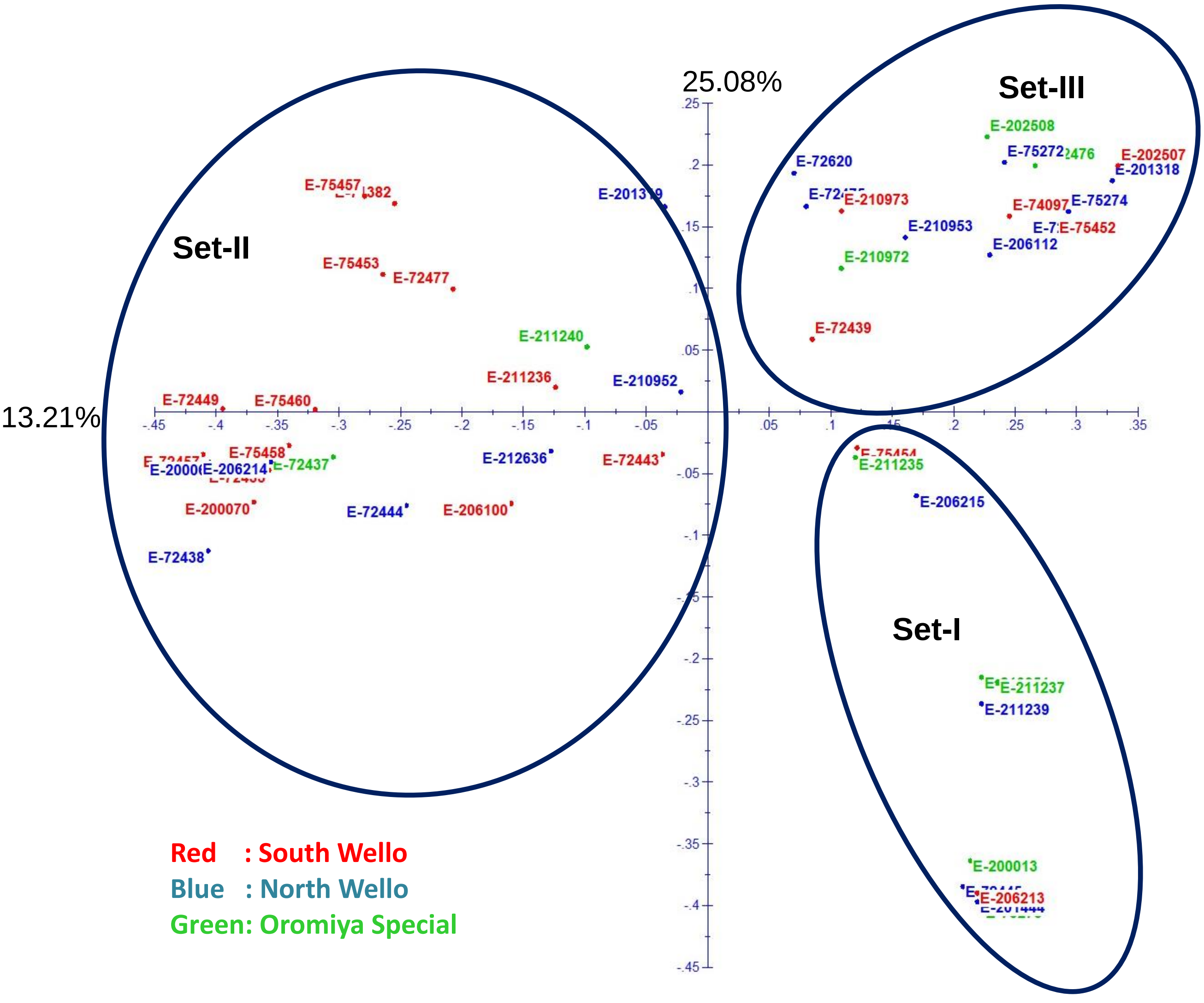

Figure 4.3 B-plot of PC1 (25.58%) and PC2 (13.21%) from principal component analysis illustrating the grouping

4.5.5 Structure Analysis

The natural logarithm of the probability of the data, proportional to the posterior probability of K, showed clear peak for K = 3 and hence the determination of the true number of populations (K) was simple. The rate of change of Napierian logarithm probability relative to the standard deviation (ΔK) as described by Evanno et al. (2005) was estimated. The results showed the highest peak at K = 3 indicating the presence of three major clusters: collections from North Wello, South Wello and Oromiya Special Zones. Structure is considered to be uniform when more than 80% of the accessions in one group have more than 80% of membership in this group.

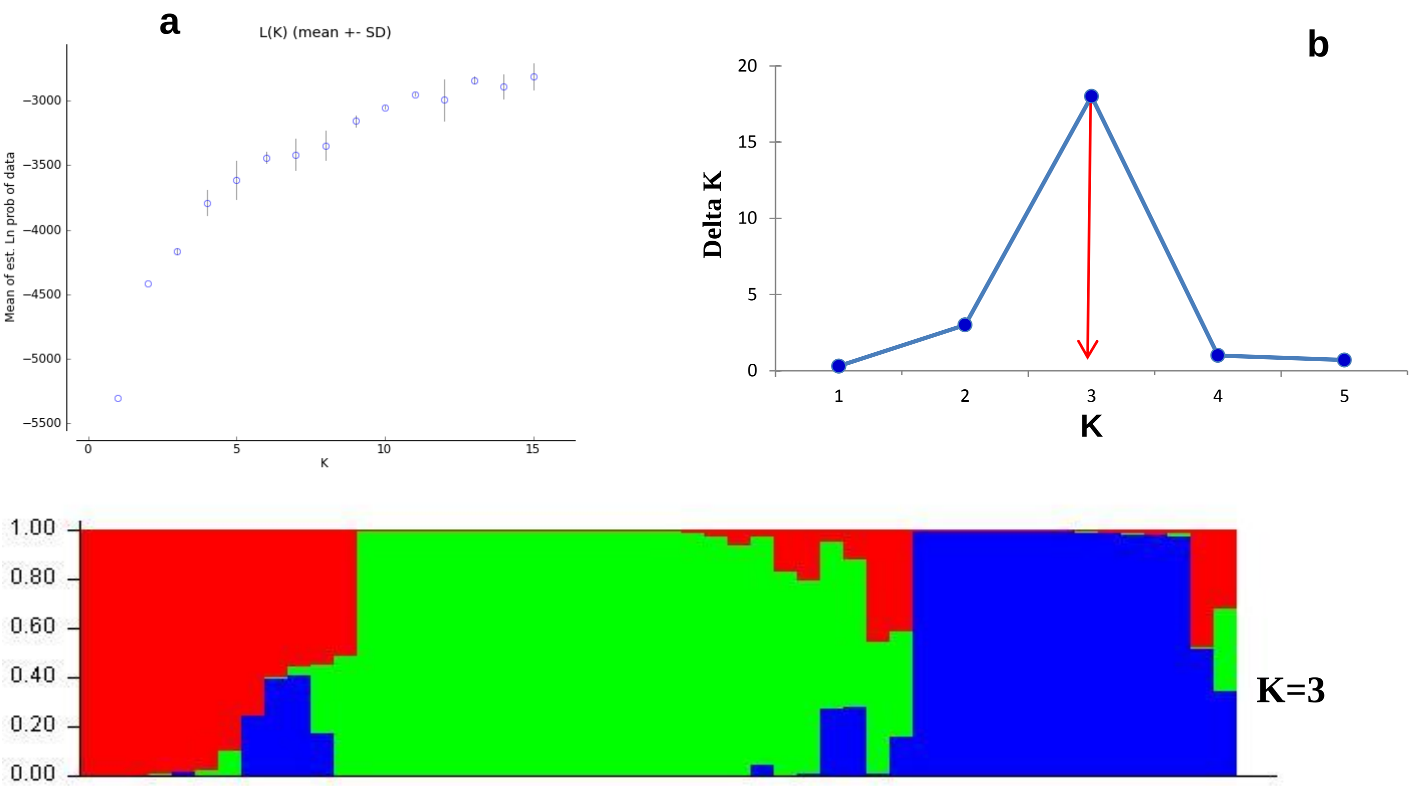

Figure 4.4 Three groups of 50 sorghum genotypes inferred from STRUCTURE analysis and the description of detected the optimum value of K by using graphical method

(**a**) Mean L (K) over 20 runs for each K value; (**b**) Maximum delta K (ΔK) values were used to determine the uppermost level of structure for K ranging from 2 to 5, here K is three and three clusters. Red zone: South Wello; Green zone: Oromiya Special; Blue zone: North Wello.

4.5.6 Analysis of Molecular Variance

To assess distinctiveness among and within the sub-populations, an Analysis of Molecular Variance was carried out. The AMOVA analysis (Table 4.3) attributes 0.91% of genetic variation to the differentiation among populations, 61.85% due to differentiation among individuals and 37.24% was due to difference within individuals in a population.

Table 4.3 Results of molecular variance analysis with 50 sorghum genotypes

Sources of variation	df	Sum of Squares	Variance components	Percentage of variation
Among population	2	39.246	0.09358	0.91
Among individuals within populations	47	779.964	6.37749	61.85
Within individuals	50	192	3.84000	37.24
Total	99	1011.21	10.31106	

4.6 Discussion

SSR analysis indicated the presence of high genetic diversity among medium-maturing sorghum genotypes. Thirty-seven of the SSRs amplified more than one fragment in the same genotype indicating a residual heterogeneity that existed within the tested genotypes confirming the results of Agrama and Tuinstra (2003).

All SSR loci used in this study exhibited a high degree of polymorphism with 2 to 18 alleles per locus with a mean of 7.15 alleles per primer (Table 4.2). Moreover, the mean number of alleles per locus (7.15) observed in this study was higher than previous studies that used SSR markers in testing sorghum accessions from North Eastern Benin which reported a mean of 7 alleles per locus (Missihoun et al., 2015), Zambia, 4.4 (Ng'Uni et al., 2011), Eastern Kenya, 5.05 (Muui et al., 2016), Eritrea, 4.8 (Tesfamichael Abraha et al., 2014) and Ethiopian collections in combination with other countries, 4.5 (Agrama and Tuinstra, 2003). Similarly, mean number of alleles recorded per locus (overall mean of 7.15) in the present study was higher than recorded by Kudadjie (2006), Barro-Kondombo et al. (2010) which were 3.7 and 4.9 respectively on their sorghum diversity studies using SSR markers. However, it is lower than the report of Cuevas and Prom (2013) (14 alleles per locus) who used population structure and diversity analysis of 137 Ethiopian sorghum germplasm conserved at USDA-ARS National Plant Germplasm System.

Higher polymorphism level observed in this study could be attributed to the extensive and regular seed exchange among farmers in Ethiopia (McGuire, 2000). Sorghum having evolved across a wide range of environments in Africa exhibits a great range of phenotypic diversity and displays considerable tolerance to abiotic and biotic stresses (Clarissa et al., 2013). The high level of the observed mean PIC (0.6) in this study also indicated the discriminatory power of the selected SSR markers. Similar findings were indicated in studies by Ceuvas and Prom (2013) and to a certain extent Agrama and Tuinstra (2003) who reported average PIC values of 0.78 and 0.622, respectively. In the same way, mean PIC value in this study (0.601) is comparable to previous studies of genetic diversity (Beyene et al., 2014) who reported a mean PIC value of 0.60. However, the observed PIC value is higher than that of Missihoun et al. (2015), and Muui et al. (2016) who reported 0.33 and 0.49, respectively. One of the most important indicators for the comparison of different markers of differentiation is their PIC. High PIC values indicate high polymorphism or represent a rare allele or alleles at indicator position, which plays an important role in the differentiation of individuals (Agrama & Tuinstra, 2004).

Neighbor-joining cluster analysis and principal component analysis grouped the 50 genotypes in to three clusters and three sets, respectively (Figure 4.2 and 4.3). Lack of differentiation among germplasms towards their geographic origin indicates the high levels of gene flow between populations. Figure 4.2 showed a clear grouping and differentiation of sorghum genotypes based on their genetic relatedness at DNA level rather than based on their ecological zones. Missihoun et al. (2015) found that the 61 samples from Benin were structured according to their botanical race and morpho-physiological characteristics of grain sorghum type using 20 SSR markers. In contrast, cluster analysis of Ethiopian and Eritrean accessions failed to group the landraces of the same region and adaptation zones together when analysed by RAPD (Ayana and Bekele, 1998).

4.7 Conclusions

The present study used microsatellite markers in estimating the genetic diversity present among north-eastern Ethiopian medium-maturing sorghum collections for the first time. The results revealed high genetic variability among the studied genotypes. Cluster, principal component and structure analyses classified the 50 sorghum genotypes into three genetic groups. However, the numbers of genotypes allocated in each set or group were variable. In addition, cluster and principal component analyses showed that the tested populations are genetically related and still have many alleles in common independent to their geographic origin probably due to a considerable amount of germplasm movement and gene flow across different Zones.

Fourteen divergent genotypes were selected and advanced based on their genetic distinctiveness. Genetically distant genotypes such as E-72457, E-206214, E-72438, E-75460, E-72435 and E-75458 were selected from Group II and Set II based on cluster and principal component analyses. Genotype E-72437 was selected from Cluster II and Set I. The remaining 7 genotypes (E-75452, E-72446, E-74097, E-201444, 75273, E-211235 and E-200013) were selected from Group III based on cluster analysis and Set III using principal component analysis. It is concluded that there is huge genetic variability among tested genotypes which can be used as great opportunity for future sorghum breeding program for the development of drought tolerant, medium-maturing and high yielding sorghum varieties.

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CHAPTER 5

Combining ability, heterosis and heritability analyses for yield and yield-related traits in medium-maturing sorghum genotypes

5.1 Abstract

Success on development of breeding populations and hybrid varieties is dependent on the availability of genetically complementary parents and families, and the magnitude of heritability of economic traits. The objective of this study was to determine combining ability, heterosis and heritability of yield and yield-related traits in medium-maturing sorghum [*Sorghum bicolor* (L.) Moench] genotypes to select promising parents and families for breeding. Crosses were performed involving seven lines and seven testers of medium-maturing selected sorghum genotypes using a line x tester mating deign. The 49 F_1 hybrids, 14 parents and a standard hybrid check were evaluated using a triple lattice design with three replications during the 2016 cropping season. Data were collected on eight yield and yield-related traits. Results showed the presence of considerable variations amongst test genotypes allowing selection of suitable parents and hybrids for traits of interest. The general combining ability (GCA) effects revealed that lines such as E-75460 and E-72435 and testers E-74097, E-75452, E-72446 and E-201444 were the most promising general combiners for grain yield. Based on specific combining ability (SCA) effects five crosses such as E-75460 x E-75273, E-72437 x E-72446, E-72457 x E-72446, E-72435 x E-74097 and E-72457 x E-75452 were selected with superior grain yields. Further, these crosses exhibited high mean performance and high heterosis for grain yield and yield-related traits. The cross, E-75460 x E-75273 showed the highest significant positive heterosis for grain yield over the standard check ESH-2. Broad sense heritability was the highest for plant height (99.77%) followed by harvest index (96.59%) and 1000-seed weight (94.99%), while narrow sense heritability values were relatively lower suggesting that dominance gene action was important in controlling the expression of all traits. The selected parents and crosses are recommended for population development and heterosis breeding.

Keywords: GCA; heritability; heterosis; sorghum; SCA.

5.2 Introduction

Sorghum is predominantly self-fertilising diploid (2n=2x=20) crop belonging to the family Gramineae. Sorghum has highly repetitive and tractable genome size of 750 Mb, about 25% of the maize or sugarcane genome size making it a model crop in functional genomics. It is a C4 plant with higher photosynthetic efficiency with relatively higher drought tolerance ability. Sorghum is an important cereal crop in drier areas of the world such as northeast Africa, India and the southern plains of the United States (Nagy et al., 1995; Paterson et al., 2009; Reddy et al., 2009; Panguluri and Kumar, 2013).

Sorghum is native to Africa with its center of diversity being in Ethiopia and Sudan. It is a multi-purpose crop serving for food, feed, bio-energy, and breweries (Reddy et al., 2009; Maikasuwa and Ala, 2013; Tari et al., 2013). It is a gluten-free cereal used as a whole grain or processed in to flour to provide essential nutrients including carbohydrates, protein, vitamins, minerals and nutraceuticals such as antioxidants, phenolics and cholesterol-lowering waxes (Taylor et al., 2006; Perazzo et al., 2014). In sub-Saharan Africa (SSA) sorghum is primarily used for food being consumed in the form of soup, porridge or bread. Sorghum stover is an important feed source to livestock in the mixed crop-livestock systems prevalent in the semi-arid tropics.

In 2014, the global area cropped with sorghum was 44.9 million hectares and the worldwide production was 68.9 million metric tons; the USA, Mexico, Nigeria, Sudan, India and Ethiopia are the main producers (FAOSTAT, 2017). In SSA >40% of the total land is allocated for sorghum production (FAOSTAT, 2017). However, yield levels in SSA have remained low (<1t ha^{-1}) due to continuous use of low yielding cultivars.

In Ethiopia a total of 4.34 million tons of sorghum is being produced per annum. Sorghum is one of the major food cereals after maize and tef in terms of number of growers, area coverage and grain production in Ethiopia (CSA, 2016). It is utilized in various forms, such as for making the local bread, “Injera”, and for the preparation of local beverages, “tela” and “areki”. It is also consumed as roasted vegetable and boiled grain. Sorghum stalks is used for feed, housing and fencing material.

The continuing demand for sorghum for food and animal fodder is reflected in the trend for increasing area under sorghum since 2006 in Ethiopia (FAOSTAT, 2017). However, the productivity of the crop has not kept pace with this increasing demand. The main causes of low yields of sorghum in the country include abiotic (drought and poor soil fertility) and biotic (pests and disease) stresses (Geremew et al., 2004; Beyene et al., 2016). Even though several improved pure line varieties have been developed and released, yield gains under smallholder farmers systems are minimal with mean national yield of 2.3 t ha^{-1}(CSA, 2016). Improvement of sorghum by selection within traditional cultivars or by selecting progeny from crosses between similar traditional cultivars has generally not been promising in enhancing yields (House, 1995).

Hybrid sorghum technology can offer an opportunity to boost the yield of sorghum. Sorghum hybrid breeding began in 1927 (Conner and Karper, 1927), but commercial hybrids were feasible only after the identification of a heritable and stable cytoplasmic male sterility systems (Stephens and Holland, 1954). Exploitation of sorghum hybrids can significantly increase yields in sorghum growing areas (House et al., 1997) because they can out-yield local cultivars and improved varieties by 20 - 60% (Bantilan et al., 2004). For instance, in Sudan the popular sorghum hybrid Hageen Dura-1 out-yielded local varieties by 50-85% on farmers' fields and 300-400% under irrigated conditions (Ejeta, 1986).

Success on development of breeding populations and hybrid varieties is dependent on the availability of genetically complementary parents and families, and the magnitude of heritability of economic traits (Hochholdinger and Hoecker, 2007). The combining ability of parents determines their potential value in breeding population and hybrid development to enhance yield and drought tolerance. Crosses between genetically unrelated parents result in vigorous F_1 hybrids and promising segregants. General combining ability (GCA) is directly related to the breeding value of the parents and is associated with additive genetic effects, while specific combining ability (SCA) is associated with non-additive genetic effect predominantly contributed by dominance, or epistatic effects (Salgotra et al., 2009). A line × tester mating design is one of the widely used genetic designs in sorghum breeding program to identify best parents (lines or testers) for population development and to identify superior hybrids, and to assign lines to new heterotic groups.

Recurrent drought is the leading cause of yield reduction in sorghum production in Ethiopia. Many attempts have been made to develop early maturing sorghum varieties that are adapted to areas where moisture scarcity is detrimental to sorghum production in the country. Even though advances have been done in developing varieties with adequate levels of drought tolerance using indigenous landraces, including selection for farmer-and market-preferred grain and stalk traits, farmers in Ethiopia are still cultivating drought-susceptible, long-maturing and low yielding local landraces. No early maturing varieties have been released that could be planted in April to the first week of June. Development of sorghum varieties with drought tolerance and early or medium-maturity would have significant value in the farming system of the north eastern Ethiopia. In an attempt to develop promising medium-maturing sorghum hybrids and breeding populations with increased yield and drought tolerance the present study selected promising parents adapted to the north eastern Ethiopian condition (Chapters 3 and 4). Detailed information on the combining ability and heterosis of the newly developed hybrids and the selected parents need to be determined for hybrid breeding. Therefore, the objective of this study was to determine combining ability, heterosis and heritability of yield and yield-related traits in medium-maturing sorghum genotypes to select promising parents and families for breeding.

5.3 Materials and methods

5.3.1 Plant materials, field planting and crosses

The study used the following 14 sorghum genotypes (Table 5.1): seven lines including E-72457, E-206214, E-72438, E-75460, E-72435, E-75458, E-72437 and seven tester parents such as E-75452, E-72446, E-74097, E-201444, E-75273, E-211235 and E-200013. The parents were selected based on their medium-maturity, genetic potential for yield and yield-related traits and based on their diverse genetic background (Chapters 3 and 4). Parental inbred lines were grown under field conditions in 2015 off-season from January to May, 2015. Each entry comprised of three-rows of 3 m length with row to row distance of 0.75 m and plant to plant distance of 0.25 m. During sowing the three rows of each entry were staggered by a week interval to extend the window period of pollen harvesting and to prolong the emasculation and pollination activity. Crosses were performed using a line x tester mating design (Kempthorne, 1957). This provided a total of 49 F_1 hybrids. Also one hybrid variety ESH-2 (Ethiopian sorghum hybrid-2) was used as a standard check. Lines were selected to utilize maternal cytoplasmic attributes such as acceptable plant height and grain colour, whereas testers were selected on the basis of superiority in pollen production apart from yielding potential and drought tolerance. Crossing was performed as follows. Briefly, from each line, all florets except those that are to be emasculated were removed with scissors, leaving only the florets that are expected to open the next day. The three anthers per spikelet were removed using forceps. Each emasculated panicle was paper bagged until the stigmas were protruded. The stigma was pollinated after three days using pollen brush.

Table 5.1 List of parents used in the study

S/No.	Name	Traits	Role in cross
1	E-72457	Medium- maturing, high yielding, drought tolerant	Line
2	E-72438	Medium- maturing, high yielding, drought tolerant	Line
3	E-72435	Medium- maturing, high yielding, drought tolerant	Line
4	E-206214	Medium- maturing, high yielding, drought tolerant	Line
5	E-75460	Medium- maturing, high yielding, drought tolerant	Line
6	E-75458	Medium- maturing, high yielding, drought tolerant	Line
7	E-72437	Medium- maturing, high yielding, drought tolerant	Line
8	E-211235	Medium-maturing, moderate in drought tolerance and yield potential	Tester
9	E-201444	Medium-maturing, moderate in drought tolerance and yield potential	Tester
10	E-200013	Medium-maturing, moderate in drought tolerance and yield potential	Tester
11	E-75273	Medium-maturing, moderate in drought tolerance and yield potential	Tester
12	E-75452	Medium-maturing, moderate in drought tolerance and yield potential	Tester
13	E-74097	Medium-maturing, moderate in drought tolerance and yield potential	Tester
14	E-72446	Medium-maturing, moderate in drought tolerance and yield potential	Tester

5.3.2 Experimental design and field management

The 49 F_1 hybrids, 14 parents and the check variety were field planted using a triple lattice design in July 2016 during main cropping season at Kobo testing site of Sirinka Agricultural Research Center in Ethiopia. Each entry was planted in two rows of 3 m length with a spacing of 0.75 m between rows and 0.25 m between plants. Standard sorghum agronomic practices and plant protection measures were followed throughout the crop growth period according to recommendation to the study area.

5.3.3 Data collected

Eight agronomic traits were collected based on sorghum descriptors (IBPGR/ICRISAT, 1993). The following data were collected:1) days to 50% flowering (DF) and 2) days to 75% maturity (DM): as the number of days from emergency to the date when 50% and 75% the plants in the plot reach 50% flowering and 75% maturity, in that order. 3) plant height (PH): measured as the mean height in centimetres from the ground to the tip of the panicle at maturity from randomly selected ten plants in a plot, 4) panicle exsertion (PE): the mean distance in centimetres from the base of the flag leaf's to the base of the lowest panicle branch at maturity, 5) 1000-seed weight (TSW): the weight of 1000 randomly sampled seeds in grams, 6) grain yield (GY): the weight of the grain harvested per plot, expressed in t ha^{-1} adjusting the weight to 12.5% moisture, 7) above ground biomass yield (ABM): measured as sun dried above ground biomass at physiological maturity and 8) harvest index (HI): measured as the percentage of the ratio of plot grain yield to the total above ground biomass yield.

5.4 Data analysis

5.4.1 Analysis of variance

The data obtained from lattice design of each plot were subjected to analysis of variance, using the linear model $Y_{ijk} = m + t_i + r_j + b_{k(j)} + e_{ijk}$ where Y_{ijk}= value observed of treatment i, in block k, with in replication j; m: general mean of the experiment; t_i= the effect of treatments (genotypes) i, $i = 1,2,3 \ldots .64$; r_j = random effect of the replication j; $j = 1\ldots3$; $b_{k(j)}$= random effect of block k, within replication j; e_{ijk} = experimental error associated to the Y_{ijk} observations. The analysis was performed using SAS (SAS, 2011). Adjusted means of assessed traits were generated and used for mean performance evaluation of parents, hybrids and to compute heterosis.

5.4.2 Line x tester analysis

Data from test genotypes were subjected to line x tester analysis according to procedure described by Kempthorne (1957) and Singh and Chaudhary (1985). Mean sum of squares that arises due to different sources of variation were estimated and their expected genetic values were calculated. The general combining ability (GCA) effects of parents and specific combining ability (SCA) effects of crosses were estimated using the following model. The GCA effects of fourteen parentages i.e., seven lines and seven testers were estimated according to procedure described by Kempthorne (1957) and Singh and Chaudhary (1985). The estimates of general combining ability (GCA) effects of line and tester are presented in Table 5.4.

$X_{ijk} = \mu + l_i + t_j + s_{ij} + e_{ijk}$

Where,

i = 1,2…i^{th} line

j = 1,2…j^{th} tester

k = Number of replications

μ = Mean

l_i = GCA effect of the i^{th} line

t_j = GCA effect of the j^{th} tester

s_{ij} = SCA effect of hybrid of i^{th} line with j^{th} tester

e_{ijk} = Error effect associated with the ijk^{th} observation

The individual effect of GCA and SCA were estimated using the following formulas:

$$\mu = \frac{X..}{rlm}$$

$$f_i = \frac{X_{i..}}{rl} - \frac{X...}{rlt} (\text{Check} \sum l_i = 0)$$

$$m_j = \frac{X_{j..}}{rt} - \frac{X...}{rlt} (\text{Check} \sum t_j = 0)$$

$$s_{ij} = \frac{X_{ij}}{r} - \frac{X_{i..}}{rt} - \frac{X_{j..}}{rt} - \frac{X...}{rlt}$$

Where,

X ... = Total of all hybrid combination.

Xi.. = Total of i^{th} line over $'t'$ tester and $'r'$ replication

Xj.. = Total of j^{th} tester over $'l'$ line and $'r'$ replication

Xij = Total of the hybrid between i^{th} line and j^{th} tester over $'r'$ replication

Significance of GCA effects of lines was tested as:

$$t = \frac{l_i}{SE(l_i)}$$

Significance of GCA effects of Testers was tested as:

$$t = \frac{t_j}{SE(t_j)}$$

Significance of SCA effects of hybrids was tested as:

$$t = \frac{S_{ij}}{SE(s_{ij})}$$

5.4.3 Estimation of heritability

If a phenotype is determined, in part, by the genotype, the heritability is known as broad-sense heritability (Bernardo, 2014) whereas, narrow-sense heritability is the degree to which a trait is passed from parent to offspring expressed as the ratio of the additive genetic variance to the total phenotypic variance. Heritability in the broad sense and narrow sense were calculated using Falconer and Mackay (1996) as follows:

Broad sense heritability = $\left(\frac{\sigma^2{}_G}{\sigma^2{}_P}\right) * 100$

Narrow sense heritability = $(\frac{\sigma^2{}_A}{\sigma^2{}_G+\sigma^2{}_E}) * 100$

Where,

$\sigma^2{}_G$ = Genetic variance

$\sigma^2{}_P$ = Phenotypic variance

Genetic variance ($\sigma^2{}_G$) = $\sigma^2{}_A + \sigma^2{}_D + \sigma^2{}_I$

Where,

$\sigma^2{}_A$ = Additive variance or breeding value

$\sigma^2{}_D$ = Dominance variance

$\sigma^2{}_I$ = Interaction or epistasis variance however, in the present study the assumption is no epistasis.

Phenotypic variance ($\sigma^2{}_p$) = $\sigma^2{}_G + \sigma^2{}_E$

Where,

$\sigma^2{}_E$ = Environmental variance

The additive variances of line and tester, and dominance variance of the cross were calculated using the method reported by Sayed and Bedawy (2016) as follows:

Additive variance ($\sigma^2{}_A$) = $\frac{[2\sigma^2{}_L+2\sigma^2{}_T]}{2} = \sigma^2{}_{AL} + \sigma^2{}_{AT}$

Where,

$\sigma^2{}_{AL}$ = Additive variance of line; $\sigma^2{}_{AT}$ = Additive variance of tester

Dominance variance ($\sigma^2{}_{LT}$) = $\frac{[Ms(LxT)-MSe]}{rt} = \sigma^2{}_D$

Where,

Ms_{LxT} = mean square of the crosses; MSe = mean square error (environmental variance); r = number of replication; t = number of treatments; $\sigma^2{}_D$= Dominance variance of the crosses

In the end phenotypic variance ($\sigma^2{}_P$) was calculated as follows:

$$\sigma^2{}_P = \sigma^2{}_L + \sigma^2{}_T + \sigma^2{}_{LxT} + \sigma^2{}_e = \sigma^2{}_A + \sigma^2{}_D + \sigma^2{}_E = \sigma^2{}_G + \sigma^2{}_E$$

5.4.4 Estimation of heterosis

Heterosis for each trait was calculated using the overall mean of each genotype. Relative heterosis, hetrobeltiosis and standard heterosis were estimated as per cent deviation of hybrid value from its mid parental, better parent and standard check values, respectively as outlined by Falconar and Mackay (1996) and Bhatt (1971). The formula used for estimating the three heterosis effects were as follows:

$$\text{Relative heterosis} = \frac{\bar{F}_1 - \overline{MP}}{\overline{MP}} x100$$

where,

$\bar{F}_1$ = Mean hybrid performance of the specific combination, and

$\overline{MP}$ = Mid parent value i.e., the arithmetic mean of two parents involved in the respective cross combination.

Heterobeltosis was calculated at the deviation of hybrid from the better parent as

$$\text{Heterobeltiosis} = \frac{\bar{F}_1 - \overline{BP}}{\overline{BP}} x100$$

Where,

$\bar{F}_1$ = Mean hybrid performance, and

$\overline{BP}$= Average performance of better parent in the respective cross combination.

Standard heterosis,

$$\text{Standard heterosis} = \frac{\bar{F}_1 - \overline{SV}}{\overline{SV}} x100$$

Where,

$\bar{F}_1$ = Mean hybrid performance of the specific combination, and

$\overline{SV}$ = Average performance of standard variety

The significance difference among the three types of heterosis was carried out by adopting ‘t’ test as suggested by Nadarajan and Gunasekaram (2005). The ‘t’ obtained was tested against the tabular ‘t’ value at error degree of freedom.

$$\text{t (relative heterosis)} = \frac{RH}{SE_{he}}$$

$$\text{t (heterobeltiosis)} = \frac{BP}{SE_{he}}$$

$$\text{t (standard heterosis)} = \frac{SH}{SE_{he}}$$

Where,

RH, BH, SH and SE_{he} represents relative heterosis, heterobeltiosis, standard heterosis and standard error of heterosis.

5.5 Results and discussion

5.5.1 Genetic variability

The analysis of variance showed the presence of considerable variations among test genotypes suggesting differential responses for effective selection for trait of interest (Table 5.2). Several authors reported considerable genetic variability for grain yield and its components in sorghum (Abdisamid et al., 2017; Shakeria et al., 2017; Sory et al., 2017).

5.5.2 Mean performance of genotypes

Selection of earlier flowering and maturing hybrids is crucial for drought tolerance breeding. In north eastern Ethiopia sorghum production is mainly challenged by post-flowering drought stress occurring at flowering and end of the growing season. Hybrids with early flowering and maturity can escape the stress. Days to flowering varied from 75.3 to 90, 75.33 to 82.67 days for hybrids and parents, respectively with a grand mean of 81.40 days (Table 5.2). Mechanisms of drought tolerance in sorghum can be described as escape, avoidance and tolerance (Reddy et al., 2009). Early maturity is a well-known ‘drought-escape’ mechanism through which the crop completes its life cycle before the onset of severe moisture deficits, and is often associated with reduced yield potential. In the present study several hybrids flowered earlier than the check cultivar, for example, E-72435 x E-75273, E-72457 x E-201444, E-72435 x E-200013, E-72457 x E-211235, E-72438 x E-75452, E-72438 x E-211235, E-72438 x E-75273, E-72457 x E-72446, E-75458 x E-75452, E-72457 x E-75273, E-72438 x E-200013, E-206214 x E-75452, E-75460 x E-72446, E-72457 x E-200013, E-72435 x E-211235 and E-72457 x E-75452 flowered earlier than 80 days. Among hybrids selected for high grain yield, the earliest flowering were E-72457 x E-72446, E-72457 x E-75452, E-75458 x E-75452, E-72435 x E-200013and E-206214 x E-201444 with mean flowering days of 77.3, 79.7, 77.3, 75.7 and 80 days, respectively. Better performing hybrids, E-72437 x E-72446 and E-75460 x E-201444 had taken relatively more number of days-to-50% flowering and 75% maturity. The number of days for grain filling was also higher. In agreement with the present study Craufurd et al. (1993) and Prasad et al. (2008) showed that sorghum accessions which have delayed maturity and higher number of days to grain filling under drought stress are better stay green genotypes. Early matured hybrid, E-72435 x E-200013 had significantly lower number of days to 50% flowering, 75% maturity and grain filling. Thus, such traits can be considered as means of drought escape mechanism in sorghum and several crop species (Turner, 1980). Generally, late maturing hybrids are more productive. However to minimize the risk of terminal water stress, late maturing hybrids are only recommended for areas with extended period of rainfall distribution, while earlier maturing hybrids are preferred for drought prone environments of north eastern Amhara Region and similar environments in the country.

Plant height is a major consideration in sorghum improvement programs in Ethiopia. It is one of the best criteria for classifying sorghums as grain sorghum, dual-purpose sorghum, fodder sorghum, sweet sorghum or forage sorghum (Panguluri and Kumar, 2013). In areas where sorghum stover is important for animal feed, breeding dual-purpose types is the best choice. Difference in plant height could be due to variation in genetic make-up related to differential hormonal balance and cell division rate that result in changes in the plant height of the different varieties (Amanullah et al., 2007). In the present study, genotypes varied with respect to plant height, which ranged from 218.33 to 225.33, 221.33 to 241.33 and 261 to 345.67 cm for testers, lines and hybrids with a grand mean of 285.70 cm. Among the hybrids evaluated E-75460 x E-75273 and E-72438 x E-72446 were dual purpose types with respect to grain yield and plant height. The shortest (6.33 cm) and longest (26 cm) panicle exsertion was recorded for hybrid E-72438 x E-75452 and E-72438 x E-211235. For this trait testers and lines showed moderate performance. The decrease in panicle exsertion is a well-known response of grain sorghum to water stress (Igartua et al., 1995), therefore, in the present experiment, the reduced panicle exsertion for some crosses may be indicative of drought susceptibility.

Analysis of variance for 1000-seed weight showed that parents and hybrids had significant effects on this trait. Hybrids E-72438 x E-75452 (13.33g) and E-75460 x E-75273 (41.67g) showed the lowest and highest 1000-seed weight in gram. Several hybrids outperformed the check hybrid for 1000-seed weight indicating that it is possible to obtain hybrids that are more drought-tolerant with greater 1000-seed weight. The hybrids E-72438 x E-75452, E-206214 x E-211235, E-75460 x E-75452 had lower 1000-seed weight. Reduction in seed weight was also found by earlier workers (Nadi, 1970; Nadi, 1975; Bakheit, 1990; Maman et al., 2004; Naim and Ahmed, 2010). They stated that grain weight tended to increase under full watered conditions than under drought stress condition. Seed weight is an important yield component, which reflects relationship between source and sink of photosynthate during grain filling stage. In this study a maximum 1000-seed weight was recorded (41.67 g) which is by far better than the previous report (28.7 g) by Tekle and Zemach (2014). The difference in grain weight between the tested genotypes may be due to difference in seed size of each genotype. These results agree with Maman et al. (2004) and Alikhani et al. (2012) who concluded that 1000-grain weight were significantly different between test genotypes.

There was significant difference among parents and hybrids in respect to grain yield. This finding is in line with the report of Nazir et al. (2011). Grain yield, which is the primary interest in most breeding programs, showed a wide range of variation. Among the lines, the lowest yield was recorded by E-75458 (3.1 t ha^{-1}) and the highest by E-206214 (3.3 t ha^{-1}). The tester E-200013 yielded the minimum (2.8 t ha^{-1}), while E-75273 had the maximum yield of 3.2 t ha^{-1}. Grain yield of hybrids varied from as low as 1.9 to as high as 5.8 t ha^{-1}. The highest mean grain yield was recorded for a cross E-75460 x E-75273 (5.8 t ha^{-1}) followed by E-72437 x E-72446 (5.7 t ha^{-1}), and E-72435 x E-74097 (5.6 t ha^{-1}). The lowest yielder cross was E-206214 x E-72446 (1.9 t ha^{-1}). Mean grain yields of 3.59, 3.4, 3.2 and 3.0 t ha^{-1} were recorded for hybrids, standard check, lines and testers, respectively. Cross E-75460 x E-75273 also had higher plant height, panicle exsertion, and highest 1000-seed weight (Table 5.2). Among the 49 hybrids evaluated 40.82% of them outperformed the standard check for grain yield.

The mean performance of hybrids for above ground biomass yield varied from 21.6 to 34.7 t ha^{-1} with grand mean of 26.18 t ha^{-1}. The higher above ground biomass yield was observed in E-72438 x E-211235 (34.7 t ha^{-1}), E-72438 x E-72446 (34.1 t ha^{-1}) and E-72438 x E-75273(33.9 t ha^{-1}). As indicated in Table 5.2, 69.39% of the hybrids outperformed the standard check in above ground biomass yield. Grain yield is the most important trait in sorghum breeding as in other crops; however stover yield is equally important in sorghum particularly in drought prone areas of Ethiopia where sorghum sotver is the leading feed source for animals.

Harvest index ranged from 12.63-41.37% with a grand mean of 23.55%. In the present study, hybrid E-72437 x E-72446 followed by E-72457 x E-75452 and E-75460 x E-201444 showed highest value of harvest index indicating the conversion efficiency of the varieties in transforming biological yield into economic yield (Table 5.2).

Table 5.2 Means for eight traits of 49 sorghum hybrids, 14 parents, and one hybrid check evaluated at Kobo testing site in 2016.

Genotypes	DF (days)	DM (days)	PH (cm)	PE (cm)	TSW (g)	GY (t/ha)	AGB (t/ha)	HI (%)
Crosses								
E-72457 x E-75452	79.7	124.3	315.0	12.0	36.3	5.5	24.7	40.4
E-72457 x E-72446	77.3	122.0	284.7	16.0	40.3	5.6	30.8	29.2
E-72457 x E-74097	81.7	120.3	269.7	18.7	30.3	2.8	25.3	18.9
E-72457 x E-201444	75.7	119.0	319.7	18.0	30.7	2.4	31.1	21.9
E-72457 x E-75273	78.0	123.3	316.3	22.3	33.3	3.5	25.1	24.8
E-72457 x E-211235	76.0	125.7	289.7	7.3	33.0	2.6	24.1	22.5
E-72457 x E-200013	79.3	130.3	282.0	16.0	35.0	2.6	22.0	23.2
E-72438 x E-75452	76.0	119.3	261.7	6.3	13.3	2.6	23.1	26.9
E-72438 x E-72446	80.3	123.3	326.0	25.0	39.0	5.3	34.1	27.9
E-72438 x E-74097	82.0	120.7	332.0	24.0	37.0	3.7	30.3	22.9
E-72438 x E-201444	83.0	125.0	342.3	23.0	35.0	3.4	32.2	20.4
E-72438 x E-75273	76.7	118.0	337.7	20.7	34.3	3.3	33.9	17.1
E-72438 x E-211235	76.0	120.0	345.7	26.0	30.3	2.5	34.7	15.5
E-72438 x E-200013	78.0	121.3	291.0	15.0	30.0	2.1	25.5	25.1
E-72435 x E-75452	84.0	123.3	302.7	12.3	40.7	4.6	27.3	27.6
E-72435 x E72446	82.0	126.3	322.3	17.3	32.0	2.8	26.2	34.6
E-72435 x E-74097	80.3	121.3	318.3	16.3	37.3	5.6	23.3	35.5
E-72435 x E-201444	80.7	122.7	294.3	18.0	30.3	2.6	22.1	22.8
E-72435 x E-75273	75.3	121.3	273.7	9.3	32.0	2.6	23.2	24.3
E-72435 x E-211235	79.3	127.0	264.7	11.0	29.0	2.8	21.6	35.1
E-72435 x E-200013	75.7	124.0	275.7	9.7	35.0	5.3	24.1	30.9
E-206214 x E-75452	78.7	120.7	326.7	21.3	30.3	2.7	30.8	15.4
E-206214 x E-72446	82.0	122.7	328.7	22.3	32.3	1.9	29.8	21.0
E-206214 x E-74097	83.7	120.7	316.3	22.7	39.7	4.6	31.6	30.8
E-206214 x E-201444	80.0	121.0	322.0	23.0	35.0	5.2	32.1	25.2
E-206214 x E-75273	81.7	122.0	323.0	22.7	30.3	2.5	27.7	18.2
E-206214 x E-211235	87.0	123.0	286.7	11.3	13.3	2.4	26.4	20.9
E-206214 x E-200013	85.7	126.7	270.3	8.3	30.3	2.9	24.5	23.4
E-75460 x E-75452	85.0	130.0	276.0	10.3	14.3	2.7	23.2	25.3
E-75460 x E-72446	78.7	128.0	283.7	18.0	36.0	3.2	23.5	30.0
E-75460 x E-74097	80.7	122.3	322.7	22.0	39.3	4.7	28.6	33.5
E-75460 x E-201444	81.3	131.7	322.0	23.7	32.3	5.4	31.7	39.1
E-75460 x E-75273	81.0	122.0	322.7	22.3	41.7	5.8	26.3	32.5
E-75460 x E-211235	84.0	124.0	271.7	18.7	35.0	2.6	24.7	26.0
E-75460 x E-200013	82.0	121.0	270.3	21.7	32.7	4.1	26.3	38.9
E-75458 x E-75452	77.3	121.7	318.0	22.0	41.0	5.4	23.1	31.7
E-75458 x E-72446	81.0	124.0	327.0	23.0	32.7	2.5	29.5	19.9
E-75458 x E-74097	80.7	123.7	281.0	16.0	35.3	2.6	22.2	34.9
E-75458 x E-201444	86.3	123.0	318.0	18.7	40.3	5.2	22.3	36.7
E-75458 x E-75273	81.0	125.3	321.7	18.7	34.7	3.3	24.9	28.5
E-75458 x E-211235	83.0	121.7	317.0	15.7	32.0	3.4	22.3	27.0
E-75458 x E-200013	90.7	129.0	290.3	16.0	33.0	2.9	24.7	27.5
E-72437 x E-75452	91.0	123.3	290.3	19.0	39.7	3.8	24.4	33.4
E-72437 x E-72446	85.0	129.7	321.0	25.3	41.3	5.7	32.1	41.4
E-72437 x E-74097	81.7	123.7	318.7	11.0	35.3	5.3	22.7	33.2
E-72437 x E-201444	84.0	132.3	328.0	19.3	33.0	2.7	27.8	18.9
E-72437 x E-75273	84.0	126.0	285.7	15.0	35.3	2.5	27.5	18.3
E-72437 x E-211235	81.3	120.7	261.0	10.3	31.0	2.4	26.7	21.7
E-72437 x E-200013	84.3	128.0	272.7	11.3	30.3	3.1	24.5	12.6

Table 5.2. Continued

Genotypes	DF (days)	DM (days)	PH (cm)	PE (cm)	TSW (g)	GY (t/ha)	AGB (t/ha)	HI (%)
Parents								
E-72457	84.0	137.7	241.3	14.0	25.7	3.2	23.6	13.6
E-72438	82.7	134.3	236.0	15.0	26.0	3.2	22.8	14.1
E-72435	83.7	133.0	237.0	12.0	24.7	3.2	27.7	11.7
E-206214	83.0	134.0	239.3	13.0	27.3	3.3	25.5	12.9
E-75460	81.7	135.0	221.3	13.0	23.0	3.2	24.8	12.9
E-75458	83.3	133.0	222.7	11.0	25.3	3.1	24.6	12.6
E-72437	84.0	135.3	233.7	14.0	27.0	3.2	22.5	14.2
E-75452	80.0	132.7	224.0	10.0	30.7	3.0	23.5	13.0
E-72446	75.3	131.7	218.3	8.0	30.3	2.9	27.4	10.7
E-74097	82.3	129.3	225.3	9.0	31.0	3.1	24.8	12.4
E-201444	82.3	132.7	222.7	10.0	32.0	2.9	25.6	11.2
E-75273	82.3	132.0	218.7	11.0	30.3	3.2	24.5	13.2
E-211235	82.3	133.0	223.7	10.0	33.0	3.1	23.6	13.1
E-200013	82.7	134.0	219.0	9.0	32.3	2.8	23.2	12.1
Check								
ESH-2	80.0	132.3	244.0	16.3	33.0	3.4	24.3	16.0
Mean of hybrids	**81.22**	**123.80**	**303.22**	**17.43**	**33.31**	**3.59**	**26.67**	**26.80**
Mean of lines	**83.19**	**134.62**	**233.05**	**13.14**	**25.57**	**3.20**	**24.50**	**13.14**
Mean of testers	**81.05**	**132.19**	**221.67**	**9.57**	**31.38**	**3.00**	**24.66**	**12.23**
Mean of standard check	**80.00**	**132.33**	**244.00**	**16.33**	**33.00**	**3.40**	**24.30**	**15.97**
Grand mean	**81.40**	**126.04**	**285.70**	**16.08**	**32.24**	**3.48**	**26.18**	**23.55**
Standard error	**1.43**	**2.91**	**7.69**	**2.45**	**3.51**	**1.39**	**4.28**	**8.32**
LSD value (0.05)	**2.34**	**2.65**	**1.81**	**2.59**	**1.41**	**0.19**	**1.63**	**1.63**

DF = Days to 50% flowering; DM = Days to 75% physiological maturity; PH = Plant height; PE = Panicle exsertion; TSW = 1000-seed weight in gram; GY = Grain yield in ton per hectare; AGB = Above ground biomass yield; HI = Harvest index in percentage

5.5.3 Line x tester analysis of variance

Results revealed significant differences among genotypes, crosses, lines, testers and line x tester interactions. The significant differences among the lines, testers and line x tester indicated that the genotypes had wide genetic variability for all traits examined (Table 5.3). The total variance due to hybrids was partitioned into components attributable to lines, testers, their interaction (line x tester) and error sources. Significant mean squares of parents vs crosses indicate a significant average heterosis among cross combinations. Significant mean squares of line x tester for all traits examined show that non-additive genetic effects have important role for controlling these traits. Therefore, the presence of significant differences among the genotypes for characters recorded led to a combining ability analysis. This allowed partitioning the genetic effects of genotypes into GCA and SCA effects. The GCA variance of parents and SCA variance of hybrids for the different characters are important basic criteria for the selection or hybridization programs. The GCA variance was the highest for panicle exsertion (0.34), followed by days to maturity (0.33), plant height (0.22), above ground biomass yield (0.21), 1000-seed weight (0.18), harvest index (0.16) and grain yield (0.03). The SCA variance was the highest for panicle exsertion (0.90), followed by days to maturity (0.88), plant height (0.58), above ground biomass yield (0.53), 1000-seed weight (0.48), harvest index (0.43) and grain yield (0.07). However, all characters exhibited greater SCA variance than GCA variance indicating the preponderance of non-additive gene action. Therefore, hybrid breeding approach will be more useful for improvement of these traits.

Table 5.3 Analysis of variance for plant height, grain yield and yield related traits of sorghum based on line x tester mating design

Source of variation	df	Mean square							
		DF	DM	PH	PE	TSW	GY	AGB	HI
Replication	2	4.59^{ns}	69.40**	50.68**	17.35**	131.12**	0.33**	35.18**	0.38^{ns}
Genotypes	62	33.74**	77.67**	4456.71**	84.88**	108.06**	3.59**	36.03**	53.88**
parents	13	14.60**	11.34**	203.61**	9.78**	31.78**	0.07**	7.53**	3.10**
Crosses	48	39.08**	34.50**	1784.26**	85.32**	115.10**	4.46**	41.52**	68.15**
Par. vs Crosses	1	26.54**	3011.84**	188024.58**	1040.17**	762.06**	7.64**	143.18**	29.25**
Testers	6	114.66**	64.86**	2151.15**	123.60**	81.44**	1.78**	120.56**	88.96**
Lines	6	14.13**	46.20**	4461.39**	188.89**	155.43**	5.49**	65.14**	73.21**
Line x Tester	36	30.64**	27.49**	1276.92**	61.68**	113.98**	4.73**	24.40**	63.83**
Error	124	2.15	2.33	1.005	2.451	0.692	0.01	0.84	0.546
Var of GCA		0.32	0.33	0.22	0.34	0.18	0.03	0.21	0.16
Var of SCA		0.85	0.88	0.58	0.90	0.48	0.07	0.53	0.43

Df = degrees of freedom; ns = non-significant; DF = Days to 50% flowering; DM = Days to 75% physiological maturity; PH = Plant height; PE = Panicle exsertion; TSW = 1000-seed weight in gram; GY = Grain yield in ton per hectare; AGB = Above ground biomass yield; HI = Harvest index in percentage; Var of GCA = Variance of general combining ability; Var of SCA = Variance of specific combining ability; ** = highly significant at P = 0.01 based on F-test.

5.5.4 General and specific combining ability

5.5.4.1 General combining ability (GCA)

The estimates of general combining ability effects represent the fixable component of genetic variance, and are important for developing superior genotypes. A negligible or negative combining ability effect indicates a limited ability of a parent to transfer its genetic superiority to hybrids. The largest significant positive values have the largest effects. On the other hand, the largest significant negative values have the smallest effects, except in case of days to 50% flowering and days to 75% physiological maturity. Breeding sorghum for Ethiopian condition requires positive general combining ability effects in a desirable direction for plant height, panicle exsertion, 1000-seed weight, grain yield, above ground biomass yield and harvest index while for days to 50% flowering and days to 75% maturity negative general combining ability effects are desirable.

5.5.4.1.1 General combining ability effects of lines

The GCA effects for days to flowering and maturity of lines varied from -2.98 (E-72457) to 3.26 (E-72437) and from -2.71 (E-72438) to 2.44 (E-72437), respectively. Lines E-72457 and E-72438 are the best general combiners for early flowering and maturity, respectively, whereas lines E-72437 and E-72437 are the best general combiners for late maturity. Among lines, E-72457, E-72438 and E-72435 showed highly significant negative GCA effects for days to flowering. Likewise, E-72438 and E-206214 showed highly significant negative GCA for days to maturity. Jain and Patel (2014) demonstrated similar findings for days to flowering and maturity on their diallel set of sorghum gene action study.

GCA effects of plant height and panicle exsertion ranged from -10.13 (E-72435) to 16.25 (E-72438) and from -4 (E-72435) to 2.57 (E-72438), respectively. Among the seven lines E-72438, E-206214 and E-75458 showed highly significant positive GCA effects for plant heat, whereas, lines E-72438, E-206214, E-75458 and E-72437 showed significant positive GCA effects for panicle exsertion. Therefore, lines E-72438 and E-72438 were the best general combiners for plant height and panicle exsertion towards the preferred positive direction.

E-75458 had the highest GCA effect (2.27) for 1000-seed weight followed by E-72437, E-72457 and E-72435 with GCA effects of 1.84, 0.84 and 0.46, respectively. The range of GCA effects of grain yield varied from -0.41 (E-206214) to 0.47 (E-75460). Lines E-75460, E-72435 and E-72437 showed significant positive GCA effects of 0.47, 0.16 and 0.07, respectively (Table 5.4). Therefore, lines E-

75458 and E-75460 were the best general combiners for 1000-seed weight and grain yield, respectively. Apart from 1000-seed weight, grain yield and above ground biomass yield some lines also registered significant general combining ability effects in a desirable direction for other traits like days to flowering (E-72457) and maturity (E-206214) (Table 5.4). Thus, it would be worthwhile to use these parents in breeding program to exploit additive gene effects. Similar results were reported by earlier workers in sorghum (Prakash et al., 2010; Mahdy et al., 2011).

For above ground biomass yield, the GCA effects of the lines ranged from -2.70 (E-72435) to 3.88 (E-72438). Among the lines only E-72438 and E-206214 showed significant positive GCA effects for this trait, while the remaining lines showed non-significant and significant GCA effects towards negative direction. The GCA effects of lines for harvest index varied from -2.89 (E-72438) to 2 (E-72435). Lines such as E-72435, E-75458 and E-75460 exhibited significant positive GCA effects of 2, 1.65 and 1.63, respectively. Thus, lines E-72438 and E-72435 appeared as best general combiners for above ground biomass yield and harvest index.

5.5.4.1.2 General combining ability effects of testers

Testers E-75273 and E-74097 had the lowest significant negative GCA effects of -1.55 and -1.99 for days to flowering and maturity, respectively; however, if sorghum breeders are seeking late maturing types tester E-200013 with significant positive GCA effects of 1.02 and 1.96 for days to flowering and maturity was the best general combiner. Among testers only tester E-75273 showed significant negative GCA effect of -1.55 for days to flowering, whereas tester E-74097, E-75273 and E-211235 showed significant negative GCA effects of -1.99, -1.23 and -0.66, respectively for days to maturity. Therefore, testers E-75273 and E-74097 were the best general combiners if breeders are looking for early maturity. Similar finding reported by Makanda et al. (2009) indicated that highly significant GCA for days to flowering and days to maturity when using 10×8 North Carolina Design II mating scheme was recorded.

GCA effects of plant height and panicle exsertion ranged from -24.32 (E-200013) to 17.68 (E-201444) and from -3.43 (E-200013) to 3.57 (E-72446), respectively. Among testers, E-201444, E-72446, E-75273 and E-74097 for plant height and testers E-72446, E-201444, E-75273 and E-74097 for panicle exsertion showed significant positive general combining ability effects, the rest showed significant negative GCA effects for these traits. Therefore, testers E-201444 and E-72446 were the best general combiners for plant height and panicle exsertion, respectively. For commercial sorghum production negative GCA effects for plant height is useful (Fellahi et al., 2013). Tester E-74097 had significant and moderate GCA effect for days to maturity, plant height and panicle exsertion and with the greatest GCA effect for 1000-seed weight (3.03). According to Syukur et al. (2012), the characters which are controlled by additive genes will be easier to be selected particularly for breeding pure line varieties.

Tester E-74097 had the greatest GCA effect (3.03) for 1000-seed weight followed by E-72446 (2.93), E-75273 (1.22) and E-201444 (0.5). The remaining three testers showed significant negative GCA effects for this trait. The range of GCA effects for grain yield varied from -0.91 (E-211235) to 0.60 (E-74097). Among the testers E-74097 (0.60), E-75452 (0.32), E-72446 (0.27) and E-201444 (0.25) showed significant positive GCA effects for grain yield. The present result confirmed earlier findings of Rani et al. (2015); Chaudhary et al. (2006); Premalatha et al. (2006); Aruna et al. (2010) and Mahdy et al. (2011), whereas additive gene action controlling the inheritance of grain yield per plant was reported by Prabhakar et al. (2013). Tester E-74097 with moderate *per se* performance (3.1 t ha^{-1}) and highly significant positive general combining ability effect for grain yield (0.60) and 1000-seed weight (3.03) indicating that this tester is promising for grain yield.

Harvest index is a ratio between economic character (grain yield) and total biomass which showed the proportion of grain yield and stover yield (Lucas, 1981). Selection of sorghum genotypes that have the genetic potential for producing biomass and grain yield is very important due to equal importance of these two traits in the case of Ethiopia. Among the testers, E-74097, E-75452 and E-201444 were good general combiners for harvest index, the remaining four testers showed significant negative GCA effects for this trait. Tester E-74097 was best general combiner for this trait, suggesting their suitability for efficient photo assimilate translocation from source to sink.

Table 5.4 Estimated values of general combining ability effects for eight traits of sorghum parents used in line x tester design.

Parents	DF	DM	PH	PE	TSW	GY	AGB	HI
Lines								
E-72457	-2.98**	-0.23^{ns}	-6.51**	-1.67**	0.84**	-0.02^{ns}	-0.51*	0.06^{ns}
E-72438	-2.36**	-2.71**	16.25**	2.57**	-2.02**	-0.30**	3.88**	-2.89**
E-72435	-1.60**	-0.09^{ns}	-10.13**	-4.00**	0.46*	0.16**	-2.70**	2.00**
E-206214	1.45**	-1.42**	7.30**	1.38**	-3.12**	-0.41**	2.32**	-2.76**
E-75460	0.59^{ns}	1.77**	-7.65**	2.10**	-0.26^{ns}	0.47**	-0.33^{ns}	1.63**
E-75458	1.64**	0.24^{ns}	7.20**	1.14**	2.27**	0.02ns	-2.53**	1.65**
E-72437	3.26**	2.44**	-6.46**	-1.52**	1.84**	0.07*	-0.12^{ns}	0.31^{ns}
Testers								
E-75452	0.45^{ns}	-0.56^{ns}	-4.61**	-2.67**	-2.50**	0.32**	-1.44**	2.08**
E-72446	-0.31^{ns}	1.34**	10.11**	3.57**	2.93**	0.27**	2.76**	-0.67**
E-74097	0.31^{ns}	-1.99**	5.16**	1.24**	3.03**	0.60**	-0.39^{ns}	2.57**
E-201444	0.35^{ns}	1.15**	17.68**	3.10**	0.50*	0.25**	1.81**	0.13^{ns}
E-75273	-1.55**	-1.23**	8.30**	1.29**	1.22**	-0.22**	0.28^{ns}	-0.94**
E-211235	-0.27^{ns}	-0.66*	-12.32**	-3.10**	-4.21**	-0.91**	-0.87**	-2.93**
E-200013	1.02**	1.96**	-24.32**	-3.43**	-0.97**	-0.31**	-2.15**	-0.23^{ns}
$SE\ f_i \& m_j$	0.32	0.33	0.22	0.34	0.18	0.03	0.21	0.16

DF = Days to 50% flowering; DM = Days to 75% physiological maturity; PH = Plant height; PE = Panicle exsertion; TSW = 1000-seed weight in gram; GY = Grain yield in ton per hectare; AGB = Above ground biomass yield; HI = Harvest index in percentage; ns = Non-significant; * and ** = Significant of GCA estimates at p = 0.05 and 0.01, respectively based on T-test.

5.5.4.2 Specific combining ability effects

Specific combining ability effect represents the non-fixable component of genetic variation that provides information on hybrid performance. Among all the 49 hybrids, the SCA effects for days to flowering and days to maturity varied from -5.97 (E-75458 x E-75452) to 6.79 (E-75458 x E-200013) and from -6.53 (E-75460 x E-200013) to 4.99 (E-75460 x E-75452), respectively. Thus, E-75458 x E-75452 for days to flowering and E-75460 x E-200013 for days to maturity were the best specific combiners. Out of 49 hybrids, 14 and 13 hybrid crosses showed negative significant SCA effects in the direction of early flowering and maturity, respectively, whereas 13 and 11 hybrid crosses exhibited positive significant SCA effects in the direction of late flowering and maturity, respectively. Twenty-two hybrids for days to flowering and 25 for days to maturity showed non-significant SCA effects. The SCA variance was greater than the GCA variance, indicating the preponderance of non-additive gene action for day to 50% flowering and days to 75% maturity. Thus, there is possibility of exploiting hybrid vigor for these traits. Similar results have also been reported by Kumar and Chand (2015) and Agarwal et al. (2005).

The range of SCA effects for plant height and panicle exsertion varied from 38.51 (E-72438 x E-211235) to 53.20 (E-72438 x E-75452) and from -11 (E-72438 x E-75452) to 9.10 (E-72438 x E-211235), respectively. Among the 49 hybrids, 28 of them exhibited significant positive SCA effects; 19 hybrids expressed significant negative SCA effects and the rest two hybrids showed non-significant effects for plant height. Depending on the interest of the growers modification of plant height could be possible in both ways as the height in the present study was determined by both additive and non-additive genes. These finding are in agreement with Makanda et al. (2009). Differently, Tadesse et al. (2008) reported the prevalence of additive gene action in determining these traits.

Positive significant non-additive effects were observed in some of the crosses for grain yield and 1000-seed weight. The SCA effects of the hybrids ranged from -1.67 (E-75460 x E-75452) to 1.93 (E-75460 x E-75273) for grain yield and from -16.22 (E-75460 x E-75452) to 9.4 (E-72435 x E-75452) for 1000-seed weight. Among the 20 hybrids that exhibited significant positive SCA effects, hybrid E-75460 x E-75273, E-72435 x E-200013, E-72437 x E-72446, E-206214 x E-201444 and E-72438 x E-72446 were the top five specific combiners for grain yield; whereas hybrid E-72435 x E-75452, E-75458 x E-75452, E-75460 x E-75273, E-72437 x E-75452 and E-206214 x E-74097 were the top five hybrids for 1000-seed weight amongst 22 crosses that showed significant positive SCA effects (Table 5.5). Both additive and non-additive gene effects were significant for these two economically important traits. Similar findings were also reported by Makanda et al. (2010) and Aruna et al. (2010).

Sixteen and 17 hybrids showed significant positive SCA effects for above ground biomass yield and harvest index, respectively. Hybrids, E-72437 x E-72446, E-72457 x E-72446, E-75460 x E-201444 and E-72435 x E-200013 exhibited significantly positive SCA effects for the two traits with remarkable grain yield potential.

Table 5.5 Specific combining ability effects for eight traits in 49 sorghum crosses

Crosses	DF	DM	PH	PE	TSW	GY	AGB	HI
E-72457 x E-75452	0.98ns	1.33ns	22.89**	-1.10ns	4.69**	1.58**	-0.05ns	6.47**
E-72457 x E-72446	-0.59ns	-2.91**	-22.16**	-3.33**	3.26**	1.73**	1.88**	5.12**
E-72457 x E-74097	3.12**	-1.24ns	-32.20**	1.67ns	-6.84**	-1.36**	-0.44ns	-5.23**
E-72457 x E-201444	-2.93**	-5.72**	5.27**	-0.86ns	-3.98**	-1.39**	3.12**	-5.99**
E-72457 x E-75273	1.31ns	0.99ns	11.32**	5.29**	-2.03**	0.18*	-1.34*	1.35**
E-72457 x E-211235	-1.97*	2.76**	5.27**	-5.33**	3.07**	-0.09ns	-1.16*	-0.09ns
E-72457 x E-200013	0.07ns	4.80**	9.61**	3.67**	1.83**	-0.66*	-2.01**	-1.63**
E-72438 x E-75452	-3.31**	-1.20ns	-53.20**	-11.00**	-15.46**	-0.97**	-5.97**	-1.42**
E-72438 x E-72446	1.79*	0.90ns	-3.59**	1.43ns	4.78**	1.74**	0.82ns	5.50**
E-72438 x E-74097	2.84**	1.56ns	7.37**	2.76**	2.69**	-0.15*	0.14ns	-0.98*
E-72438 x E-201444	3.79**	2.76**	5.18**	-0.10ns	3.21**	-0.14*	-0.19ns	-0.31ns
E-72438 x E-75273	-0.64ns	-1.86*	9.89**	-0.62ns	1.83**	0.26**	3.08**	0.03ns
E-72438 x E-211235	-2.59**	-0.44ns	38.51**	9.10**	3.26**	0.16**	5.05**	-0.54ns
E-72438 x E-200013	-1.88*	-1.72*	-4.16**	-1.57ns	-0.31ns	-0.88**	-2.93**	-2.28**
E-72435 x E-75452	3.93**	0.18ns	14.18**	1.57ns	9.40**	0.53**	4.77**	-0.87*
E-72435 x E72446	2.69**	1.28ns	19.13**	0.33ns	-4.69**	-1.22**	-0.57ns	-4.25**
E-72435 x E-74097	0.41ns	-0.39ns	20.08**	1.67ns	0.54ns	1.22**	-0.32ns	5.77**
E-72435 x E-201444	0.69ns	-2.20*	-16.44**	1.48ns	-3.93**	-1.44**	-3.66**	-4.16**
E-72435 x E-75273	-2.73**	-1.15ns	-27.73**	-5.38**	-2.98**	-0.94**	-1.02ns	-3.49**
E-72435 x E-211235	-0.02ns	3.95**	-16.11**	0.67ns	-0.55ns	-0.01ns	-1.48*	0.40ns
E-72435 x E-200013	-4.97**	-1.67ns	6.89**	-0.33ns	2.21**	1.86**	2.28**	6.60**
E-206214 x E-75452	-4.45**	-1.15ns	20.75**	5.19**	2.64**	-0.76**	3.22**	-4.05**
E-206214 x E-72446	-0.35ns	-1.05ns	8.03**	-0.05ns	-0.79ns	-1.52**	-1.95**	-3.73**
E-206214 x E-74097	0.69ns	0.28ns	0.65ns	2.62*	6.45**	0.82**	3.00**	1.12*
E-206214 x E-201444	-3.02**	-2.53*	-6.20**	1.10ns	4.31**	1.76**	1.33*	5.23**
E-206214 x E-75273	0.55ns	0.85ns	4.18**	2.57*	-1.07*	-0.46**	-1.53*	-0.90*
E-206214 x E-211235	4.60**	1.28ns	-11.54**	-4.38**	-12.65**	0.16*	-1.76**	1.29**
E-206214 x E-200013	1.98*	2.33*	-15.87**	-7.05**	1.12*	-0.01ns	-2.30**	1.05*
E-75460 x E-75452	2.74**	4.99**	-14.97**	-6.52**	-16.22**	-1.67**	-1.73**	-5.64**
E-75460 x E-72446	-2.83**	1.09ns	-22.01**	-5.10**	0.02ns	-1.13**	-5.57**	-0.95*
E-75460 x E-74097	-1.45ns	-1.24ns	21.94**	1.24ns	3.26**	0.05ns	2.65**	-1.40**
E-75460 x E-201444	-0.83ns	4.95**	8.75**	1.05ns	-1.22*	1.09**	3.55**	1.67**
E-75460 x E-75273	0.74ns	-2.34*	18.80**	1.52ns	7.40**	1.93**	-0.28ns	7.71**
E-75460 x E-211235	2.46*	-0.91ns	-11.59**	2.24*	6.16**	-0.58**	-0.77ns	-1.90**

Table 5.5. continued

Crosses	DF	DM	PH	PE	TSW	GY	AGB	HI
E-75460 x E-200013	-0.83ns	-6.53**	-0.92ns	5.57**	0.59ns	0.32**	2.15**	0.50ns
E-75458 x E-75452	-5.97**	-1.82*	12.18**	6.10**	7.93**	1.47**	0.43ns	6.00**
E-75458 x E-72446	-1.54ns	-1.39ns	6.46**	0.86ns	-5.84**	-1.41**	2.56**	-6.24**
E-75458 x E-74097	-2.50*	1.61ns	-34.59**	-3.81**	-3.27**	-1.64**	-1.56*	-6.29**
E-75458 x E-201444	3.12**	-2.20*	-10.11**	-3.00**	4.26**	1.34**	-3.62**	7.88**
E-75458 x E-75273	-0.31ns	2.52*	2.94**	-1.19ns	-2.12**	-0.06ns	0.45ns	-0.94*
E-75458 x E-211235	0.41ns	-1.72*	18.89**	0.19ns	0.64ns	0.67**	-0.94ns	2.75**
E-75458 x E-200013	6.79**	2.99**	4.22**	0.86ns	-1.60**	-0.37**	2.68**	-3.16**
E-72437 x E-75452	6.07**	-2.34*	-1.82**	5.76**	7.02**	-0.18*	-0.67ns	-0.48ns
E-72437 x E-72446	0.84ns	2.09*	14.13**	5.86**	3.26**	1.80**	2.82**	4.57**
E-72437 x E-74097	-3.12**	-0.58ns	16.75**	-6.14**	-2.84**	1.07**	-3.46**	6.99**
E-72437 x E-201444	-0.83ns	4.95**	13.56**	0.33ns	-2.65**	-1.22**	-0.53ns	-4.33**
E-72437 x E-75273	1.07ns	0.99ns	-19.39**	-2.19*	-1.03*	-0.91**	0.64ns	-3.76**
E-72437 x E-211235	-2.88**	-4.91**	-23.44**	-2.48*	0.07ns	-0.32**	1.05*	-1.91**
E-72437 x E-200013	-1.16ns	-0.20ns	0.22ns	-1.14ns	-3.84**	-0.25**	0.14ns	-1.08*
SE	0.85	0.88	0.58	0.90	0.48	0.07	0.53	0.43

DF = Days to 50% flowering; DM = Days to 75% physiological maturity; PH = Plant height; PE = Panicle exsertion; TSW = 1000-seed weight; GY = Grain yield; AGB = Above ground biomass yield; HI = Harvest index in percentage; SE = Standard error of crosses; ns = Non-significant; * and ** = Significant of GCA estimates at p = 0.05 and 0.01, respectively based on T-test.

5.5.5 Heritability

Heritability is the heritable portion of the phenotypic variance. Heritability in broad sense is the ratio of genetic variance to the total phenotypic variance (Lush, 1940). Mather (1949) devised the way of partitioning the genotypic variance into additive and non-additive components. Later on, Robinson (1966) suggested the ways to determine heritability in narrow sense as the ratio of additive genetic variance to the phenotypic variance. If the heritability is 100 percent then phenotype provides a perfect measure of the genotypic value. The broad sense heritability estimates were categorized as low (<50%), moderate (50-70%) and high (>70%) as suggested by Robinson (1966).

5.5.5.1 Broad-sense heritability

If a phenotype is determined, in part, by the genotype, the heritability is known as broad-sense heritability (Bernardo, 2014). Moderate to high estimates of broad sense heritability were recorded for most of the characters and varied from 71.83 (grain yield) to 99.77% (plant height) (Table 5.6). The highest heritability estimate was for plant height (99.77%), followed by 1000-seed weight (94.99%) and panicle exsertion (92.81%) indicating that this character is highly genetically controlled and less affected by the environment. Desai and Shukla (1995) reported that additive and non-additive gene effects controlled the inheritance of most of the traits and the later being more important in sorghum; grain yield and panicle components were under the control of dominance gene action, the exploitation of hybrid vigour seems to be beneficial. Can et al. (1998) pointed out that high heritability estimates coupled with high genetic advance were observed for dry weight of leaves, plant height and 100-grain weight, indicating that these traits are controlled by additive gene action.

5.5.5.2 Narrow-sense heritability

Narrow-sense heritability is the degree to which a trait is passed from parent to offspring expressed as the ratio of the additive genetic variance to the total phenotypic variance. Narrow-sense heritability estimates of the traits studied varied from 0.088 (1000-seed weight) to 5.822 (above ground biomass yield). Low level of narrow-sense heritability estimates was manifested by almost all traits indicating that the additive genetic variance contribution to the performance of the genotype was minimal. Relative to grain yield and 1000-seed weight continues selection will improve traits like above ground biomass, plant height and panicle exsertion (Table 5.6).

Table 5.6 Estimates of broad-sense and narrow-sense heritability from 14 parents and 49 hybrids of sorghum

Traits	σ^2_A	σ^2_D	σ^2_E	H^2(%)	h^2(%)
Days to 50% flowering (days)	0.268	9.495	1.487	86.781	2.382
Days to 75 % maturity (days)	0.223	8.385	1.548	84.755	2.196
Plant height (cm)	16.106	425.304	1.016	99.770	3.640
Panicle exsertion (cm)	0.751	19.742	1.587	92.811	3.401
1000-seed weight (g)	0.035	37.763	1.993	94.991	0.088
grain yield (t ha-1)	0.009	1.572	0.620	71.834	0.409
Above ground biomass yield (t ha-1)	0.543	7.856	0.927	90.058	5.822
Harvest index (%)	0.137	21.096	0.749	96.591	0.623

σ^2_A = Additive variance; σ^2_D= Dominance Variance; σ^2_E = Environmental variance; H^2 = Heritability in Broad sense; h^2= Heritability in Narrow sense

5.6 Heterosis

Exploitation of hybrid vigour is an appropriate alternative for making further breakthroughs in increasing sorghum yield. A higher yield with medium maturity over high yielding check varieties could be instrumental in a rapid adoption of hybrid sorghum in Ethiopia. The magnitude of heterosis for yield, yield components and quality traits depends to a large extent on genetic variation, genetic base and adaptability of parents. The presence of significant amount of non-additive gene action is a prerequisite for the commercial exploitation of heterosis. Heterosis is expressed as percentage increase or decrease of F_1 hybrid over the mid parental value which is known as relative heterosis. The superiority of F_1 hybrid over the better of two parents is known as heterobeltiosis, while F_1 superiority over the standard check is termed as standard heterosis.

The three types of heterosis viz., relative heterosis, heterobeltiosis and standard heterosis were estimated for the eight traits considered (Tables 5.7 and 5.8). The relative heterosis for days to flowering and days to maturity varied from -9.20 (E-72435 x E-200013) to 10.98 per cent (E-72437 x E-75452) and from -11.71 (E-72438 x E-75452) to -0.75 percent (E-72437 x E-201444), respectively. Among the 49 hybrids, 15 and 37 hybrids showed significant negative heterosis for days to flowering and maturity, respectively. For days to flowering, the highest significant relative heterosis was depicted by cross E-72435 x E-200013 (-9.20%) followed by E-72457 x E-201444 (-8.47%) and E-72438 x E-211235 (-8.25%), whereas for days to maturity hybrid E-72438 x E-75452 exhibited the greatest significant negative relative heterosis (-11.71%) followed by E-72438 x E-75273 (-11.61%), E-72457 x E-201444 (10.75%), E-206214 x E-75452 (-10.73) and E-75460 x E-200013 (-10.15).

The heterobeltiosis varied from -9.92 (E-72435 x E-200013) to 8.33 per cent (E-72437 x E-75452) and from -13.32 (E-72438 x E-75452) to -1.24 percent (E-72437 x E-201444) for days to flowering and maturity, respectively. Among the 49 crosses, 22 for days to flowering and 39 for days to maturity showed significant negative heterobeltiosis in a desirable direction (Table 5.7). Rest of the hybrids showed either significant positive or non-significant heterobeltiosis for these traits.

The range of standard heterosis for the number of days to flowering and maturity varied from -5.83 (E-72435 x E-75273) to 13.75 percent (E-72437 x E-75452) and from -10.83 (E-72438 x E-75273) to zero percent (E-72437 x E-201444), respectively. The standard heterosis in the negative direction was considered to be desirable for these two traits. The current findings of heterosis for earliness were also in accordance with the findings of Atkins (1979), Kenga et al. (2004), Umakanth et al. (2006), Premalatha et al. (2006), Hovny and El-Dsouky (2007), Mahdy et al. (2011), Abou-Amer and Kewan (2014) and Amir and Mohamed (2015).

In case of plant height, all the hybrids were taller than their respective mid-parents, better parents and the standard check, whereas for panicle exsertion, among the 49 hybrids 37, 36 and 27 showed significant positive relative heterosis, heterobeltiosis and standard heterosis, respectively. Plant height varied from 12.46% (E-72438 x E-75452) to 54.89% (E-72438 x E-211235), from 8.43% (E-72438 x E-75452) to 54.55% (E-72438 x E-211235) and from 6.97 % (E-72437 x E-211235) 41.67% (E-72438 x E-211235) for relative heterosis, heterobeltiosis and standard heterosis, respectively. The maximum plant height (345.67 cm) was recorded for E-72438 x E-211235, followed by E-72438 x E-201444 (342.33 cm) and E-72438 x E-75273 (337.67 cm). The maximum panicle exsertion (26 cm) for all the crosses was set by E-72438 x E-211235 with heterosis values of 147.62%, 136.36% and 59.18% for relative heterosis, heterobeltiosis and standard heterosis, respectively. El-Mottaleb and Asran (2004) reported that better parent heterosis was generally manifested for plant height, panicle length, panicle width and grain yield per plant and heterosis for 1000-grain weight was observed for few of the crosses and the highest positive significant heterosis for grain yield (87.88%) was manifested by the cross ICSA-37 x ICSR-93023. Sharma and Sharma (2006) reported similar results that the crosses SPV 1518 x IS 18580, IS 18580 x Raj 13 and SPV 1514 x Raj 36 had exhibited high heterosis over mid parent and better parent for grain yield per plant, panicle weight and panicle length. El-Dardeer et al. (2011) also studied heterosis under normal and water stressed conditions and reported the better parent heterosis was generally manifested for plant height, panicle length, panicle width and grain yield per plant and crosses viz., ICSA-364 x ICSR- 66, ICSA-364 x ICSR-102 and ICSA-490 x ICSR-66 had exhibited significant standard heterosis for grain yield over the check, Shandaweel-1. Makanda et al. (2010) found that hybrids were predominant for grain yield and displayed up to 285% standard heterosis and over all 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. Kanbar et al. (2011) observed that the two hybrids Baladi-4 x SPL-10A and Baladi-3 x ATX-629 recorded high significant positive values of heterosis and also high levels of mid and better parent heterosis were recorded for grain yield in all hybrids except Ezraa-3 x SPL10-A and Ezraa-5 x ATX-629.

Table 5.7 Relative heterosis, heterobeltiosis and standard heterosis for days to flowering, days to maturity, plant height and panicle exsertion for the 49 crosses of sorghum

	DF			DM			PH			PE		
Cross	RH	BH	SH	RH	BH	SH	RH	BH	SH	RH	BH	SH
E-72457 x E-75452	-2.85*	-5.16**	-0.42ns	-8.01*	-9.69**	-6.05*	35.39**	30.52**	29.10**	0.00ns	-14.29**	-26.53**
E-72457 x E-72446	-2.11ns	-6.45**	-3.33*	-8.27*	-9.18**	-7.81*	25.31**	20.62*	16.67*	39.13**	6.67*	-2.04ns
E-72457 x E-74097	-1.61ns	-2.39ns	2.08ns	-8.26*	-9.52**	-9.07**	16.65**	13.78ns	10.52ns	77.78**	55.56**	14.29**
E-72457 x E-201444	-8.47**	-8.84**	-5.42**	-10.75**	-11.19**	-10.08**	38.38**	33.57**	31.01**	56.52**	38.46**	10.20**
E-72457 x E-75273	-4.88**	-5.26**	-2.50ns	-7.62*	-8.64*	-6.80*	43.79**	42.92**	29.64**	86.11**	71.79**	36.73**
E-72457 x E-211235	-8.25**	-8.80**	-5.00**	-5.51ns	-5.51ns	-5.04ns	29.80**	29.51**	18.72*	-30.16**	-33.33**	-55.10**
E-72457 x E-200013	-4.80**	-5.56**	-0.83ns	-3.22ns	-3.69ns	-1.51ns	24.59**	20.68*	15.57*	39.13**	14.29**	-2.04ns
E-72438 x E-75452	-7.32**	-9.52**	-5.00**	-11.71**	-13.32**	-9.82**	12.46ns	8.43ns	7.24ns	-47.22**	-54.76**	-61.22**
E-72438 x E-72446	1.69ns	-2.82ns	0.42ns	-7.27*	-8.19*	-6.80*	43.51**	38.14**	33.61**	117.39**	66.67**	53.06**
E-72438 x E-74097	-1.20ns	-1.99ns	2.50ns	-8.01*	-9.27**	-8.82**	43.62**	40.08**	36.07**	128.57**	100.00**	46.94**
E-72438 x E-201444	0.40ns	0.00ns	3.75*	-6.25*	-6.72*	-5.54*	48.20**	43.04**	40.30**	100.00**	76.92**	40.82**
E-72438 x E-75273	-6.50**	-6.88**	-4.17*	-11.61**	-12.59**	-10.83**	53.48**	52.56**	38.39**	72.22**	58.97**	26.53**
E-72438 x E-211235	-8.25**	-8.80**	-5.00**	-9.77**	-9.77**	-9.32**	54.89**	54.55**	41.67**	147.62**	136.36**	59.18**
E-72438 x E-200013	-6.40**	-7.14**	-2.50ns	-9.90**	-10.34**	-8.31*	28.57**	24.54**	19.26*	30.43**	7.14**	-8.16**
E-72435 x E-75452	2.44ns	0.00ns	5.00**	-8.75**	-10.41**	-6.80*	30.09**	25.41**	24.04**	2.78ns	-11.90**	-24.49**
E-72435 x E72446	3.80*	-0.81ns	2.50ns	-5.01ns	-5.96*	-4.53ns	41.89**	36.58**	32.10**	50.72**	15.56**	6.12*
E-72435 x E-74097	-3.21*	-3.98*	0.42ns	-7.50*	-8.77**	-8.31*	37.71**	34.32**	30.46**	55.56**	36.11**	0.00ns
E-72435 x E-201444	-2.42ns	-2.81*	0.83ns	-8.00*	-8.46*	-7.30*	27.42**	22.98*	20.63*	56.52**	38.46**	10.20**
E-72435 x E-75273	-8.13**	-8.50**	-5.83**	-9.11**	-10.12**	-8.31*	24.39**	23.64**	12.16ns	-22.22**	-28.21**	-42.86**
E-72435 x E-211235	-4.23**	-4.80**	-0.83ns	-4.51ns	-4.51ns	-4.03ns	18.60*	18.33*	8.47ns	4.76ns	0.00ns	-32.65**
E-72435 x E-200013	-9.20**	-9.92**	-5.42**	-7.92*	-8.37*	-6.30*	21.80*	17.97*	12.98ns	-15.94**	-30.95**	-40.82**
E-206214 x E-75452	-4.07*	-6.35**	-1.67ns	-10.73**	-12.35**	-8.82**	40.40**	35.36**	33.88**	77.78**	52.38**	30.61**
E-206214 x E-72446	3.80*	-0.81ns	2.50ns	-7.77*	-8.68*	-7.30*	44.68**	39.27**	34.70**	94.20**	48.89**	36.73**
E-206214 x E-74097	0.80ns	0.00ns	4.58**	-8.01*	-9.27**	-8.82**	36.84**	33.47**	29.64**	115.87**	88.89**	38.78**
E-206214 x E-201444	-3.23*	-3.61*	0.00ns	-9.25**	-9.70**	-8.56*	39.39**	34.54**	31.97**	100.00**	76.92**	40.82**
E-206214 x E-75273	-0.41ns	-0.81ns	2.08ns	-8.61*	-9.63**	-7.81*	46.82**	45.93**	32.38**	88.89**	74.36**	38.78**
E-206214 x E-211235	5.03**	4.40**	8.75**	-7.52*	-7.52*	-7.05*	28.45**	28.17**	17.49*	7.94**	3.03ns	-30.61**
E-206214 x E-200013	2.80*	1.98*	7.08**	-5.94*	-6.40*	-4.28ns	19.44*	15.69*	10.79ns	-27.54**	-40.48**	-48.98**
E-75460 x E-75452	3.66*	1.19ns	6.25**	-3.82ns	-5.57ns	-1.76ns	18.62*	14.36ns	13.11ns	-13.89**	-26.19**	-36.73**
E-75460 x E-72446	-0.42ns	-4.84**	-1.67ns	-3.76ns	-4.71ns	-3.27ns	24.87**	20.20*	16.26*	56.52**	20.00**	10.20**
E-75460 x E-74097	-2.81ns	-3.59*	0.83ns	-6.73*	-8.02*	-7.56*	39.58**	36.15**	32.24**	109.52**	83.33**	34.69**

Table 5. 7. Continued

	DF			DM			PH			PE		
Cross	RH	BH	SH	RH	BH	SH	RH	BH	SH	RH	BH	SH
E-75460 x E-201444	-1.61ns	-2.01ns	1.67ns	-1.25ns	-1.74ns	-0.50ns	39.39**	34.54**	31.97**	105.80**	82.05**	44.90**
E-75460 x E-75273	-1.22ns	-1.62ns	1.25ns	-8.61*	-9.63**	-7.81*	46.67**	45.78**	32.24**	86.11**	71.79**	36.73**
E-75460 x E-211235	1.41ns	0.80ns	5.00**	-6.77*	-6.77*	-6.30*	21.73*	21.46*	11.34ns	77.78**	69.70**	14.29**
E-75460 x E-200013	-1.60ns	-2.38ns	2.50ns	-10.15**	-10.59**	-8.56*	19.44*	15.69*	10.79ns	88.41**	54.76**	32.65**
E-75458 x E-75452	-5.69**	-7.94**	-3.33*	-9.99**	-11.62**	-8.06*	36.68**	31.77**	30.33*	83.33**	57.14**	34.69**
E-75458 x E-72446	2.53ns	-2.02ns	1.25ns	-6.77*	-7.69*	-6.30*	43.95**	38.56**	34.02**	100.00**	53.33**	40.82**
E-75458 x E-74097	-2.81ns	-3.59*	0.83ns	-5.72ns	-7.02*	-6.55*	21.56*	18.57*	15.16ns	52.38**	33.33**	-2.04ns
E-75458 x E-201444	4.44**	4. 02*	7.92**	-7.75*	-8.21*	-7.05*	37.66**	32.87**	30.33**	62.32**	43.59**	14.29**
E-75458 x E-75273	-1.22ns	-1.62ns	1.25ns	-6.12*	-7.16*	-5.29*	46.21**	45.33**	31.83**	55.56**	43.59**	14.29**
E-75458 x E-211235	0.20ns	-0.40ns	3.75*	-8.52*	-8.52*	-8.06*	42.05**	41.73**	29.92**	49.21**	42.42**	-4.08*
E-75458 x E-200013	8.80**	7.94**	13.33**	-4.21ns	-4.68ns	-2.52ns	28.28**	24.25**	18.99*	39.13**	14.29**	-2.04ns
E-72437 x E-75452	10.98**	8.33**	13.75**	-8.75**	-10.41**	-6.80*	24.79**	20.30*	18.99*	58.33**	35.71**	16.33ns
E-72437 x E-72446	7.59**	2.82*	6.25**	-2.51ns	-3.47ns	-2.02ns	41.31**	36.02**	31.56**	120.29**	68.89**	55.10**
E-72437 x E-74097	-1.61ns	-2.39ns	2.08ns	-5.72ns	-7.02*	-6.55*	37.85**	34.46**	30.60**	4.76ns	-8.33**	-32.65**
E-72437 x E-201444	1.61ns	1.20ns	5.00**	-0.75ns	-1.24ns	0.00ns	41.99**	37.05**	34.43**	68.12**	48.72**	18.37**
E-72437 x E-75273	2.44ns	2.02ns	5.00**	-5.62ns	-6.67*	-4.79ns	29.85**	29.07**	17.08*	25.00**	15.38**	-8.16**
E-72437 x E-211235	-1.81ns	-2.40ns	1.67ns	-9.27**	-9.27**	-8.82**	16.95*	16.69*	6.97ns	-1.59ns	-6.06*	-36.73**
E-72437 x E-200013	1.20ns	0.40ns	5.42**	-4.95ns	-5.42ns	-3.27ns	20.47*	16.69*	11.75ns	-1.45ns	-19.05**	-30.61**
SE		1.43			2.91			7.69			2.45	

DF = Days to 50% flowering; DM = Days to 75% physiological maturity; PH = Plant height; PE = Panicle exsertion; RH = Relative heterosis; BH = heterobeltiosis; SH = Standard heterosis; SE = Standard error; ns = Non-significant; * and ** = Significant of heterosis at p = 0.05 and 0.01, respectively based on T-test.

For 1000-seed weight, the hybrids displayed a relative heterosis ranging from -54.29 (E-206214 x E-211235) to 56.25 per cent (E-75460 x E-75273), heterobeltiosis from -59.60 (E-206214 x E-211235) to 37.36 per cent (E-75460 x E-75273) and standard heterosis from -59.60 (E-206214 x E-211235) to 26.26 (E-75460 x E-75273) (Table 5.8). Thirty seven hybrids expressed significant positive relative heterosis ranging from 8.98 (E-72457 x E-74097) to 56.25 per cent (E-75460 x E-75273), while 25 hybrids manifested significant positive heterobeltiosis ranging from 7.69 (E-75458 x E-72446) to 37.36 per cent (E-75460 x E-75273). Among 17 hybrids that showed significant positive standard heterosis, hybrid E-75460 x E-75273 depicted the maximum (26.26%) over the standard check (Table 5.8). Significant heterosis for 1000-seed weight was reported by Premalatha et al. (2006) and Mahdy et al. (2011).

The range of relative heterosis, heterobeltiosis and standard heterosis for grain yield was from -36.96 (E-206214 x E-72446) to 86.96% (E-72437 x E-72446), from -39.58 (E-206214 x E-72446) to 80.21% (E-75460 x E-75273) and from -43.14 (E-206214 x E-72446) to 69.61 (E-75460 x E-75273) (Table 5.8). As many as 25, 22 and 19 hybrids expressed significant positive relative heterosis, heterobeltiosis and standard heterosis for this trait. The highest significant positive relative heterosis, heterobeltiosis and standard heterosis larger than 50% was found in hybrids E-72437 x E-72446, E-72457 x E-72446, E-75460 x E-75273, E-72435 x E-74097, E-72435 x E-200013, E-72457 x E-75452, E-75460 x E-201444, E-75458 x E-75452, E-72438 x E-72446, E-72437 x E-74097, E-75458 x E-201444 and E-206214 x E-201444. The present result is inconsistent with the findings of Makanda et al. (2010), Kanbar et al. (2011) and Premalatha et al. (2006). The five hybrids significantly superior over the check ESH-2 in grain yield are presented in Figure 5.1. The hybrid E-72437 x E-72446 recorded superior heterotic expression for either of the three or all the heterosis, namely relative heterosis, heterobeltiosis and standard heterosis for grain yield per hectare. The hybrids, viz., E-72457 x E-72446, E-75460 x E-75273, E-72435 x E-74097 and E-72435 x E-200013 recorded significant heterosis for grain yield per hectare coupled with good mean performance and high SCA effects. Among the hybrids, the performance of cross combinations E-72457 x E-75452, E-75460 x E-201444, E-75458 x E-75452 and E-72438 x E-72446 was considerably good and exhibited good level of heterosis for most of the characters that contributes to yield. Significant positive heterosis for grain yield per plant was reported by Kenga et al. (2004). Both mid parent and better parent positive heterosis were reported by Sharma and Sharma (2006) and El-Dardeer et.al. (2011). Standard heterosis for grain yield was reported by Mahmoud and Ahmed (2010).

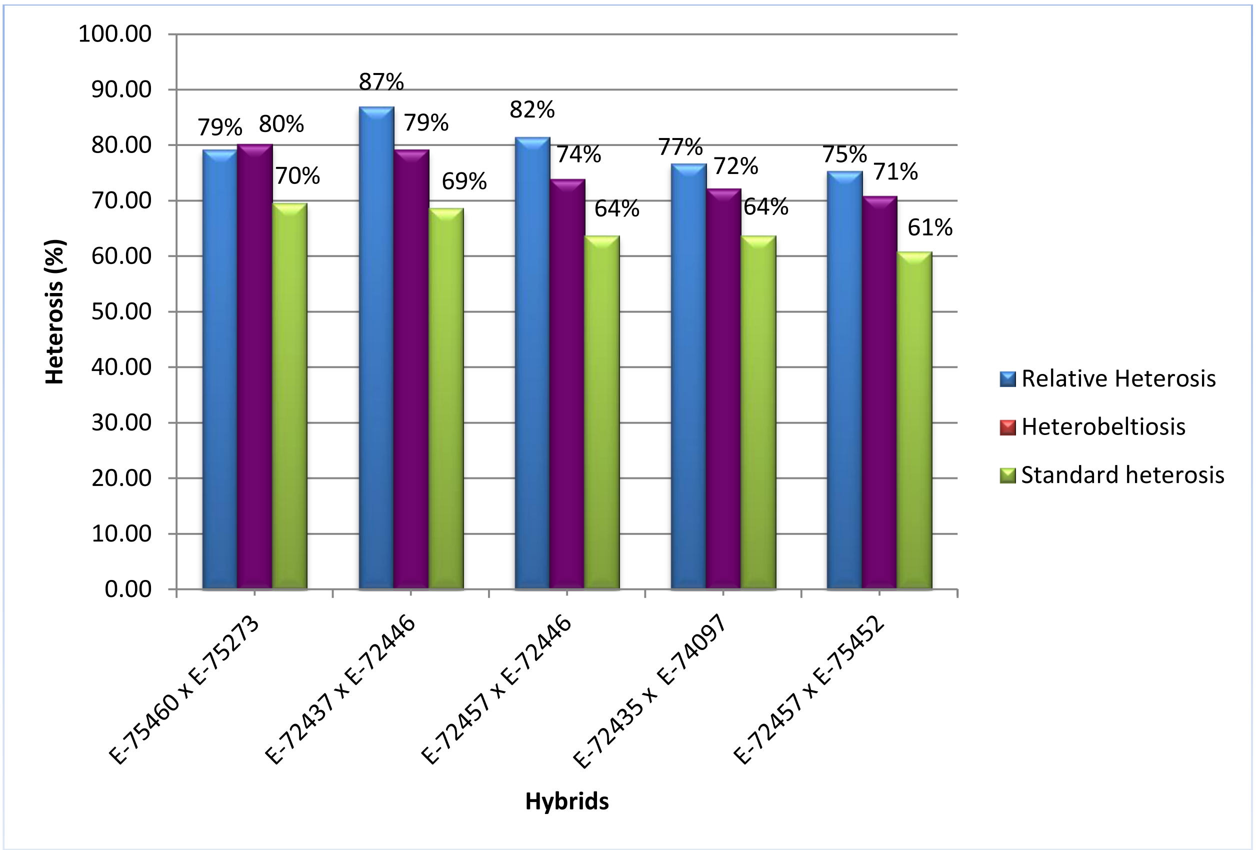

Figure 5.1 Top five hybrids based on standard heterosis (%) over the check hybrid along with heterobeltiosis(%) and relative heterosis (%) for grain yield

The relative heterosis for above ground biomass yield ranged from -15.43 (E-75458 x E-74097) to 44.12%t (E-72438 x E-211235). Among 49 hybrids, 23 hybrids showed significant positive relative heterosis and six hybrids showed significant negative relative heterosis for this trait. The highest significant positive relative heterosis was depicted by cross E-72438 x E-211235 (44.12%) followed by E-72438 x E-75273 (37.43%) and E-72438 x E-72446 (35.99%). Heterobeltiosis of this trait ranged from -19.95%t (E-75458 x E-74097) to 41.38% (E-72438 x E-211235). The standard heterosis for above ground biomass yield varied from -10.97 (E-72435 x E-211235) to 42.94% (E-72438 x E-211235).

For harvest index relative heterosis, heterobeltiosis and standard heterosis estimates ranged from -3.91 (E-72437 x E-200013) to 234.09% (E-72437 x E-72446), from -11.16 (E-72437 x E-200013) to 202.17% (E-75460 x E-201444) and from -20.89 (E-72437 x E-200013) to 159.07% (E-72437 x E-72446), respectively. Similar findings were reported by Steduto et al. (2012). Hammer and Broad (2003) found that the higher yields in their study were achieved by maximizing both biomass yield and harvest index of sorghum.

Table 5.8 Relative heterosis, heterobeltiosis and standard heterosis for 1000-seed weight, grain yield, above ground biomass yield and harvest index for the 49 crosses of sorghum

	TSW			GY			AGB			HI		
Cross	RH	BH	SH	RH	BH	SH	RH	BH	SH	RH	BH	SH
E-72457 x E-75452	28.99**	18.48**	10.10**	75.40**	70.83**	60.78**	4.89ns	4.67ns	1.51ns	204.40**	197.32**	152.95**
E-72457 x E-72446	43.20**	32.97**	22.22**	81.52**	73.96**	63.73**	22.71**	12.27*	26.75**	135.70**	107.59**	82.78**
E-72457 x E-74097	8.98*	-2.15ns	-8.08*	-11.11**	-13.40**	-17.65**	-3.49ns	-8.65*	4.25*	56.94**	52.30**	18.21*
E-72457 x E-201444	3.37ns	-4.17ns	-7.07*	-21.08**	-26.26**	-28.43**	21.72**	21.48**	27.98**	81.66**	69.54**	37.33**
E-72457 x E-75273	25.00**	9.89*	1.01ns	9.84**	10.42**	3.92*	1.76ns	1.07ns	3.29**	89.80**	87.64**	55.13**
E-72457 x E-211235	13.14**	0.00ns	0.00ns	-17.20**	-17.20**	-24.51**	0.14ns	-1.76ns	-0.69ns	74.71**	71.58**	40.87**
E-72457 x E-200013	17.98**	8.25*	6.06ns	-13.33**	-18.75**	-23.53**	-3.79ns	-5.17ns	-9.47**	76.53**	63.23*	45.35**
E-72438 x E-75452	-52.66**	-56.52**	-59.60**	-15.51**	-17.71**	-22.55**	-1.63ns	-1.84ns	-4.80**	102.88**	98.16**	68.59**
E-72438 x E-72446	38.46**	28.57**	18.18**	72.83**	65.63**	55.88**	35.99**	24.42**	40.47**	125.01**	98.17**	74.48**
E-72438 x E-74097	32.93**	19.35**	12.12**	18.52**	15.46**	9.80**	15.43**	9.25*	24.69**	90.34**	84.72**	43.37**
E-72438 x E-201444	17.98**	9.38**	6.06ns	10.27**	3.03*	0.00ns	25.90**	25.65**	32.37**	69.02**	57.75**	27.78**
E-72438 x E-75273	28.75**	13.19**	4.04ns	3.63*	4.17**	-1.96ns	37.43**	36.51**	39.51**	31.20**	29.71**	7.23ns
E-72438 x E-211235	4.00ns	-8.08*	-8.08*	-18.28**	-18.28**	-25.49**	44.12**	41.38**	42.94**	20.59*	18.43*	-2.77ns
E-72438 x E-200013	1.12ns	-7.22*	-9.09*	-30.00**	-34.38**	-38.24**	11.37*	9.77*	4.80*	90.81**	76.43**	57.11**
E-72435 x E-75452	44.38**	32.61**	23.23**	47.59**	43.75**	35.29**	16.09**	15.84**	12.35**	107.69**	102.86**	72.58**
E-72435 x E72446	13.61**	5.49ns	-3.03ns	-8.70**	-12.50**	-17.65**	4.25ns	-4.62ns	7.68**	179.82**	146.45**	116.99**
E-72435 x E-74097	34.13**	20.43**	13.13**	76.72**	72.16**	63.73**	-11.37*	-16.11**	-4.25ns	195.50**	186.78**	122.58**
E-72435 x E-201444	2.25ns	-5.21ns	-8.08*	-16.76**	-22.22**	-24.51**	-13.37**	-13.54--	-8.92*	88.72**	76.14**	42.68**
E-72435 x E-75273	20.00*	5.49ns	-3.03ns	-19.17**	-18.75**	-23.53**	-5.81ns	-6.44ns	-4.39*	86.16**	84.04**	52.15**
E-72435 x E-211235	-0.57ns	-12.12**	-12.12**	-8.60**	-8.60**	-16.67**	-10.24*	-11.94*	-10.97**	172.93**	168.05**	120.07**
E-72435 x E-200013	17.98**	8.25*	6.06ns	76.67**	65.63**	55.88**	5.39ns	3.88ns	-0.82ns	135.13**	117.41**	93.60**
E-206214 x E-75452	7.69*	-1.09ns	-8.08*	-12.30**	-14.58**	-19.61**	30.83**	30.55**	26.61**	15.83ns	13.13ns	-3.75ns
E-206214 x E-72446	14.79**	6.59ns	-2.02ns	-36.96**	-39.58**	-43.14**	18.73**	8.63*	22.63**	69.99**	49.71**	31.82**
E-206214 x E-74097	42.51**	27.96**	20.20**	46.03**	42.27**	35.29**	20.38**	13.94**	30.04**	155.83**	148.28**	92.70**
E-206214 x E-201444	17.98**	9.38*	6.06ns	68.65**	57.58**	52.94**	25.77**	25.52**	32.24**	108.94**	95.00**	57.96**
E-206214 x E-75273	13.75**	0.00ns	-8.08*	-22.28**	-21.88**	-26.47**	12.43*	11.68*	14.13**	39.81**	38.22**	14.27ns
E-206214 x E-211235	-54.29**	-59.60**	-59.60**	-21.51**	-21.51**	-28.43**	9.41*	7.33ns	8.50**	62.48**	59.58**	31.01**
E-206214 x E-200013	2.25ns	-6.19ns	-8.08*	-4.44**	-10.42**	-15.69**	7.29ns	5.75ns	0.96ns	77.62**	64.24**	46.25**
E-75460 x E-75452	-49.11**	-53.26**	-56.57**	-13.37**	-15.63**	-20.59**	-1.49ns	-1.70ns	-4.66**	90.44**	86.01**	58.25**
E-75460 x E-72446	27.81**	18.68**	9.09*	4.35**	0.00ns	-5.88**	-6.24ns	-14.22**	-3.16ns	142.70**	113.75**	88.20**

Table 5.8. Continued

	TSW			GY			AGB			HI		
Cross	RH	BH	SH	RH	BH	SH	RH	BH	SH	RH	BH	SH
E-75460 x E-74097	41.32**	26.88**	19.19**	49.21**	45.36**	38.24**	8.95*	3.13ns	17.70**	178.51**	170.29**	109.78**
E-75460 x E-201444	8.99*	1.04ns	-2.02ns	75.14**	63.64**	58.82**	24.07**	23.83**	30.45**	223.76**	202.17**	144.76**
E-75460 x E-75273	56.25**	37.36**	26.26**	79.27**	80.21**	69.61**	6.76ns	6.04ns	8.37**	148.78**	145.96**	103.33**
E-75460 x E-211235	20.00**	6.06ns	6.06ns	-17.20**	-17.20**	-24.51**	2.49ns	0.54ns	1.65**	101.57**	97.97**	62.53**
E-75460 x E-200013	10.11*	1.03ns	-1.01ns	35.56**	27.08**	19.61**	15.16**	13.51**	8.37*	195.59**	173.31**	143.37**
E-75458 x E-75452	45.56**	33.70**	24.24**	73.26**	68.75**	58.82**	-1.63ns	-1.84ns	-4.80**	139.08**	133.51**	98.66**
E-75458 x E-72446	15.98**	7.69*	-1.01ns	-19.57**	-22.92**	-27.45**	17.40**	7.41ns	21.26**	61.04**	41.83**	24.88**
E-75458 x E-74097	26.95**	13.98**	7.07*	-18.52**	-20.62**	-24.51**	-15.43**	-19.95**	-8.64ns	189.91**	181.35**	118.37*
E-75458 x E-201444	35.96**	26.04**	22.22**	68.65**	57.58**	52.94**	-12.59*	-12.76*	-8.09*	204.10**	183.82**	129.90**
E-75458 x E-75273	30.00**	14.29**	5.05ns	3.63*	4.17**	-1.96ns	0.81ns	0.13ns	2.33**	118.36**	115.88**	78.47**
E-75458 x E-211235	9.71*	-3.03ns	-3.03ns	8.60**	8.60**	-0.98ns	-7.33ns	-9.09*	-8.09**	109.55**	105.80**	68.96**
E-75458 x E-200013	11.24**	2.06ns	0.00ns	-2.22ns	-8.33**	-13.73**	7.87ns	6.32ns	1.51ns	108.82**	93.08**	71.93**
E-72437 x E-75452	40.83**	29.35**	20.20**	21.93**	18.75**	11.76**	3.90ns	3.68ns	0.55ns	151.79**	145.93**	109.23**
E-72437 x E-72446	46.75**	36.26**	25.25**	86.96**	79.17**	68.63**	28.02**	17.13**	32.24**	234.09**	194.24**	159.07**
E-72437 x E-74097	26.95**	13.98**	7.07*	69.31**	64.95**	56.86**	-13.52**	-18.15**	-6.58ns	176.46**	168.30**	108.24**
E-72437 x E-201444	11.24**	3.13ns	0.00ns	-12.43**	-18.18**	-20.59**	8.94*	8.72*	14.54**	56.93**	46.46**	18.64*
E-72437 x E-75273	32.50**	16.48**	7.07*	-21.24**	-20.83**	-25.49**	11.35*	10.60*	13.03**	40.47**	38.87**	14.81ns
E-72437 x E-211235	6.29ns	-6.06ns	-6.06ns	-21.51**	-21.51**	-28.43**	10.93*	8.82*	10.01**	68.90**	65.88**	36.19**
E-72437 x E-200013	2.25ns	-6.19ns	-8.08*	3.33*	-3.13*	-8.82**	7.29ns	5.75ns	0.96ns	-3.91ns	-11.16ns	-20.89*
SE		3.51			1.39			4.28			8.32	

TSW = 1000-seed weight; GY = Grain yield; AGB = Above ground biomass; HI = Harvest index; RH = Relative heterosis; BH = heterobeltiosis; SH = Standard heterosis; SE = Standard error; ns = Non-significant; * and ** = Significant of heterosis at p = 0.05 and 0.01, respectively based on T-test.

5.7 Conclusions

Sorghum is an important food and feed source in mixed crop-livestock production systems where its dual usage is a preferred option, especially among the resource poor small-scale farmers. This study evaluated 14 parents, 49 F_1 hybrids and one check hybrid (ESH-2) and estimated combining ability effects, heterosis and heritability values using a line x tester mating design. Data were recorded on eight quantitative characters.

Analysis of variance and combining ability analysis revealed the presence of significant differences among lines, testers, crosses and line x tester interactions for all the traits studied indicating that there were adequate genetic variations in the materials evaluated. Both GCA and SCA variances were important in the controlling of expression of assessed traits. However, all characters exhibited greater SCA variance than GCA variance which indicated the preponderance of non-additive gene action. The general combining ability (GCA) effects revealed that lines such as E-75460 and E-72435 and testers E-74097, E-75452, E-72446 and E-201444 were the most promising general combiners for grain yield. Based on specific combining ability (SCA) effects five crosses such as E-75460 x E-75273, E-72437 x E-72446, E-72457 x E-72446, E-72435 x E-74097 and E-72457 x E-75452 were selected with superior grain yields.

Significant positive relative heterosis, heterobeltiosis and standard heterosis has been observed for grain yield and yield components in majority of the crosses. The maximum heterosis recorded for 1000-seed weight and grain yield were 56.25 and 86.96%, respectively. Most of the hybrids exhibited significant positive heterosis over standard check for all traits considered. Similarly, results of broad- and narrow-sense heritability indicated that both additive and non-additive genetic variance were important than the environmental variance in the expression of each trait. However, the contribution of additive genetic variance in the expression of each trait studied was minimum.

The above selected parents with significant GCA effects in a desirable direction and crosses with better SCA values for grain yield related traits are recommended for population development and heterosis breeding.

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CHAPTER 6

An overview of the research findings

6.1 Introduction and objective of the study

Sorghum [*Sorghum bicolor* (L.) Moench] is a multipurpose C4 crop belonging to the family poaceae. Sorghum is cultivated in warmer climates of the world with its' primary source of origin being the Ethiopian Highlands and Southern Sudan. Sorghum is the world's fifth most important cereal crop after maize, rice, wheat and barley. It is the dietary staple of more than 500 million people in more than 30 countries. Sorghum production and productivity in sub-Saharan Africa is affected by abiotic, biotic and socio-economic constraints. Among the abiotic stresses, recurrent drought is the major cause of yield losses varying from 40% to 60%. Occasionally severe drought stress can cause complete crop loss in the major sorghum production areas in Ethiopia. Several attempts have been made to breed for drought tolerant sorghum genotypes that could fit the frequent moisture deficit events in Ethiopia. However, farmers are still growing low yielding, drought susceptible and long maturing local landraces. Development of medium-maturing sorghum varieties which can be conveniently grown in farmers planting period (April to May each year) is most indispensable to increase the production and productivity of the crop. This chapter highlights the study objectives with subsequent summary of the core findings of each objective, and their implications towards breeding for drought tolerance in sorghum.

The objectives of the study were:

1. To determine the impact of drought on sorghum production and productivity over time and space, and to identify farmers' production constraints and coping strategies when dealing with drought in north eastern Ethiopia.
2. To characterise sorghum landraces for drought tolerance and to select farmer-preferred medium-maturing genotypes under managed stress condition.
3. To assess the genetic diversity present among diverse medium-maturing sorghum genotypes based on simple sequence repeat (SSR) markers and phenotypic traits to select unique genotypes for breeding.
4. To determine combining ability, heterosis and heritability of yield and yield-related traits in medium-maturing sorghum genotypes to select promising parents and families for breeding.

6.2 Research findings in brief

A diagnostic survey on the impact of drought on sorghum production, and farmer's varietal and trait preferences, in the north eastern Ethiopia: implication for breeding

A participatory rural appraisal (PRA) was conducted using semi-structured interview and focus group discussions involving 180 sorghum growing farmers selected from three Administrative zones in north eastern Ethiopia. The main findings of the study were:

- About 69% of the farmers preferred to grow medium-maturing sorghum landraces to avoid post-flowering drought stress as a drought coping strategy.
- The major sorghum production constraints identified in the area includes recurrent drought, *Striga* infestation, insects, birds, diseases, lack of farmers-preferred varieties, limited policy support, lack of access to improved seed, poor sorghum production practices, low level of input, and poor soil fertility.
- Amongst production constraints, farmers rated drought as the most challenging and leading threat in affecting sorghum productivity and narrowing its genetic diversity.
- Grain yield followed by drought tolerance, medium-maturity and good biomass yield were the most important traits in sorghum variety preferred by farmers.

Agro-morphological characterization of sorghum landraces for drought tolerance and selection of farmers-preferred medium-maturity genotypes under managed stress

One-hundred ninety-six medium-maturing sorghum inbred lines adapted to north eastern Amhara were screened under managed drought stressed conditions. Genotypes were assessed using lattice square design with two replications at Kobo trial site, Ethiopia. The following major outputs were obtained.

- Significant phenotypic variations were observed for drought tolerance among test genotypes for all measured traits under both stressed and non-stressed conditions.
- Seven genotypes [E-72457, E-72438, E-72435, E-206214, E-72449, E-75460 and E-75458] with superior agronomic performance and drought tolerance were selected and recommend for large-scale production or for further breeding under drought prone sorghum growing agro-ecologies of the country.

- Seven genotypes [E-72435, E-72438, E-206214, E-72457, E-75454 and E-72449] with better yield performance were selected and recommended for production or breeding under optimal moisture conditions.
- Grain yield had significant and positive correlation with yield-related traits assessed under both test conditions.
- Path coefficient analysis revealed that days to maturity under drought stressed condition and harvest index under non-stressed condition had the highest positive direct effect on grain yield.
- The first three principal components (PCs) explained 79.4% and 86.78% of the total variation present among genotypes evaluated under non-stressed and drought-stressed, respectively.
- Suitable medium-maturing farmers-preferred genotypes were selected for future breeding emphasising on drought tolerance and medium maturity.

Assessment of the genetic diversity of medium-maturing sorghum genotypes based on simple sequence repeat markers and phenotypic traits

Fifty medium-maturing sorghum genotypes advanced from the screening experiment with good drought tolerance and yielding performance were genotyped using 39 polymorphic simple sequence repeat markers (SSR) markers and the results were indicated as follows:

- Considerable genetic diversity at molecular level was observed among medium-maturing tested sorghum genotypes.
- A total of 279 putative alleles were generated with a mean of 7.15 alleles per locus and the PIC values ranged from 0.24 to 0.89 with a mean value of 0.60.
- A population structure analysis with the SSR markers yielded three genetic groups agreeing to the results of cluster and factorial analyses using phenotypic traits.
- Genotypes collected from different origins were allocated together across clusters, sets and groups indicating similar genetic backgrounds, and evidence of gene flow between administrative zones where test genotypes were sampled.
- Fourteen genetically divergent medium-maturing sorghum genotypes [E-72457, E-206214, E-72438, E-75460, E-72435, E-75458, E-72437, E-75452, E-72446, E-74097, E-201444, E-75273, E-211235 and E-200013] were selected for future breeding.

Combining ability, heterosis and heritability analyses for yield and yield-related traits in medium-maturing sorghum genotypes

Forty-nine sorghum hybrids generated from a 7 x 7 line x tester crosses and one standard hybrid check were field evaluated for eight traits using a triple lattice design at Kobo trial site, Ethiopia. The core findings of the study were:

- There was significant variation among hybrids and parents in terms of all measured traits allowing selection of suitable parents and hybrids for traits of interest.
- Lines E-75460 and E-72435 and testers E-74097, E-75452, E-72446 and E-201444 were the most promising general combiners for grain yield.
- Five crosses [E-75460 x E-75273, E-72437 x E-72446, E-72457 x E-72446, E-72435 x E-74097 and E-72457 x E-75452] were selected based on their specific combining ability effects of superior grain yields. These crosses also exhibited high heterosis for grain yield and yield-related traits.
- The cross, E-75460 x E-75273 expressed the highest significant positive heterosis for grain yield over the standard check ESH-2.
- Heritability analysis indicated broad-sense heritability effects were higher than narrow-sense heritability reflecting that the effect of additive gene action was minimal for each trait examined.
- Both additive and non-additive genetic variances were significant however, the variance of non-additive gene action was much higher than the additive variance indicating that dominance gene action was important in controlling the expression of all traits
- Therefore, the preponderance effect of non-additive gene action was useful for exploiting heterosis in medium-maturing sorghum breeding.

6.3 Implications of the study for population improvement and hybrid breeding of sorghum with drought tolerance.

- The PRA study showed that farmers preferred to grow medium-maturing sorghum landraces as a drought coping strategy rather than relying on short stature exotic varieties that lack most of farmers preferred traits. Farmers identified recurrent drought, *Striga* infestation, insects, birds, diseases, lack of farmers-preferred varieties, limited policy support, lack of access to improved seed, poor sorghum production practices, low level of input, and poor soil fertility as the major sorghum production constraints. Farmers identified drought as the most challenging and leading threat in affecting sorghum productivity and narrowing its genetic diversity. Higher grain yield, drought tolerance, medium-maturity and good biomass yield were the most important traits in sorghum variety preferred by farmers. This indicates the need to incorporate farmers views in future sorghum breeding programs for better adoption and impact of improved technologies.
- Significant phenotypic variation for drought tolerance observed among medium-maturing sorghum genotypes in both stressed and non-stressed conditions indicated that there is immense potential for selection of genotypes for higher grain yield with higher level of drought tolerance.
- Considerable genetic diversity at molecular level was observed among medium-maturing sorghum genotypes which imply the possibility of exploiting heterosis through hybridization of distantly related genotypes.
- Both additive and non-additive variance effects were significant in controlling the expression of eight traits under rain-fed condition which indicated that both population improvement through selection and heterosis breeding can be successfully implemented.
- Therefore, parents and crosses with good GCA and SCA effects towards desirable direction are recommended for population development and heterosis breeding, respectively.