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RESPONSE OF SORGHUM (*Sorghum bicolor* L. Moench) TO CLIMATE DATA AND POSSIBLE ADAPTATION STRATEGIES FOR IMPROVING YIELDS IN BURKINA FASO

BY

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Soil Science

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DECLARATION

Candidate's Declaration

I hereby declare that this thesis is the result of my own original research and that no part of it has been presented for another degree in this university or elsewhere.

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Supervisors' Declaration

We hereby declare that the preparation and presentation of the thesis were supervised in accordance with the guidelines on supervision of thesis laid down by the University of Cape Coast.

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ABSTRACT

The objective of this study was to study the effect of some climatic parameters on sorghum production and to explore a wide range of possible sorghum crop management adaptation strategies that could enhance its production and contribute to food security. The study was conducted in the Central region of Burkina Faso in 2014. Three experiments were carried out under three climatic conditions: two dry experiments were conducted during the hot (March) and the cold (October) seasons respectively, while the rainfed experiment was conducted early in July. These experiments used a split-plot design. The two dry season experiments were subjected to two watering regimes (well-watered and water stress) and the entire experiments were subjected to two nitrogen levels (0 and 60 kg $ha^{-1}$of urea) and two sorghum genotypes (local, *Kapelga* and improved, *Sariaso* 14). These factors were evaluated for genotypic performance on root growth, reproductive cycle, yield and yield components, and nitrogen and water use efficiencies. The result showed that the variations in the climatic parameters decreased the long term sorghum yield in Saria. It was also observed that the growth conditions mostly affected sorghum production followed by watering regimes, genotypes performance and nitrogen levels. The third growth condition (dry cold experiment) was found to be the most productive. Genotype *Sariaso* 14 was highly productive in irrigated experiments. It was also found that WUE and NUE were the two factors limiting sorghum production. This knowledge is expected to be of tremendous benefit to farmers as rainfed agriculture is particularly vulnerable to climate change.

KEY WORDS

Burkina Faso

Climate change

Nitrogen levels

Sorghum genotypes

Watering regimes

Sorghum production

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DEDICATION

In memory of my parents, Bernard Coulibaly and Angele Traoré, to my uncle, Philippe Wattara. To my husband Sié Samuel Coulibaly and to my daughters Hope Auxanges, Kim Faith, and Grâce Blessing.

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LIST OF ACRONYMS

AE:	Agronomic Efficiency
C/N:	Carbon to Nitrogen ratio
ca^{2+}:	Calcium Ion
CEC:	Cation Exchange Capacity
PET:	Potential Evapotranspiration
FAO:	Food and Agriculture Organization of the United Nations
GDP:	Gross Domestic Product
GRP/CC:	Graduate Research Programme on Climate Change
GK:	Genotype Kapelga
GS:	Genotype Sariaso 14
HI:	Harvest Index
IPCC:	Intergovernmental Panel on Climate Change
IPR/IFRA:	IInstitut Polytechnique Rural de Formation et de Recherche Appliquée
INERA:	Institut de l'Environnement et de Recherches Agricoles
K:	Total Potassium
KCL:	Muriate of Potash
Mg^{2+}:	Magnesium Ion
N:	Total Nitrogen
NUE:	Nitrogen Use Efficiency
P:	Total Phosphorus
PCA:	Principal Component Analysis
PFP:	Partial Factor Productivity

PIF:	Plan d'Investissement Forestier
SCADD:	Stratégie de croissance accélérée et de développement durable
SOC:	Soil Organic Carbon
TSP:	Triple Super Phosphate
UCC:	University of Cape Coast
US:	United States
WASCAL:	West African Science Service Center on Climate Change and Adapted Land Use
WU:	Water Use
WUE:	Water Use Efficiency

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CHAPTER ONE

INTRODUCTION

Sorghum crop is crucially important to food security in Africa (Taylor, 2003). In Burkina Faso, it contributes also to economic growth (Sultan, Guan, & Lobell, 2014) as it is processed into a very wide variety of attractive and nutritious traditional foods and drinks. Its production is mainly rainfed and dominated by small-scale farmers (Somé, Jalloh, Zougmoré, Gerald, & Timothy, 2012). However, nowadays, this rainfed agriculture is at a high risk of being severely affected by climate change or climate variability because of its strong dependence on natural resources and the climate itself (Enete, & Taofeeq, 2010). 25% of decrease in sorghum yield is expected in Burkina and 1.7 million of people are likely to be at risk of food insecurity (FAO, 2011). This study is therefore undertaken in order to explore a wide range of possible sorghum crop management adaptation strategies that could enhance its production and contribute to food security.

Background of the study

Agriculture is the engine of economic growth in most African countries. According to Lopes (2014), about 75% of Africans rely on agriculture as their primary source of livelihood. It provides 32% of Africa's total gross domestic product (GDP) and 65% of its total export earnings (Chauvin, Mulangu, & Porto, 2012). Therefore, baring major societal transformation, agricultural activities have important role in the reduction of poverty in West Africa.

In Burkina Faso, agricultural activities supplies to 90% of the population with their basic needs (Funk & Rowland, 2012). It is mainly rainfed and dominated by small-scale farmers (Somé, Jalloh, Zougmoré, Gerald & Timothy, 2012). Nowadays, this rainfed agriculture is affected by climate change and climate variability. According to Wreford, Moran, and Adger (2010), climate change is defined as a "statistically significant variation in the average condition of the climate or in its variability, a variation that persists over a long period of time (decades or more)". Increasingly, there is a growing concern that climate change or climate variability can potentially lead to significant yield reductions. Drought stress affects crop yield more than any other environmental stress worldwide (Ings, Luis, Mur, Robson, H., & Bosch 2013), with negative impacts on plant growth, development, survival, and crop productivity. Climate change is likely to adversely affect food security in many regions of the world and especially in developing countries (IPCC, 2014). According to Sultan et al. (2013) under temperatures between 21.9 °C and 34.4 °C and mean rainfall of 900 mm, it is predicted in West Africa, a negative impact of climate change on sorghum yields up to 41% reduction for 6 °C temperature increase and 20% increase for rainfall.

In such a context, several strategies such as stone bunds, zaï and half-moon techniques are developed in the Sahalian areas including Burkina Faso. Combining these with application of organic/inorganic sources of nutrients and improved land management systems can lead to increased soil fertility and soil moisture (Bationo, Kihara, Waswa, Ouattara, & Vanlauwe, 2014). These strategies are considered climate-smart agricultural practices that secure farmers' livelihoods, while contributing to ecosystem services (Zougmoré, Jalloh, & Tioro, 2014) and minimizing risk from climate variability. However, the adoption of these profitable soil fertility-enhancing technologies is hampered by the low investment capacity of farmers (Bationo et al., 2014).

In recent years, more researches are directed to other means of adaptation to climate variability and productivity problems. These include the use of staple crops, the use of improved seed varieties, and the use of organic and inorganic fertilizers, etc. (Sawadogo, Bock, Lacroix, & Zombré, 2011).

Considering its economic aspects, and its importance in food security, sorghum is one of the resistant and main staple crops in the Sudano- Sahelian regions of West Africa (Sultan et al., 2014). Sorghum is also identified as an adaptation crop to climate change (Sultan et al.). It is processed into a very wide variety of attractive and nutritious traditional foods and drinks.

The resistance of sorghum to drought, according to Wenrao, Zhang, Shan, and Eneji (2011) is linked to its roots which develop nodes below the soil surface which store and provide nutrients such as nitrogen and phosphorus to the plant. These nutrients improve water use efficiency (WUE) and seem to induce higher grain yield both during a low and high rainfall year (Krishna, Biradarpatil, & Channappagoudar 2008). As sorghum is the staple and the adaptation crop to climate change, for its high production, a sustainable adaptation strategy to climate change vulnerability is immediately required as noticed by Gornall et al. (2010).

Statement of the problem

In Burkina Faso, climate change may be expected to result in more frequent drought events as temperatures increase causing crops to use more water (González & Belemviré, 2011). Strong rains lead to soil erosion and flash floods increase natural resources degradation. Adding to the desertification mainly in the northern part of the country, these factors have major socio-economic and biophysical consequences: food insecurity, population migration, increase of soils degradation (SCADD, 2011). This situation has a negative impact on agriculture, forestry and animals production systems (Benoît, 2008).

Despite a number of adaptation strategies to deal with rainfall variability and improvement techniques developed in the country (PIF, 2011), rainfed agriculture remains highly vulnerable to climate change (Lyimo & Kangalawe, 2010). Sorghum yield also remains always low and is at 800 kg ha^{-1} (Olembo, M'mboyi, Kiplagat, Sitieney, & Oyugi, 2010). In the Central region of Burkina (Saria Research Center), whereas increases in temperature, in rainfall and in rain days are observed over 32 years, a decrease is noted in the potential evapotranspiration. These variations in climate conditions in Saria may lead to decrease the long term sorghum grain yields over 32 years (from 1980 to 2012).

Climate change, therefore, because of its likely large adverse effects on agriculture, is expected to affect food security (Niang et al., 2014, Connolly-Boutin, and Smit, 2015). Indeed, the study of Dixon, Smith and Guill (2003) supports that the increase in temperature is expected to lead to significant declines in the yields of the main staple crops in Sub-Saharan Africa. According to Meehl et al. (2007), the increase in temperature damages patterns of rainfall; this situation may contribute to the increase in climatic extreme events such as droughts and floods and hence may decrease crop yields and increase production risks in rainfed agriculture. According to Lobell and Gourdji (2012), temperature is likely to continue increasing and agriculture may be also affected. This increase in temperature may decrease sorghum yield since it is shown the negative impact of increased temperature in the yields. This assertion by Lobell and Gourdji is confirmed in this study since despite the improved crop management practices, sorghum yield continues to decrease in Saria Center. It is also reported that in addition to food security issue, climate change is expected to affect food quality (DaMatta, Grandis, Arenque, & Buckeridge, 2009) because of the increasing temperature and decreasing crop growth period (Kang, Khan, & Ma, 2009). Food quality may be degraded because of the great acceleration of carbon emissions which decrease protein and mineral nutrients concentration and lipid composition (DaMatta et al., 2009). In such a context, a sustainable adaptation strategy to adapt to climate vulnerability is required.

Purpose of the Study

The purpose of this study was to study the effect of some climatic parameters on sorghum production and to explore a wide range of possible sorghum crop management adaptation strategies that could enhance sorghum production and contribute to food security.

Research Objectives and Hypotheses

Research objectives

The research objectives were to:

- Study the effect of some climatic parameters on long term sorghum grain yields
- Evaluate the effect of three growth conditions on sorghum production (dry hot condition, rainfed condition and dry cold condition)
- Evaluate the effect of irrigation (watering regimes) on sorghum production
- Evaluate the effect of nitrogen levels and genotypes performance (i.e. drought resistant, early maturity, and high grain yield) on sorghum production
- Assess the effect of growing sorghum in dry and rainfed conditions on selected soil properties.

Research hypotheses

For this study, the following hypotheses are formulated:

- The variations in climatic conditions may affect sorghum grain yield
- The variation in sorghum productivity may be due to the climatic condition under which it is produced
- Cropping sorghum under irrigation in dry condition may enhance sorghum production
- Nitrogen application may increase root growth and thus WUE and grain yield
- The variation in sorghum productivity may be due to its genotype performance
- The growth conditions under which sorghum is cropped may affect certain soil chemical properties.

Significance of the Study

The study seeks to look for some sustainable adaptive strategies to enhance sorghum production identified as a staple and an adaptation crop to climate change. The study shows the feasibility to produce high sorghum yield under integrated crop management practices in dry cold season under temperature < 35 ^{o}C and when water, nitrogen fertilizer and sorghum improved variety are accessible. This study will be tested during many years before transferring the results to the decision makers. The results obtained would be progressively published to allow scientific people to have access to them. The knowledge from this study would also serve after as data base to direct national agricultural policies, solving a national crisis. Then, this study would be beneficial to farmers since rainfed agriculture is strongly affected by climate variability.

Delimitations

The study was conducted at Saria Research Center in Burkina Faso located in the central region of Burkina Faso between Ouagadougou (at 82 km in south-west from Ouagadougou) and Koudougou (at 23 km in North-east from Koudougou). It is located at 12°16' N, 2°9'W and 300 m of altitude in the agro ecological zone with rainfall between 700 and 900 mm (Soudan – Sahel zone). The study was conducted using only nitrogen from urea and the variety used was the earlier one. Usually, the first fertilizer applied to sorghum crop is NPK 14-23-14 at 100 kg ha^{-1} and the variety sown depends on the agro ecological zone.

Limitations

First, because of the financial issue, the research was conducted only in the research station. Therefore, to generalize the results, the study should have involved on farm experiments and done over more years (long term experiments).

Second, the study could not accommodate modeling for different climate change scenarios, for different soil chemical properties for the three different experiments conducted under different growth conditions. These might have implications on cropping sorghum under the experimental conditions and on soil fertility.

Finally, the study has not captured the economic or social costs of irrigation that should indicate whether or not cropping sorghum under irrigation in dry season will be beneficial to farmers.

Definition of terms

Climate change

According to IPCC (2007), Climate change refers to a change in the state of the climate that can be identified (e.g. using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. It refers to any change in climate over time, whether due to natural variability or as a result of human activity.

According to UNFCCC (2011), Climate Change refers to a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time periods.

Adaptation to climate change

The adaptation to climate change is an adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities. Various types of adaptation can be distinguished, including anticipatory and reactive adaptation, private and public adaptation, and autonomous and planned adaptation (IPCC, 2001).

Nitrogen use efficiency

Nitrogen use efficiency (NUE) is a critically important concept in the evaluation of crop production systems and can be greatly impacted by fertilizer management as well as by soil and plant water management (Fixen, Brentrup, & Zingore, 2015). NUE is obtained from the ratio between the amount of fertilizer N applied and the amount of N removed with the harvest (Fixen, et al., 2015).

Water use efficiency:

Water use efficiency (WUE) is a measure of a crop's capacity to convert water into plant biomass or grain (Sadras, & Glenn, 2012). It is calculated by dividing total dry forage yield by seasonal evapotranspiration (Kuslu, Sahin, Tunc, & Kiziloglu, 2010) or by dividing grain yield by seasonal evapotranspiration (De Pascale et al., 2011).

Organization of the Study

The thesis is structured into six chapters. After the general introduction (Chapter 1) setting the problem, defining the objectives and research hypotheses, Chapter 2 reviews relevant literature. Chapter 3 gives a general description of the study area and the materials and methodology used to collect data. Chapter 4 describes the results related to the research objectives. The results are discussed in Chapter 5. The thesis concludes in Chapter 6 with a summary of the major findings, their usefulness in a scientific field and some recommendations and an outlook for further study.

CHAPTER TWO

LITERATURE REVIEW

Climate change impact on agriculture production

Worldwide, agriculture is an important sector. In the United States, it contributes more than $300 billion to the economy each year (Hatfield et al., 2014). It also contributes more than $750 billion to the gross domestic product (USDA, 2016). Changes in the frequency and severity of droughts and floods posed challenges for farmers and ranchers and threaten food safety (Ziska et al., 2016). In US, according to Ziska, warmer water temperatures are likely to make ecosystems more difficult to grow crops, raise animals, and catch fish. In China, climate change is likely to reduce the yields of rice, wheat, and corn respectively by 9.31%, 4.52%, and 45.04% by the end of this century (Peng, Junjie and Minpend, 2015).

In Sub-Saharan West Africa, a better quantification and understanding of the impact of climate change on crop yields is urgently needed (Sultan et al., 2014). The long-term impacts of climate change on food security and environmental sustainability are continuously gaining attention (Maccarthy, & Vlek, 2012). According to Lobell, Burke, and Naylor, (2008), and IPCC (2014), developing countries are already facing chronic hunger and malnutrition and will depend on the effective adaptation of agriculture to climate change. Wasige, (2009) note that agricultural production, including access to food, in many African countries is compromised. Others also showed that any varietal adaptation is a challenge, because of uncertainties both in regional climate change scenarios (Christensen, Hewitson, & Whetton, 2007) and in the response of crops to changing climate (Barnabás, Jäger, & Fehér, 2008). Climate change is expected to affect food security in Africa (Niang et al., 2014, Connolly-Boutin and Smit, 2015). Dixon, Smith, and Guill,. (2003) observed that the high variability in rainfall and the increase in temperature significantly reduce the yields of the main staple crops in Sub-Saharan Africa. According to Meehl et al. (2007), increase in temperature may damage patterns of rainfall; a situation that contributes to increase in extreme climatic events such as droughts and floods and hence weakened crop yields and increased production risks in rainfed agriculture. It is reported that in addition to food security issue, climate change is likely to affect food quality (DaMatta et al., 2009) because of the increasing temperature and decreasing crop growth period (Kang et al. (2009). Food quality may also be degraded because of the great acceleration of carbon emissions which decrease protein and mineral nutrient concentration and lipid composition (DaMatta et al.). According to Lobell and Gourdji (2012), temperature is always high in agricultural areas due to global warming. This increase in temperature decreases sorghum yield because of the negative impact of increased temperature on crop yields. This assertion is confirmed by Lobell and Gourdji who show that despite the improved crop management practices, sorghum yield continue to decrease.

Burkina Faso stands now as the most vulnerable country, severely impacted by climate change due to the strong dependence on the natural resources and the difficult living conditions of the majority of a constant growing population (PANA, 2007 and Mendelsohn et al., 2000). With regard to agriculture, the length of the growing season is reduced from five to three months with some dry spells and flash floods. This is one of the major causes decreasing crop yields in the country. Moreover, 25% of decrease in sorghum yield is expected in Burkina and 1.7 million of people will be at risk of food insecurity (FAO, 2011).Therefore, a sustainable adaptation strategy to climate change vulnerability is immediately required as notice by Gornall et al. (2010).

Some crop management strategies to adapt to climate change in Saharan areas.

Sorghum production as an adaptation strategy

The agriculture sectors and the economies of Sub-Saharan Africa (SSA), and especially those of Burkina Faso, are highly sensitive to climatic variability (Shiferaw et al., 2014). According to these authors, drought represents one of the most important natural factors contributing to malnutrition and famine in many parts of the region. Furthermore, Wasige (2009) report that the current agricultural practices may not be sustainable under future climate change, whereas under current climatic conditions, the drought resistant food crops variety is well adapted to water stress condition.

According to Cazares, Ramirez-Ortega, Flores-Elenes, and Ruiz-Medrano (2010), the use of drought tolerant crop varieties is one of the major strategies for managing water limitation in agriculture. The long years of plant breeding activities leading to yield increases in drought, affect environments for many crops (Cattivelli, Rizza, Badeck, Mazzucotelli, & Mastrangelo, 2008). The term drought is used for a period without appreciable precipitation, during which soil water content is reduced to such an extent that plants suffer from lack of water (Larcher, 1995). According to Yoshida (1981), drought is defined as an imbalance between water uptake and water lost through transpiration.

The main drought resistance crop developed in West Africa, and especially in Burkina Faso, is sorghum (*Sorghum bicolor* L. Moench). Sultan et al. (2013) in West Africa, show that photoperiod-sensitive traditional cultivars of sorghum that are used by local farmers for centuries are more resilient to harsh climatic conditions than modern cultivars that are bred for high yield potential. In Uganda, for most areas, sorghum grain yield also is higher under future climatic conditions than millet and maize grain yield (Wasige, 2009). Kapanigowda et al. (2013) report that sorghum, because of its drought tolerance, has a wide adaptability range and can be grown in wide selection of environments.

Assefa and Staggenborg (2010) find that sorghum has production and economic advantage over maize in dryland regions. It is drought and temperature tolerant, and is more capable of taking up nutrients from soil in drought conditions than maize (Assefa and Staggenborg). The drought tolerance of sorghum is due to its root system, which develops nodes below the soil surface and provides the crop with water and nutrients from the soil (Wenrao et al., 2011).

The characteristics and extent of sorghum root are considered to be major factors affecting plant response to water stress (Abd Allah, Shimaa, Zayed, & El Gohary, 2010) and the distribution of root length density in the root system is an important indicator of potential water uptake. Furthermore, root morphological traits responsible for drought tolerance include a long and thick root system with various secondary and tertiary roots and with high root penetration ability (Comas et al., 2013).

According to Assefa et al. (2010), even though Sorghum is often grown in environments where water stress is expected sorghum yields under dryland conditions are much lower than irrigated sorghum yields. This suggested that drought tolerance is not absolute. Cândido et al. (2014) report that water stress decreases plant productivity, evidenced by the low number of grains plant, grain mass and grain yield. Another study evaluates ten different accessions of sorghum for their drought tolerance, and shows that all the yield components are affected by the stress even if it is not at the same degree (Saddam, Bibi, Sadaqat & Usman, 2014).

Dry and fresh root weights decreases during a drought period as leaf size remaines small to minimize transpiration, and ultimately plant dry and fresh weight are also reduced (Saddam et al., 2014). Water stress has diverse effects on sorghum depending on the development stage at which it occurs (Shah, Chaturvedi, Chowdhury, Venables & Petros, 2014). Therefore, irrigation may be one solution to reduce the negative effects of drought on crop production.

Importance of the use of sorghum improved genotypes

Sorghum is long-time considered as the resistant crop that can be produced under little management practice. Stichler, McFarland, and Coffman (1997) contrary note that sorghum yield can be severely decreased by environmental stresses under little crop management techniques.

Sorghum production is supposed to be improved nowadays by the techniques used such as the use of staple crops, the use of organic and inorganic fertilizers, etc. However, because of climate change and climate variability, sorghum yield remains always low and is at 800 kg ha^{-1} (Olembo, M'mboyi, Kiplagat, Sitieney, & Oyugi, 2010).

Another strategy to improve sorghum production is the use of the improved genotypes. Breeding programmes are extending modern genotypes with high yielding potential (Brocke et al., 2010), and earlier maturation (Timu, Mulwa, Okello & Kamau 2014). High yielding potential crop varieties are supposed to use water more efficiently to avoid drought stress (Blum, 2005).

According to Sadras and Glenn (2012), water use efficiency is a crop's capacity to uptake water from the soil and transfer it into plant for sorghum grain production. Water use efficiency may be increased when water is available into the soil (Song et al., 2010). Subsequently, sorghum yield is improved under higher water use efficiency.

High yielding sorghum varieties also use nitrogen fertilizer more efficiently but in West Africa, sorghum is grown under lower nitrogen fertilization conditions on degraded land (Maranville, Pandey & Sirifi, 2002). Numerous studies conducted show some advantages in cropping improved sorghum varieties. According to Timu et al. (2014), the improved seed variety has desirable production and this include early maturing, more marketable, drought tolerance and higher in grain yield. A study conducted by Tekle and Zemach (2014) shows that by using two improved varieties, sorghum yields are increased by 3.3667 t ha^{-1} and 2.4733 t ha^{-1} over the local variety. Lamptey, Nyarko, Falon, & Yeboah, (2014) also find that all growth and yield parameters are more improved for the improved sorghum variety than the local variety. In Kenya, Ochieng, Mathenge, and Muasya (2013) compare the germination and vigour test of the improved variety and the local variety. They find that seed selection time does not influence seed vigour, viability and yield but these are influenced by sorghum variety. The improved variety is found more vigour, viable and higher in grain yield than the local variety. Therefore, it is necessary to identify the most suitable crop varieties, having robust characteristics to abate the effect of climate change on sorghum yield.

Use of Soil and Water Conservation techniques

Several soil and water conservation techniques are designed to rehabilitate the land's productive capacity (Sawadogo, 2011). These soil and water conservation techniques can help secure agricultural production in unpredictable climates (Sawadogo). More of these techniques increase soil fertility level as well. According to Lal (2004), in Argentina, cereal grain yield is increased up to 40 kg ha^{-1} due to the application of organic matter. In Sahel West Africa especially in Burkina Faso and Niger, soil fertility is increased due to *stone bunds* and *zaï* techniques. Zougmoré et al. (2014) and Bationo et al. (2014) reported that stone bunds techniques may contribute to increase crop yield up to 2 to 5 times more than crop yield on soil without these techniques. In Saria, Burkina Faso, sorghum grain yield is improved (about 142%) due to the combination of stone bunds with an application of compost (Zougmoré, et al., 2004). According to Yaméogo, Somé, Lykke, Hien, and Nacro (2013), the use of zaï and stone bunds systems contributes to increase sorghum development and grain yield. They also report an improvement in soil pH and chemical properties and an improvement in the infiltration rate of water into the soil.

Bationo et al (2014) note that other cropping systems such as crop rotation and intercropping improves fertilizer use efficiency by increasing biological nitrogen fixation. They observe also that the locally available phosphate rock may be used to improve soil phosphorus that is usually deficit in the soil of Burkina Faso.

Some other techniques such as the use of legumes (peanut, mucuna and cowpea) as other cropping are implemented. The legumes by their ability to fix nitrogen from the atmosphere through the process of symbiotic nitrogen fixation contribute to improve soil fertility by 13 to 40% and crop yields by 60 to 300% (Bado, 2002).

In addition, agroforestry, the integration of trees and shrubs with crops and livestock systems is much used nowadays. This system has strong potential in addressing problems of food insecurity in developing countries (Van Vark, 2013). Van Vark notes that when well done, agroforestry can allow farmers to boost their field crop yields, diversify income, and increase resilience to climate change.

Use of inorganic and organic fertilizers

Soil is a fundamental requirement for crop production as it provides plants with water and nutrients. The nutrients present into the soil are to be supplemented by external application of organic and inorganic fertilizers for better plant growth and yield improvement (Reddy and Susila, 2015).

The inorganic or mineral fertilizers are used to provide the soil with high levels of nutrients and to improve crop yield and quality (Bekeko, 2013). The most widely mineral fertilizers used are nitrogen, potassium and phosphorus (Reddy and Susila, 2015).

In the majority of agricultural growing regions, crop production is highly dependent on the use of nitrogen (N) fertilizers. Quantitatively, nitrogen is the most important nutrient in a plant and often a limiting factor in plant growth and development (Kraiser, Gras & Gutierrez, 2011, Mueller, et al., 2012). According to Song et al. (2010), under drought conditions fertilization often results in less root biomass, increases leaf sensitivity to stress, depresses plant growth and leads to high seedling mortality. Therefore, Aroca, Porcel and Ruiz-Lozano (2012) believe that nutrient stress may enhance the tolerance of plants to drought and may possibly lead to some other stresses as well. In contrast, some other study note that increased N application can improve water use efficiency, and alleviate drought stress effects on plant growth in arid systems by preventing cell membrane damage and enhancing osmoregulation (Rahimi, Sayadi & Tajabadi, 2013).

Nitrogen supply is shown to be an important environmental factor affecting drought tolerance in plants: Soltani, Waismoradi, Heidari, and Rahmati (2013) observe an increase of grain yield with nitrogen supply under well-watered conditions; Frabboni, Giuseppina, and Russo (2013) find that N deficiency delays both vegetative and reproductive phenological development, and reduces leaf emergence rate, yield and yield components. Nitrogen is also a critical component in the efficient use of nitrogen by plants (Weih, 2014).

Nitrogen use efficiency (NUE) is an important concept in the evaluation of crop production systems and can be greatly impacted by fertilizer management as well as by soil- and plant-water management (Fixen et al., 2015). Different methods are used to estimate NUE. NUE is defined as the ratio between the amount of fertilizer N applied and the amount of N removed with the harvest (Fixen et al., 2015). For Weih (2014), overall NUE ($g\ g^{-1}$) is the ability of nitrogen accumulated in the perennial part of plant, to migrate to the seeds. Under climatic change, increasing NUE becomes more important (Pires, Cunha, Matos & Costa, 2015; Yu, Li, White & Li, 2015), as this may contribute to increasing the overall performance of cropping systems by providing economically optimum nutrients to the crop. Moreover, it can reduce nitrogen losses from the field and support agricultural system sustainability through contributions to soil fertility or other components of soil quality (Fixen et al., 2015). This contribution to soil fertility is due to some microorganisms that are able to metabolize the nitrogen remaining into the soil.

Nitrogen fertilization is also found to influence the efficient use of water by plants (Rahimi et al., 2013). Indeed, Water use efficiency (WUE) is a measure of a crop's capacity to convert water into plant biomass or grain (Sadras & Glenn, 2012). It is calculated by dividing total dry forage yield by seasonal evapotranspiration (Kuslu, Sahin, Tunc & Kiziloglu, 2010) or by dividing grain yield by seasonal evapotranspiration (De Pascale, Costa, Vallone, SBarbieri & Maggio, 2011). Therefore, WUE includes both the use of water stored in the soil and rainfall during the growing season. According to Sadras and Glenn (2012), WUE relies on the soil's ability to capture and store water, the crop's ability to access water stored in the soil and use rainfall during the season.

As water and nitrogen are essential requirements for plant growth and survival, drought and low concentrations of soil nitrogen limit crop growth and production in arid and semiarid regions (Aslam et al., 2013). These researchers also show that the effects of water and N are correlated and that low concentrations of nitrogen enhance drought tolerance and WUE. Hence, they suggest using an appropriately low supply of nitrogen under dry conditions.

Liu et al. (2012) find in arid and semiarid regions, drought as the primary limiting factor, while nitrogen has only a secondary role. Two mechanisms through which N supply affects plant drought tolerance and WUE are described by Liu et al.: first, an increased availability of soil nitrogen may lead to higher leaf area, rate of photosynthesis, and biomass production, and, hence, improve drought tolerance and WUE. Second, an adequate N supply may lead to a greater root biomass, which can enhance water uptake and then result in a higher drought tolerance and WUE. Moreover, WUE is the functional indicator most strongly related to plant development and health under moisture deficit and is dependent upon the amount of water used for growth and biomass production (Zhang, Chen, Sun, Pei & Wang, 2008). Ma et al. (2010) note that WUE may be improved when water is limited, whereas Song et al. (2010) show the opposite.

The positive effect of nitrogen in high grain yield production is greatly demonstrated (Lust et al., 2016). However, Novara, Gristina, Guaitoli, Santoro and Cerdà (2013) find that the excess use of nitrogen may increase its noxiousness to the environment. Moreover, Jones (1976) support that the continuous use of nitrogen is harmful since it led to the rapid soil acidification indicated by the decrease in soil pH. The inadequate supply of nutrients leads thus to soil fertility and crop yield decline and that is the problem faced nowadays by the smallholder farmers in Africa (Achieng, Ouma, Odhiambo & Muyekho, 2010).

Importance of the use of irrigation to crop production

Low water potential caused by a soil water deficit is one of the major natural limitations of plant productivity, resulting in large economic losses in many regions (Boutraa, Akhkha, Abdulkhaliq & Al-Shoaibi, 2010). By using irrigation water is permanently around root zones and this is beneficial to crop (Nazarli, Zardashti, Darvishzadeh & Solmaz, 2010). Irrigation is thus a vital component of the world agriculture (De Pascale et al., 2011).

According to Morison, Baker, Mullineaux and Davies, (2008), world irrigated agriculture extends over an area of 270 million hectares but only 18% of this area is effectively irrigated.

Reuben, Girmay, Bizoza and Genet (2012) noted that Sub-Saharan Africa has vast untapped water resources, yet only 4% (6 million ha) of the region's total cultivated area is irrigated, compared to 37% in Asia and 14% in Latin America (YOU, Ringler & Sun, 2010). It is far from achieving its irrigation potential, estimated at 42.5 million ha, even though irrigation has the potential to enhance food security and economic growth (Reuben et al., 2012).

In Burkina Faso, according to Mimault (2013), only 0.6% of cultivated area is irrigated for agricultural production, but the productivity of irrigated land is approximately three times greater than that of rain-fed land. Irrigation may allow farmers to grow high-value crops for export throughout the region (Berning, 2015). It is therefore necessary to expand the irrigated area, as this has the potential to make a substantial contribution to agricultural development and address the problem of food insecurity. Irrigation also is an important tool in helping farmers insure against droughts, and plays an integral role in the transition from subsistence to commercial farming (Reuben et al., 2012). Investing in irrigation development may therefore provide insurance against erratic rainfall and stabilize agricultural output, boosting crop productivity and allowing farmers to diversify.

For maximum production to face food security issue, the irrigation agriculture needs to be done in the appropriate conditions. According to Wolf, Ouattara and Supit (2015), the best condition of farm is very important for agricultural production. This best condition contributes to the great productivity of sorghum biomass and grain yield (Rao et al., 2013). Zafar et al. (2010) reported that optimum planting condition is determinant for yield appreciation. The condition of expanding irrigated areas may also improve crop yields (Kang et al., 2009). According to Lobell et al. (2012), irrigated systems are generally less harmed than rainfed systems.

The implementation of the irrigation system may be also more efficient when it is used to produce high potential yielding varieties. These are varieties that used more efficiently water in water limited condition to produce high yield (Blum, 2005). According to this author, the high yield potential crops are determined by the genetic factors and have an effect on a breeding program designed nowadays to select better yielding genotypes under water limited conditions. The genetic characteristics such as the optimum temperature and the sensitivity to CO_2 and O_3 of crop species are determinant for their productivity (Lobell et al., 2012). Hatfield et al. (2011) in their study listed optimal season average temperature for some crops including sorghum which temperature optimal is 25 °C.

Under irrigation, farmers are thus able to choose the best conditions including appropriate temperature for their farming. Some studies especially that of Hatfield and Prueger (2015) advised sorghum cropping in cooler condition when the cultivation area is warm. For Jean (2008), temperatures between 20-30 °C are suitable for sorghum high yield production.

CHAPTER THREE

MATERIALS AND METHODS

Study site description

The study was conducted at Saria Research Station in Burkina Faso. Established in 1923, this station is located in the central region of Burkina Faso between Ouagadougou (at 82 km in south-west from Ouagadougou) and Koudougou (at 23 km in North-east from Koudougou) (refer Appendix A). It is located at 12°16' N, 2°9'W and 300 m of altitude in the agro ecological zone with rainfall between 700 and 900 mm (Soudan –Sahel zone). According to the last 35 years (from 1980 to 2015) rainfall data collected from the meteorology station in Saria, the average annual rainfall is 811.4 mm and mean rainy days is 63. Rainfall and rainy days during the study year are presented in Figure 1.

Saria station covers 400 ha of land, predominantly savannah consisting of annual and perennial grasses, trees and shrubs. According to Sedogo (1981) soils are leached tropical ferruginous with granite rock as parent material. The production system is based on the intercropping sorghum – cowpea grown under rainfed (Zougmore, Kambou and Ouattara, 2000) from July to November.

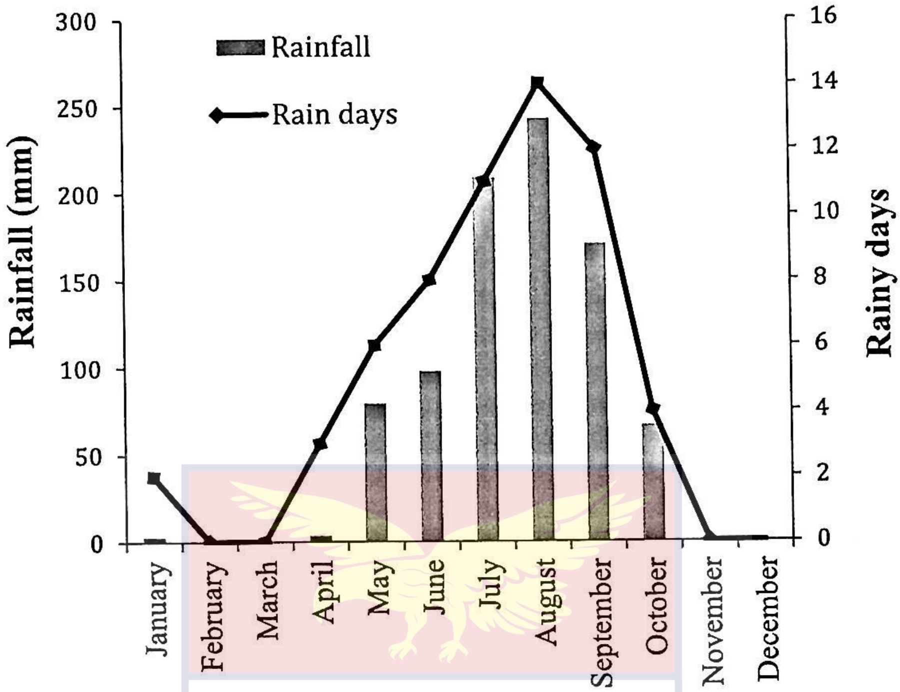


Figure 1: Rainfall distribution in 2014 at Saria.

The World Base Reference states that the soils are Luvisoils (FAO, 2006). These soils have upper horizons textures of sandy loam to sandy clay and generally a continuous and massive structure with low level of fertility.

Justification of the choice of the study site

Four essential criteria were considered for the choice:

Type of the soil*:* The tropical ferruginous soil is the type of soil found in Saria. It is the most dominant soil on which sorghum is produced in Burkina Faso.

The suitability of sorghum growth: Saria is located in the area with rainfall between 700 and 900 mm. This amount of rainfall is sufficient for sorghum production that needs rainfall between 400 and 800 mm (Jean, 2008). In addition, the rainy season in Saria lasts 3-5 months.

Possibility for irrigation: Saria can carry experiments under rainfed and irrigated conditions since it has available water source.

Previous studies in Saria over 35 years: Long term trials on sorghum crop have been done in Saria Research center and enough data are available to study the effect of climatic parameters on sorghum yields. Three types of experiments designated Saria I, Saria II and Saria III were conducted in the station to assess the impact of cropping systems and different soil management practices on soil fertility and on sorghum yields.

Methodology for data collection

Three experiments were set up in 2014 under three different growth conditions: First dry season starting in March 17th (under temperature > 35° C and the potential evapotranspiration of 7 mm day^{-1} m^{-2} and watered permanently) was called dry hot experiment; rainy season experiment in July 5th, (under environmental stresses: daily variations in the temperature, dry spells, pests) was called rainfed experiment and second dry season in October 20th (under temperature < 35° C and potential evapotranspiration of 3 mm day^{-1} m^{-2} and watered permanently) was called dry cold experiment. Figure 2 shows rainfall distribution during the growing period (in periods of ten days).

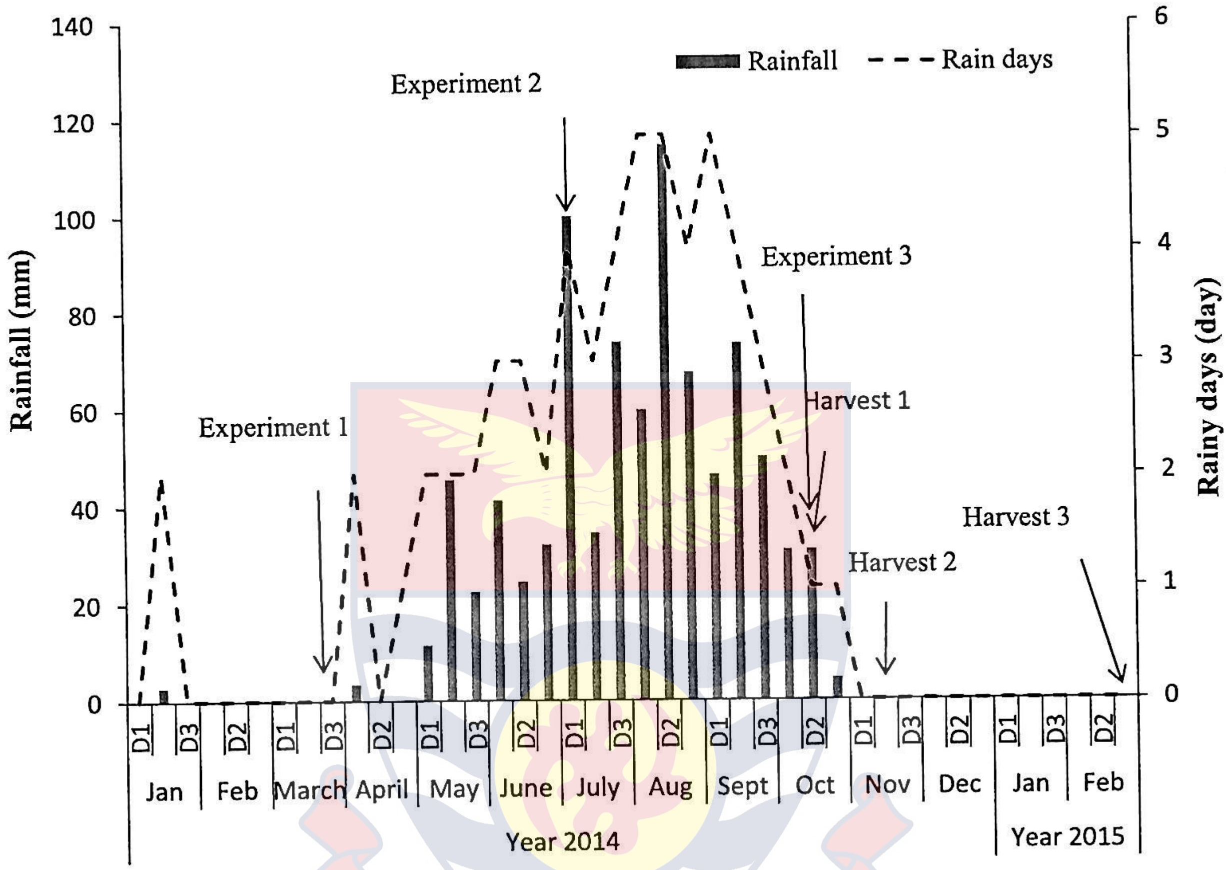


Figure 2: Decades rainfall during the experiments from March 2014 to February 2015.

D1: first decade (10 days) D2: Second decade (10 days)

D3: third decade (10 days)

The growth conditions and the seeding dates of sorghum can be summarized as follow:

Table 1: *Experimental conditions of the study*

Experiments	Seeding dates	T min	T max	PET min	PET max	Harvest date
Dry hot experiment	17-Mar-14	19.8	39.3	4	7	15-Oct-14
Rainfed experiment	5-Jul-14	Rainfed condition				11-Nov-14
Dry cold experiment	20-Oct-14	21.2	35.9	2	3	21-Feb-15

T min: minimum temperature T max: maximum temperature
PET: potential evapotranspiration

Treatments

The following treatments measuring the effects of three factors were applied:

Factor 1: Two watering regimes: water stress (WS) condition using 50% of the potential evapotranspiration during the entire period of production and well-watered (WW) condition using water amount calculated from the rate of the potential evapotranspiration. And the water used in this well-watered condition depends on the growth stages of sorghum plants.

- 50% of the rate of the potential evapotranspiration (PET) was used during the first four weeks
- 100% of the rate of the potential evapotranspiration (PET) was used from the fifth week to the grain filling period

- 50% of the rate of the potential evapotranspiration (PET) was then used from the grain filling period to the physiological maturity period.

Water was applied twice per day in equal amounts: 6 a.m. and 4 p.m.

Factor 2: Two nitrogen levels (0 and 60 kg ha^{-1}):

Two nitrogen levels (0 and 60 kg ha^{-1}) were used to assess their effect as well in the rainfed experiment and in the two dry experiments. Urea was the source of nitrogen and was applied in two equal half doses to the fertilized plants: the first dose was applied at 15 days after emergence and the second at 45 days after emergence. Generally, 60 kg ha^{-1} is the recommended dose of nitrogen (50 kg NPK + 50 kg urea) for fertilizing sorghum in the areas where rainfall is below 600 mm in Burkina Faso.

Factor 3: Two Sorghum Genotypes/ (*Kapelga* and *Sariaso* 14):

Kapelga (100-105 days) is a local genotype, while *Sariasso* 14 (110–115 days) is an improved sorghum genotypes developed in Saria. These genotypes have been chosen for their genotype performances. The grain of *Kapelga* was high quality. It produces flour that is highly appreciated by women. *Sariasso* 14 produces high fresh biomass. This biomass stays green even after harvesting and is highly appreciated by animals.

Experimental design

The experiments were laid out in a split-plot design with four replications (refer Appendix B). The main plot treatment was water regime while the sub-plots treatment was N levels by sorghum genotypes. The main plot size was 28.6 m x 7 m (200.2 m^2) and the sub-plot size was 6.4 m x 7 m (8 rows) (44.8 m^2) and a total of 32 plots for the dry irrigated experiments and 16 plots for the rainfed one. The site size was 6.4 m x 7 m x 32, i.e. 1433.6 m^2.

The factors were:

2 watering regimes → 100% PET; 50% PET

2 nitrogen levels → 0 kg ha^{-1}; 60 kg ha^{-1}

2 sorghum genotypes → Genotype Kapelga; Genotype Sariaso 14

The treatments were:

1. 100% PET * genotype Kapelga * 0 kg ha^{-1}
2. 100% PET * genotype Kapelga * 60 kg ha^{-1}
3. 100% PET * genotype Sariaso 14 * 0 kg ha^{-1}
4. 100% PET*genotype Sariaso 14 * 60 kg ha^{-1}
5. 50% PET * genotype Kapelga * 0 kg ha^{-1}
6. 50% PET * genotype Kapelga * 60 kg ha^{-1}
7. 50% PET * genotype Sariaso 14 * 0 kg ha^{-1}
8. 50% PET * genotype Sariaso 14 * 60 kg ha^{-1}

Husbandry practices

The experimental areas were ploughed by tractor and harrowed manually before sowing. A basal application of P at 23 kg ha^{-1} and K at 14 kg ha^{-1} was then applied using TSP and KCl respectively. The sorghum seeds were treated with a binary pesticide Calthio C 50 WS (thiram 25%, chlorpyrifos ethyl 25%) at 4 g kg^{-1} of seed before sowing in order to reduce the effects of *Curvularia Boedijn*, *Fusarium Link*, and *Phoma Sacchari* on seedling emergence. The seed rows spacing was 80 cm x 40 cm. Two weeks after emergence, sorghum plants were thinned out to two plants per seed hill. Mechanical weed control was done during the whole experiment.

Irrigation of the experiments carried out in dry seasons

The experiments were watered using a drip irrigation system. The water regime was imposed to the dry hot and dry cold experiments using an approximate estimate of the rate of an unstressed sorghum canopy's potential evapotranspiration (PET), of 4 - 7 mm day^{-1} m^{-2} from March to June and 2 - 3 mm day^{-1} m^{-2} from October to February. These rates of the potential evapotranspiration have been collected from the meteorology station of Saria Research Station.

Soil sampling and laboratory analyses

For each experiment, two composite soil samples were taken before sowing at horizons 0-20 cm and 20-40 cm. After harvest, soil samples were again taken from all treatment and also at the two horizons (0-20 cm and 20-

40 cm). The samples were air-dried and ground to pass a 2 mm and 0.5 mm sieve. The samples were analyzed at the INERA Kamboinsé soil, water and plant analysis laboratory for pH, soil organic carbon (SOC), total nitrogen, total phosphorus, total potassium, available phosphorus, exchangeable bases (Ca^{2+}, Mg^{2+}) and CEC.

Determination of soil organic carbon (SOC)

The SOC was determined using the Walkley and Black (1934) method. A quantity of 2 g of soil sample was weighed into an Erlenmeyer flask. The carbon in the soil sample was oxidized by adding 10 ml of a 1 N potassium dichromate solution (in excess) and 20 ml of concentrated sulfuric acid. After 30 minutes, 150 ml distilled water was added and the excess potassium dichromate (i.e not reduced by the carbon) was titrated using a 0.5 N solution of Mohr's salt ($Fe(NH_4)_2(SO_4)_2$) in the presence of a ortho–phenanthroline–ferrous complex indicator. A blank was included to correct for the experimental errors. The soil organic Carbon (SOC) was calculated as:

$$1. \quad SOC\ (kg\ ha^{-1}) = \frac{N\ (V1 - V2) * 0.39 * 10}{W}$$

Where:

N: the normality of salt of Mohr

V1: the amount in ml of Mohr's salt in the blank titration (ml)

V2: the amount of Mohr's salt added in the sample titration (ml)

W: the weight of the sample (g)

0.39: a correction factor used to compensate the incomplete oxidation of the organic matter

10: a factor to convert the unit of SOC from percentage to g kg^{-1}.

Determination of soil pH

Soil pH was measured with a pH-meter (WTW InoLab, Weilheim, Germany) in 2.5:1 water to soil solution according to Afnor (1981). A quantity of 20 g of soil was weighed into plastic tubes and 50 ml of distilled water added. The soil and water solution was then shaken for an hour. After shaking, the pH was read directly by immersing the electrode of the pH-metter in the solution.

Determination of soil total nitrogen and phosphorus

Soil total nitrogen and phosphorus were determined by first digesting soil samples using a complex of H_2SO_4-Se-H_2O_2 according to Okalebo, Gathua, and Woomer (2002). A 0.5 g portion of soil was weighed in a Kjeldahl digestion flask and 5 ml of a concentrated sulfuric acid and selenium mixture were added, mixed carefully and digested at 110 °C for an hour. The digest was allowed to cool and three successive 1 ml portions of hydrogen peroxide were added. The temperature was raised to 330 °C to continue the digestion till the solution became colorless. To the digest 25 ml of water was added and mixed well. The digest was allowed to cool and the volume made up to 50 ml with distilled water. Total P and N were measured in the digest with a SKALAR automatic colorimeter (Skalar SANplus Segmented flow analyser, Model 4000-02, Breda, Holland).

Determination of soil available phosphorus

Soil available phosphorus was determined by the Bray-1 Method using a solution of 0.025 N HCl and 0.03 N NH_4F. 1 g of air-dried soil and 7 milliliters of the solution are shaken for 5 minutes and filtered through a Whatman paper. The amount of phosphorus extracted is determined by measuring the intensity of the blue color developed in the filtrate when treated with molybadate- ascorbic acid reagent. Available P was measured in the digest with a SKALAR automatic colorimeter (Skalar SANplus Segmented flow analyser, Model 4000-02, Breda, Holland). The result is reported in milligram of available phosphorus per kilogram of soil (mg kg^{-1}).

Determination of cation exchange capacity (CEC) and soil exchangeable bases

CEC and exchangeable bases were determined using the silver thiourea method (Rayment and Higginson, 1992). 50 ml of a silver thiourea solution was added to 2 g of soil, and the suspension was shaken four 2 hours. After shaking, the soil suspension was filtered through a Whatman paper. The concentrations of Calcium (Ca^{2+}) and Magnesium (Mg^{2+}) were determined using an atomic absorption spectrometer (Perkin Elmer, AAS 100). The CEC was calculated from the concentration of the silver thiourea in the filtrate.

Observation and measurements

There were 8 lines and 16 seed hills in total. Two lines and two seed hills were left in each side (excluded from sampling) resulting in 4 lines and 12 seed hills for the measurements. The total area for the measurement was 14.08 m^2.

The observations and measurements are described as follows:

Field observation on sorghum phenology

Daily field observations of sorghum were made from booting period until maturity to estimate sorghum reproductive cycle. The observations consisted of noting the number of booting plants per day, and the number of panicle per day. The period of 50% flowering and maximum maturity was noted. The total number of panicles was also counted.

Soil water content

Soil water content was determined gravimetrically in all treatment. Soil samples were taken every two weeks within the four middle lines and in three locations. The samples from the three locations were then mixed to take one composite sample. These samplings were done in the entire treatments in six horizons (0-20, 20-40, 40-60, 60-80, 80-100 and 100-120 cm) with a graduated drill (refer Appendix C). The samples were weighed, oven dried at 105 °C for 24 hours and weighed again. Soil water content was calculated as the percentage of the difference between the wet and the dried weight divided by the dried weight.

Root growth and distribution

The profile wall method (Böhm, 1979) was used for determining root growth and distribution. Holes of 180 cm wide by 120 cm deep oriented perpendicularly to the plant rows were dug for each treatment. The 180 cm corresponds to two rows plus two half rows (one on each side, refer Appendix D). The roots were exposed for counting using a sharp tipped iron. The counting was done using a 5 cm x 5 cm wire mesh from 8 cm x 4 cm grid.

The counting was done left to right and from top to bottom for each 5 cm of soil layer. The number of roots was noted for each grid cell. Root growth measurements were based on rooting depth, root number, and root length density.

Root lengths density (RLD) was obtained using the equation suggested by Tennant (1975):

2. $$RLD\ (cm\ cm^{-3}) = \frac{\mathrm{RL\ (cm)}}{\mathrm{V}}$$

Where:

V: Volume of the soil where roots are found and

3. $$V\ (cm^3) = 5\ \mathrm{cm} \times 5cm \times 5cm$$

RL (cm): Root length was determined as:

4. $$RL\ (cm) = \frac{11}{14} \times number\ of\ intersects\ x\ grid\ unit\ (cm)$$

Yield and yield components

Three weeks after emergence, some tillers were developed and their numbers were noted. At the reproductive period, some secondary tillers were found to developed panicles filled of grains. To estimate yield, the area for which the plants where sampled was determined. Afterwards, the straw (including panicles from the main plants and from the tillers) was harvested and weighed. All panicles were harvested and weighed; the empty and full panicles were separated and also counted and weighed. Then, the full panicles were sun-dried, threshed, winnowed and the grains weighed.

Straw yield and grains yield, harvest index, the partial factor of productivity and agronomic efficiency were estimated to evaluate the productivity of sorghum. The formulas used for the estimations are:

5. $$\text{Grain yield (kg ha}^{-1}) = \frac{\text{Grain weight (kg)}}{\text{Area (ha)}} \times 10$$

6. $$\text{Straw yield (kg ha}^{-1}) = \frac{\text{Straw weight (kg)}}{\text{Area (ha)}} \times 10$$

7. $$\text{Harvest index} = \frac{\text{Grain yield (kg ha}^{-1})}{\text{Straw yield (kg ha}^{-1})} \times 10$$

8. $$\text{Partial factor of productivity (PFP)} = \frac{\text{Grain yield with N}}{\text{N applied}}$$

9. $$Agronomy\ efficiency\ (AE) = \frac{Yield\ with\ N - yield\ without\ N}{N\ applied}$$

Water use efficiency (WUE)

The total water consumption (ET) or water use (WU) during these experiments was calculated according to water balance equation given below by Bandyopadhyay, Mallick, and Rana (2005) and Saleh, Kiyoshi, and Nur. (2008):

10. $$ET = P + I + \Delta SW - R - D.$$

Where ET is the total soil water consumption or water use (including soil evaporation and plant transpiration); P (mm) is the rainfall, I (mm) is irrigation amount, R (mm) is the surface runoff, D (mm) is the water drainage below the crop root zone and ΔSW (mm) is the soil water change from sowing to maturity. In our experiment, R and D are assumed to insignificant only in the dry experiments. This led to:

11. Dry hot experiment: $ET\ (mm) = P + I + \Delta SW$

12. Rainfed experiment: $ET\ (mm) = P + R + D + \Delta SW$

13. Dry cold experiment: $ET\ (mm) = I + \Delta SW.$

Water use efficiency (WUE) was calculated according to Wang, Wei, Wang, Ma, & Ma, (2011):

14. $$WUE\ (kg\ ha^{-1}mm^{-1}) = \frac{Grain\ yield}{WU}$$

Where WU (mm) are the total soil water consumption (refer Appendix F) for the three experiments.

Nitrogen use efficiency (NUE)

To estimate NUE, laboratory analysis has been done on sorghum residues (grains, roots and stem) harvested at maturity period in all treatments. After these residues have been ground, nitrogen content has been measured in the Skalar SANplus Segmented flow analyser, (Model 4000-02, Breda, Holland) (refer to Chapter 3 for the method). In this study, the formula used to estimate NUE was:

$$15. \quad NUE\ (\%) = \frac{Nitrogen\ uptake}{Nitrogen\ applied + N\ stocked} \times 100$$

Nitrogen uptake: obtained by the laboratory analysis

N stocked: nitrogen obtained by initial soil analysis before setting up the experiments.

Climatic and yield data collection

The climatic data and the long sorghum trials yields data used in this study were collected from Saria Research center.

The sorghum yields were obtained by the following treatments:

The first treatment (FM) combined 100 kg ha^{-1} of NPK to 100 kg ha^{-1} of urea and to 50 kg ha^{-1} of the muriate of potash.

The second treatment (fm) combined 100 kg ha^{-1} of NPK to 50 kg ha^{-1} of urea.

The third treatment (FMO) is the combination of 100 kg ha^{-1} of NPK + 100 kg ha^{-1} of urea + 40 t ha^{-1} of organic matter every two years.

The fourth treatment (fmo) is the combination of 100 kg ha^{-1} of NPK + 50 kg ha^{-1} of urea + 5 t ha^{-1} of organic matter every two years.

Statistical analysis

The statistical analysis used two pieces of software (XLSTAT version 2016 and GenStat 9th edition). XLSTAT was used for the principal component analysis (PCA) and GenStat for the analysis of variance.

According to Smitch (2002), the principal component analysis (PCA) is based around the idea that there has a big set of data, and there is a need to analyze that set in terms of the relationships between the individual points in that data set. The PCA technique will identify patterns in those data, and express them in such a way as to highlight their similarities and differences (i.e. this PCA was used to analyze the different correlations among all parameters of the study: climate data, soil data and yield data as sorghum straw and grain yield and harvest index).

The general analysis of variance in a split-plot design was used to determine whether the correlations showed by the principal component analysis were confirmed. The means of the main and the combined effects of the studied factors were compared using the L.S.D. at 0.05 of probability level. The ANOVA tables are presented in Appendix G.

CHAPTER FOUR

RESULTS

Study of the effect of some climatic parameters on sorghum grain yield in INERA Saria from 1980 to 2012

Variation in rainfall and in rainy days

The analysis of variance showed some variations but not significant among annual rainfall and rainy days over 32 years (Table 2). Figures 3 present the annual total rainfall. This figure highlighted the variation in annual rainfall in Saria station during 32 years with an increasing trend ((Table 2). The Figure 3 also showed the annual rainfall between 600 and 1200 mm, with an average of 842 mm.

Similar to rainfall, Figures 4 showed some variations in annual total rainy days over the 32 years. The total number of rain days ranged from 51 to 86 with an average of 63 days.

Highly significant positive correlation was found between the amount of rainfall per year and the number of rainy days (Table 2). Rainfall increased when rainy days increased. A significant positive correlation was also found between rainfall and maximum and minimum temperatures (Table 2). Rainfall increased when temperatures increased.

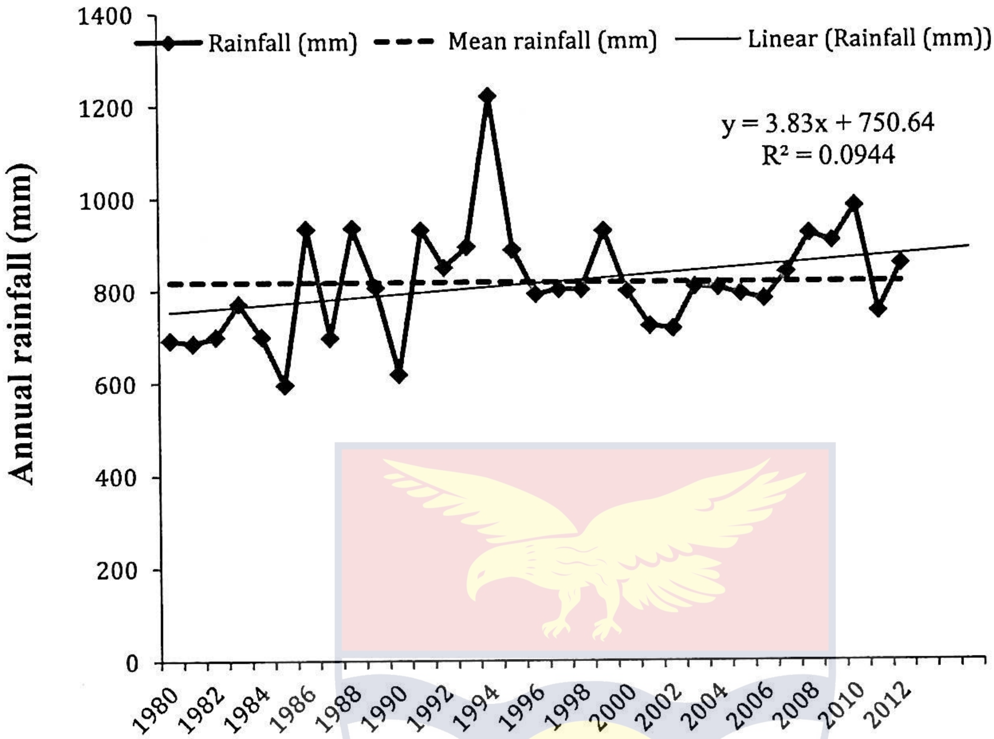


Figure 3: Annual total rainfall from 1980 to 2012.

Source: Data collected from the meteorological station of Saria

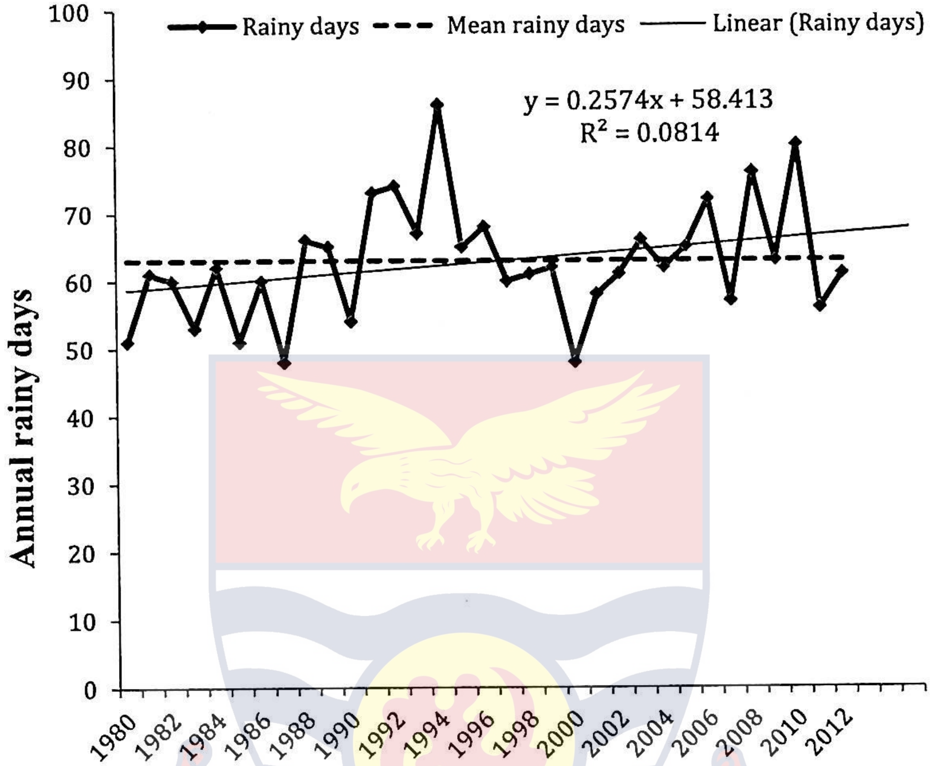


Figure 4: Annual total rainy days from 1980 to 2012.

Source: Data collected from the meteorological station of Saria

Variation in minimum and maximum temperatures

The correlation analysis showed significant and highly significant variations respectively in annual minimum and maximum temperatures (Table 2). The variations noted in annual maximum temperature were greater than the variation noted in annual minimum temperatures in Saria. Moreover, the variations indicated an increase in these temperatures over 32 years. These results are presented in Figure 5 and 6. The difference between the lowest and the highest temperatures for the minimum and the maximum temperatures during these 32 years was 8.8 °C and 7.4 °C respectively. The minimum and the maximum temperatures observed during 32 years were respectively 14.2 °C and 39.6 °C. Between the last two decades, an increase of 0.3 °C and 0.5 °C was noted in the minimum and maximum temperatures respectively. From the first decade (1980-1989) to the last half decade (2010-2015) an increase of respectively 0.8 °C and 1.1 °C was found in the minimum and maximum temperatures. The average minimum and maximum temperatures recorded are respectively 20.9 and 35.1 °C.

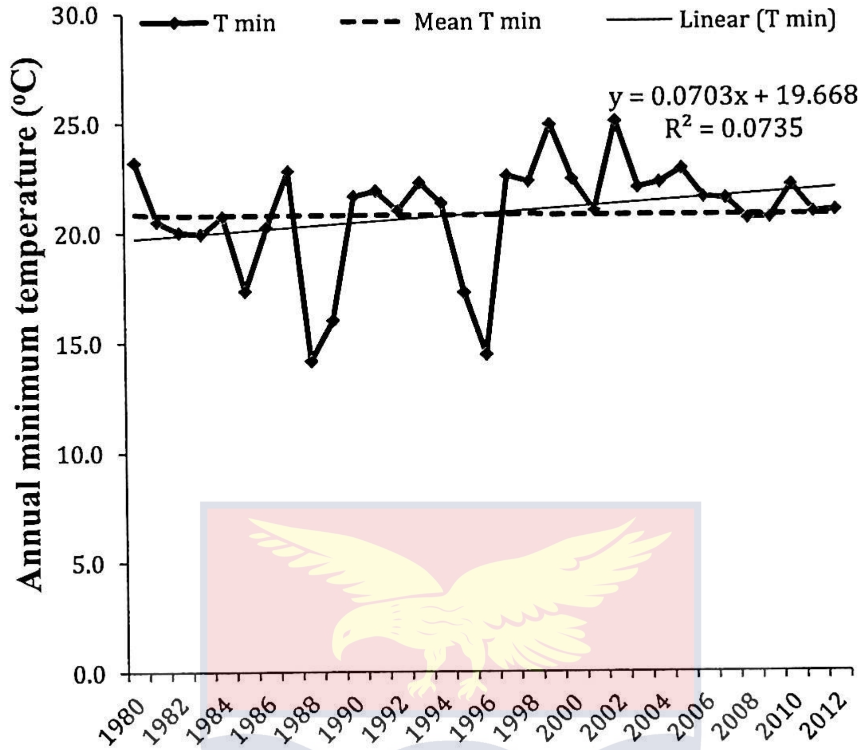


Figure 5: Annual total minimum temperatures from 1980 to 2012.

Source: Data collected from the meteorological station of Saria

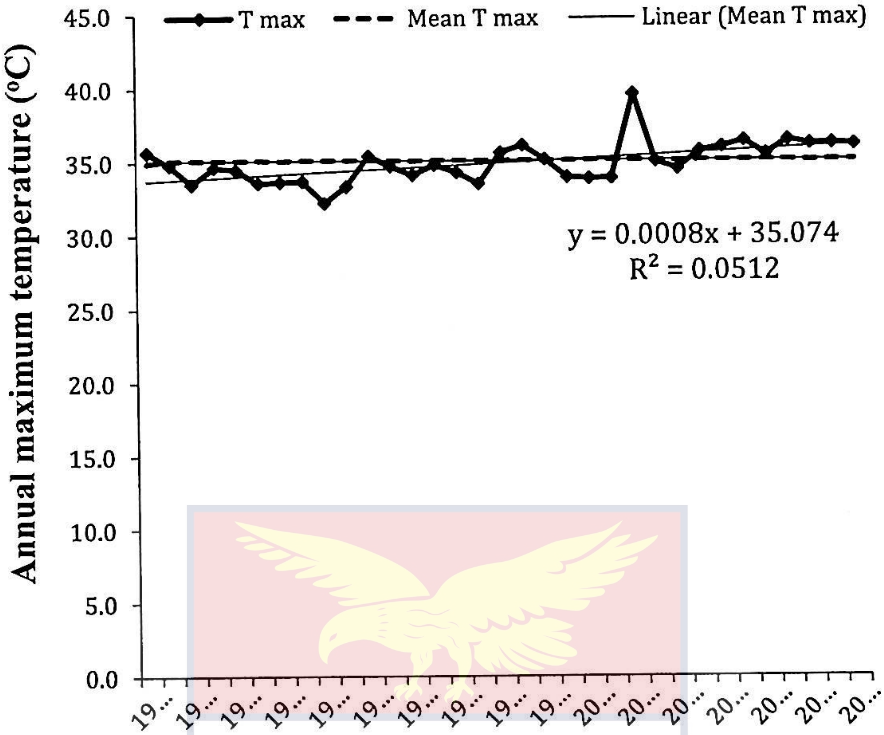


Figure 6: Annual total minimum temperatures from 1980 to 2102.

Source: Data collected from the meteorological station of Saria

Variation in potential evapotranspiration (PET)

Figures 7 displayed the variation but not significant in annual PET at Saria center during 32 years (1980-2012) (Table 2). The mean annual PET was between 160 and 120 mm, with an average of 122 mm and a standard variation of -0.85 mm showing a slight decline over the 32 years period (Figure 7). A slight negative correlation was found between the 32 years and the potential evapotranspiration and between the PET and the minimum and maximum temperatures.

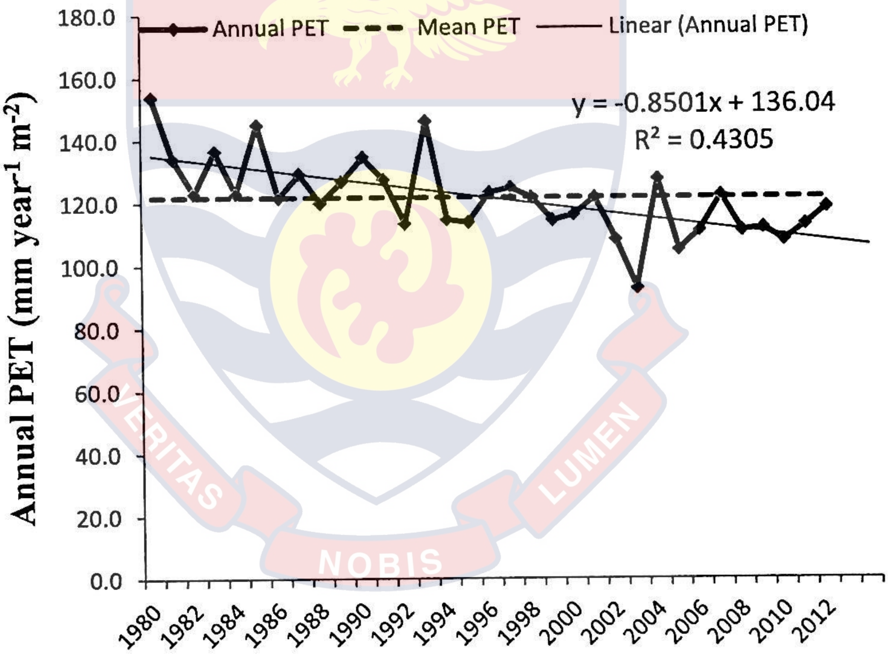


Figure 7: Mean annual potential evapotranspiration from 1980 at 2012.

Source: Data collected from the meteorological station of Saria

Variation in the long term sorghum trials yields in Saria Research center from 1980 to 2012

Figure 8 presented sorghum grain yields measured over 32 years (1980 to 2012) in long term sorghum trials yields in Saria Research center. The production trend showed the last decade as the least productive (average of 716.1 kg ha^{-1} of grain yield) and the second decade as the most productive (2375.5 kg ha^{-1}).

The correlation analysis (Table 2) showed that the variations noted in annual sorghum grain yields were highly significant. Significant correlation was found between maximum temperature and grain yields. The combined effect of rainy days with the maximum temperature has also affected sorghum grain yield.

The sorghum grain yields have been found to decrease over the 32 years and have been also decreased under higher maximum temperature. In addition, the variations in daily temperature affected negatively sorghum yield.

Figures 8 and 9 represent sorghum yields from the trials in Saria. They showed a decrease in sorghum yield cropped under nitrogen fertilization only and also under nitrogen fertilization combined with organic matter over the 32 years.

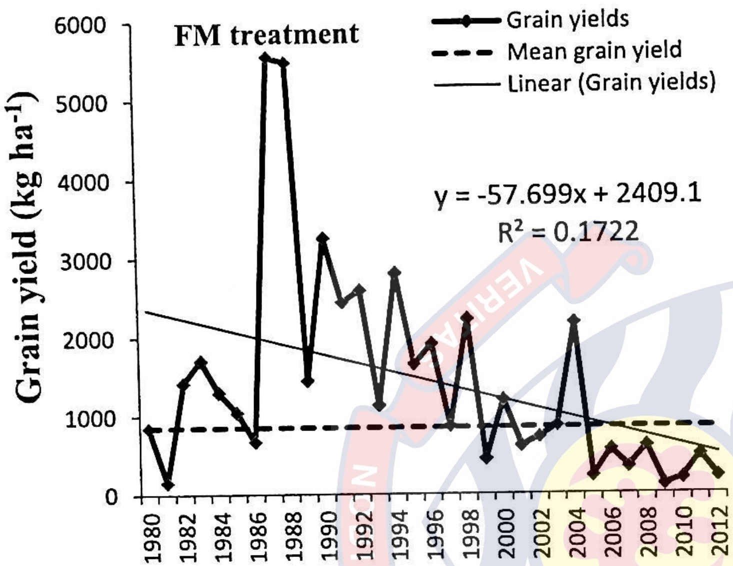
Table 2: *Pearson's Correlation Coefficient of climate and yield data in FM treatment*

Parameters	Years	Rainfall (mm)	Rain days	T min (°C)	T max (°C)	PET (mm d^{-1})	Yield (kg ha^{-1})
Years	1						
Rainfall (mm)	0.175	1					
Rain days	0.226	0.156	1				
T min(°C)	**0.371***	**0.328***	**0.378***	1			
T max (°C)	**0.718****	**0.336***	**0.361***	**0.465****	1		
PET(mm d^{-1})	-0.045	0.008	0.027	0.092	0.033	1	
Yield (kg ha^{-1})	**-0.688****	-0.030	-0.216	-0.049	**-0.506****	-0.066	1

** Correlation is significant at the 0.01 level (2-tailed test)

*Correlation is significant at the 0.05 level (2-tailed test)

Source: Saria meteorology and long term trials



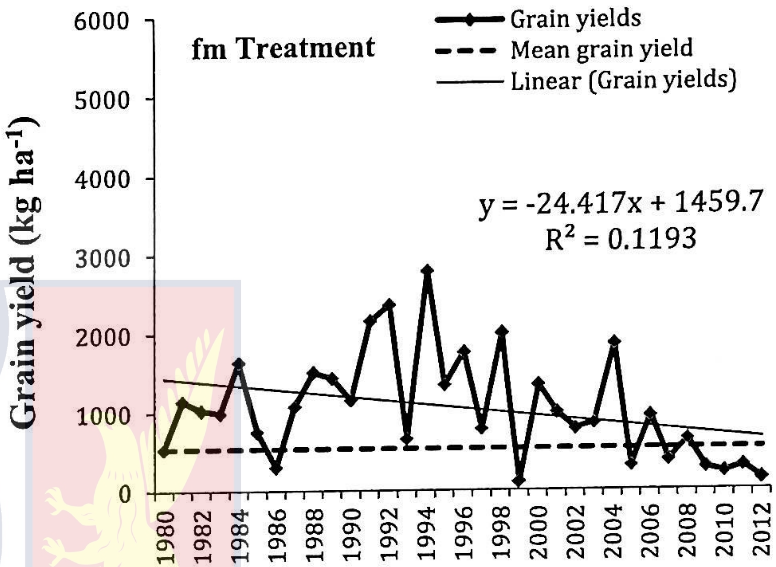


Figure 8: Variations in annual sorghum grain yields from 1980 to 2012 cropped under nitrogen fertilization.

FM: 100 kg ha^{-1} of NPK + 100 kg ha^{-1} of urea + 50 kg ha^{-1} of KCl

fm: 100 kg ha^{-1} of NPK + 50 kg ha^{-1} of urea

Source: Saria Research center long term sorghum trials yields

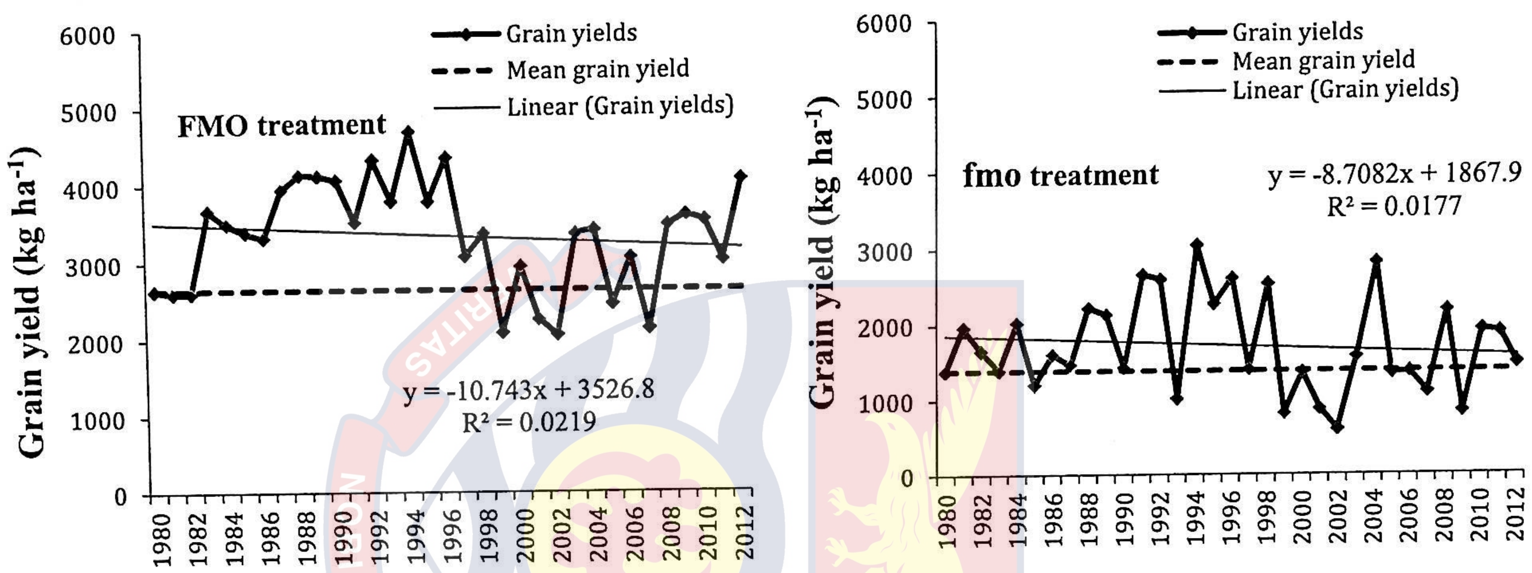


Figure 9: Variation in sorghum grain yield from 1980 to 2012 cropped under nitrogen fertilization and organic matter.

FMO: 100 kg NPK + 100 kg Urea + 50 kg KCl + (40 tons of organic matter every 2 years)

fmo: 100 kg NPK + 50 kg Urea + (5 tons of organic matter every 2 years)

Source: Saria Research center long term sorghum trials yields

Exploration of possible sorghum crop management adaptation strategies able to enhance sorghum production

The following paragraphs report the results from the three experiments conducted under three growth conditions.

The first growth condition (dry hot experiment) was conducted at low minimum temperature (19.8 °C) and high maximum temperature 39.3 °C. At flowering period, the minimum and maximum temperatures were respectively 26.5 °C and 38°C.

The rainfed condition (rainfed experiment) was led under environmental stresses (many variations in the daily temperature, dry spell, runoffs, and diseases etc.)

The dry cold condition (dry cold experiment) was done at low minimum temperature (21.2 °C) and low maximum temperature 35.9 °C. At flowering period, the minimum and maximum temperatures were respectively 15 °C and 35.3 °C.

Results from the correlations analysis by the principal component analysis (PCA)

The Principal Component Analysis (PCA) was performed to assess the effect of growth conditions (temperature > 35 °C, temperature < 35 °C), watering regimes (well-watered: 100% of PET and water stress: 50% of PET), nitrogen fertilization (0 and 60 kg ha^{-1}), genotype performance (Kapelga and Sariaso 14) on the length of sorghum reproductive cycle, root growth, panicle yield, straw yield, grain yield, thousand grain weight and harvest index and on soil fertility. The results are presented in Figure 10.

Table 3: *Major results from the principal component analysis*

Major factors	Information obtained
Under temperature > 35 °C	Sorghum reproductive cycle is lengthened, high number of empty panicles, high straw and grain yield but low harvest index.
Under temperature < 35 °C	Sorghum reproductive cycle is shortened; high panicle yield and high harvest index were shown.
Under rain	Root growth is high but low panicle yield, low grain yield and low harvest index.

The PCA showed that the growth conditions are the most affecting sorghum production followed 2nd by watering regimes, 3rd by genotypes performance and then 4th by nitrogen levels. Nitrogen stocked into the soil was not significantly affected.

In this analysis, the following cases were observed:

The first growth condition materialized by Tmax (i.e. high temperature > 35 °C), was positively correlated with the reproductive cycle, the number of empty panicles, the straw yield and grain yield (Figure 10) i.e. that number of empty panicle, straw yield, grain yield and reproductive cycle increased under temperature > 35 °C.

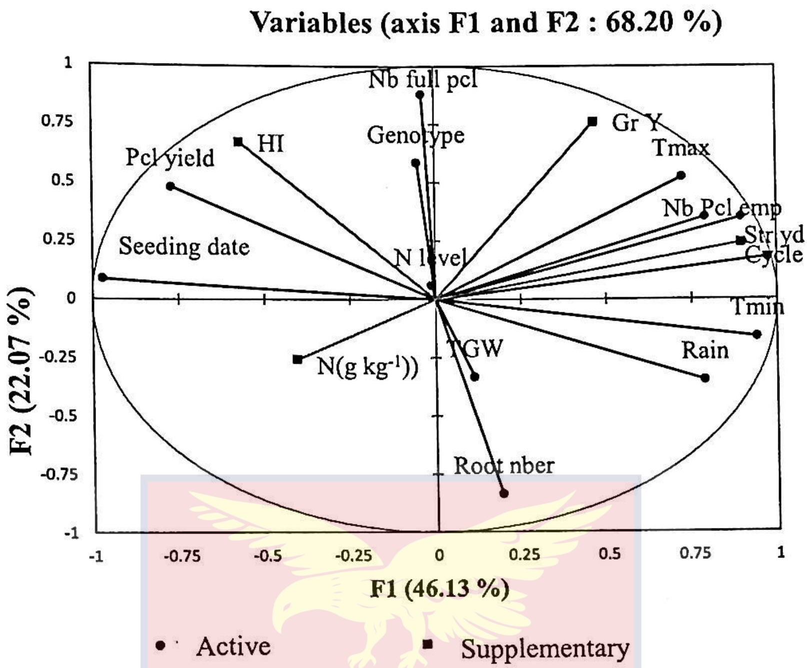


Figure 10: Representation of sorghum parameters studied by Principal Component Analysis (PCA).

Acronyms

F1: Vertical axis representing the factors

F2: Horizontal axis representing the variables

Cycle: sorghum production cycle

Gr Y (kg ha^{-1}): grain yield:

Pcl yield: panicle yield:

Nb Pcl empty: number of the empty panicle

N (g kg^{-1}): soil nitrogen after harvest

Root nber: number of roots

Tmax (°C): maximum temperature

TGW (g): thousand grain weight

Genotypes: sorghum genotype

HI: harvest index

N level: nitrogen levels

Nb full pcl: number of full panicle

Rain (mm): Water from rainy

Str yd (kg ha^{-1}): straw yield

Tmin (°C): minimum temperature

The second growth condition materialized by rain (i.e. rainfed experiment), is positively correlated with the root numbers but negatively correlated with the number of full panicles, panicle yield and harvest index (Figure 10) i.e. that root numbers was high under rainfed condition but this rainfed condition decreased the number of full panicle, panicle yield and harvest index.

The third growth condition materialized by Tmin i.e. temperature < 35 °C was negatively correlated with the number of full panicles, panicle yield and harvest index (Figure 10) i.e. that the number of full panicles, panicle yield and harvest index were increased when the temperature was low.

The principal component analysis allows classification of cropping practices. In Figure 11, four groups can be distinguished:

Above the horizontal axis, practices (1) and (2) were more efficient than practices (3) and (4) below the axis. The practices (1) and (3) to the right of the vertical axis were more efficient than practices (2) and (4) to the left of the axis.

Description of the practices identified by the PCA

Practice 1 is composed by the first growth condition combined to the two watering regimes (Water stress WS and well-watered WW), the two nitrogen levels (0 and 60 N) and to the genotype Sariaso 14 (Figure 11).

Practice 2 is composed by the third growth condition combined to the two water regimes (WS and WW), to the two nitrogen levels (0 and 60 N) and to the genotype *Sariaso 14* (GS); also combined to genotype *Kapelga* (GK) under WW condition (Figure 11).

Practice 3 is composed by the first growth condition combined to the two watering regimes (WS and WW), the two nitrogen levels (0 and 60 N) and to the genotype *Kapelga* (Figure 11).

Practice 4 is mainly composed by the second growth condition (rainfed condition) combined to the two nitrogen levels (0 and 60 N) and the two genotypes (GK and GS). In this practice 4, it was also found that the third growth condition combined to the two watering regimes (WS and WW), the two nitrogen levels (0 and 60 N) and to the genotype *Kapelga* (Figure 11)

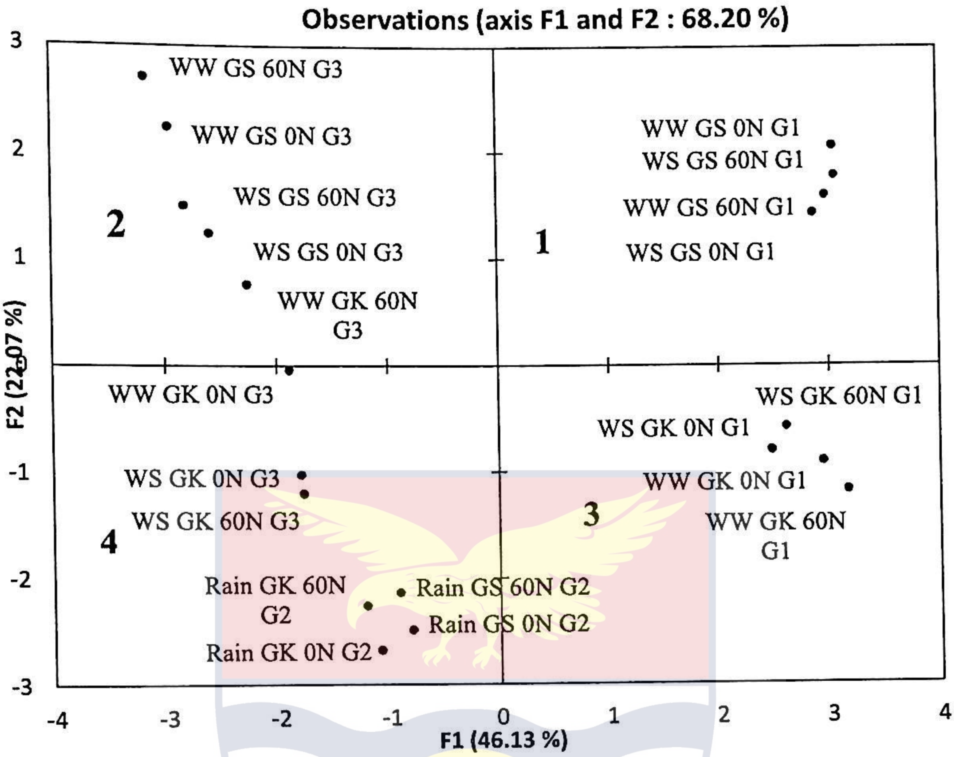


Figure 11: Representation of sorghum cropping practices by PCA.

Acronyms

G1: First growth condition (March 17th) corresponding to the first dry season experiment under temperatures > 35 °C

G2: Second growth condition (July 5th) corresponding to the rainfed experiment

G3: Third growth conditions (October 20th), second dry season experiment under temperatures < 35 °C

WW: Watering regime for the well-watered condition

WS: Watering regime for the water stress condition

GK: genotype *Kapelga* GS: genotype *Sariaso* 14

0N: 0 kg ha^{-1} (control treatment) 60N: Application of 60 kg ha^{-1} of urea

Effect of growth conditions on sorghum production

The main effect of the growth conditions on sorghum production are presented in the following paragraphs. The values reported on the tables are mean values. The bars in figures represent the standard errors and the values above the histograms are L.S.D. values.

Effect of growth conditions on sorghum water use and water use efficiency

The effect of growth conditions on sorghum water use (WU) and water use efficiency (WUE) was assessed (Table 4). The analysis of variance on data collected according to the growth conditions indicated a significant influence of the two dry seasons growth conditions on WU and WUE i.e. that a high use of water contributed to a low WUE (Table 4). Results indicated that the dry cold experiment consumed less water (316 mm) to produce high WUE (4.05 kg ha^{-1} mm^{-1}), compared to the rainfed experiment that consumed more water (878 mm) to produce low WUE (0.7 kg ha^{-1} mm^{-1}) . This WUE value was very low comparing to WUE from the dry season experiments (dry hot and cold experiments).

Comparing the two dry season experiments, although water use by the dry hot experiment was 63.7% larger than that of the dry cold experiment, it was found that in the dry cold experiment, water was used 31% more efficiently than in the dry hot experiment.

Table 4: *Water use efficiency (WUE) as affected by growth conditions*

Growth conditions	WU (mm)	WUE (kg ha^{-1} mm^{-1})
Dry hot experiment	871	2.78
Dry cold experiment	316	4.05
Rainfed experiment	878	0.7
L.S.D. (5%)	NS	0.8

Effect of growth conditions on sorghum nitrogen use and nitrogen use efficiency

The effect of growth conditions on nitrogen use efficiency (NUE) was assessed. Results are presented in Table 5.

Significant effect of growth conditions on crop nitrogen uptake, and nitrogen use efficiency (NUE) was shown (Table 5). For NUE, all the interaction effects were also found significant. However for nitrogen uptake, only the interaction effect between the growth conditions and nitrogen levels was significant.

Comparing NUE of the three growth conditions, it was found that the rainfed experiment recorded the highest NUE (15%) (Table 5) followed by the dry cold experiment. The dry hot experiment grown under temperature > 35 °C presented the lowest NUE. NUE in this dry hot experiment was 50% and 20% lower than those of the dry cold and rainfed experiments respectively.

Table 5: *Nitrogen use efficiency as affected by growth conditions*

Growth conditions (GC)	N uptake	NUE (%)
Dry hot experiment	2.76	6
Dry cold Experiment	5.05	12
Rainfed Experiment	6.33	15
L.S.D (0.05)	1.13	0.06

Effect of growth conditions on sorghum root growth

Studying root growth, it was found that the growth conditions had significant effect on sorghum root numbers, root length and root length density (Table 6).

Analysis of variance showed that root growth was linked to the amount of water used in the experiments (Table 6). For the rainfed experiment using the highest amount of water, the highest number of roots was also found in this rainfed experiment, and the dry cold experiment using the lowest amount of water, recorded also the lowest root numbers.

Table 6: *Sorghum root growth as affected by growth conditions*

Growth conditions (GC)	Root nber	Root length (cm)	Root length density (cm cm^{-3})
Dry hot experiment	22	109	0.7
Dry cold Experiment	16	64	0.52
Rainfed Experiment	36	139	1.12
L.S.D	4.13	16.25	0.13

Water use efficiency as affected by the root growth of sorghum

To find whether or not sorghum root growth has an influence on WUE, the values of WUE were compared according to the number of root and root length. The results are presented in Table 7.

The values presented in Table 7 showed that sorghum WUE was not proportional to root growth. WUE was reduced when sorghum root number and root length were high. The dry cold experiment showed highest WUE while the rainfed experiment presented the lowest WUE. This showed that WUE was not linked to root growth.

Table 7: *Water use efficiency as affected by root growth of sorghum*

Growth conditions GC)	Root nber	Root length (cm)	WUE (kg ha^{-1} mm^{-1})
Dry hot experiment	22	109	2.78
Dry cold Experiment	16	64	4.05
Rainfed Experiment	36	139	0.7
L.S.D (0.05)	4.13	16.25	0.8

Nitrogen use efficiency as affected by the root growth of sorghum

This analysis determines whether or not sorghum root growth has influence on nitrogen use efficiency (NUE). The values of NUE were compared with the number of roots and the root length. Table 8 shows the results.

Nitrogen use efficiency was not influenced by root growth of sorghum. The Table 8 shows that the dry cold experiment having the lowest root numbers had NUE greater than that of the dry hot experiment. In this Table 8, the dry hot experiment grown under temperature > 35° C recorded the lowest NUE, showing that there is no link between root growth and nitrogen use efficiency.

Table 8: *Nitrogen use efficiency as affected by root growth of sorghum*

Growth conditions GC)	Root nber	Root length (cm)	NUE (%)
Dry hot experiment	22	109	6
Dry cold Experiment	16	64	12
Rainfed Experiment	36	139	15
L.S.D (0.05)	4.13	16.25	0.06

Effect of growth conditions on sorghum reproductive cycle

The effects of growth conditions on sorghum reproductive cycle are shown in Table 9.

It was shown in Table 9 that in the rainfed experiment, sorghum reproductive cycle was similar to that of the production fact sheet. With regards to the dry hot experiment, sorghum reproductive cycle was found significantly longer while in the dry cold experiment, the reproductive cycle was found significantly shorter.

In the dry hot experiment, genotype *Kapelga* flowering days were longer than that of genotype *Sariaso* 14. Flowering and maturity dates were about 50 days longer in *Kapelga* than in *Sariaso* 14, where the delay in flowering and maturity days was just about 5 days for *Sariaso* 14 (Table 9).

The dry cold experiment caused early flowering and maturity of the two sorghum genotypes. Flowering and maturity in the *Kapelga* genotype were 11 and 9 days respectively earlier than indicated in the production fact sheet. For *Sariaso* 14, the cycle was 19 and 30 days earlier in the flowering and maturity periods respectively (Table 9).

Table 9: *Sorghum reproductive cycle as affected by growth conditions (in days)*

Growth conditions	Beginning of flowering		50% of flowering		Maturity	
	Kapelga	Sariaso 14	Kapelga	Sariaso 14	Kapelga	Sariaso 14
Reproduction fact sheet	69	76	76	82	105-110	110-115
Rainfed Experiment	65	74	75	85	105	115
Dry hot Experiment	120	80	133	95	160	125
Dry cold Experiment	58	57	82	72	101	85
L.S.D (0.05) for the two dry experiments	9.74	4.605	9.031	6.335	9.15	8.999

Effect of growth conditions on sorghum yield and yield components

Figure 12 showed significant effect of growth condition on sorghum straw and grain yields (refer to Appendix E). Concerning the harvest index, significant effect of growth conditions was noted on the dry hot and dry cold experiments and between the dry cold and the rainfed experiments. However between the dry hot and the rainfed experiment, no significant effect was found.

The dry hot experiment recorded the highest straw and grain yields. Sorghum reproductive cycle was lengthened in this experiment. The length of the reproductive cycle increased the straw yield and at the same time, some secondary tillers were formed. And when the rains started, the secondary panicles coming from the tillers flowered once and formed grains. Yields from these secondary panicles were assessed and found greater than the yield from rainfed and the dry cold experiments.

For the harvest index, the dry cold experiment recorded the highest value (Figure 12), while the rainfed one was the least productive. The analysis of variance revealed that in the dry hot experiment, grain yield was 47% and 73% higher than those of the dry cold and rainfed experiments respectively. In the dry cold experiment, grain yield was 48% higher than that of the rainfed experiment. With regards to the harvest index, in the dry cold experiment, ANOVA revealed that the harvest index was 58% and 67% higher than those of the dry hot and rainfed experiment respectively.

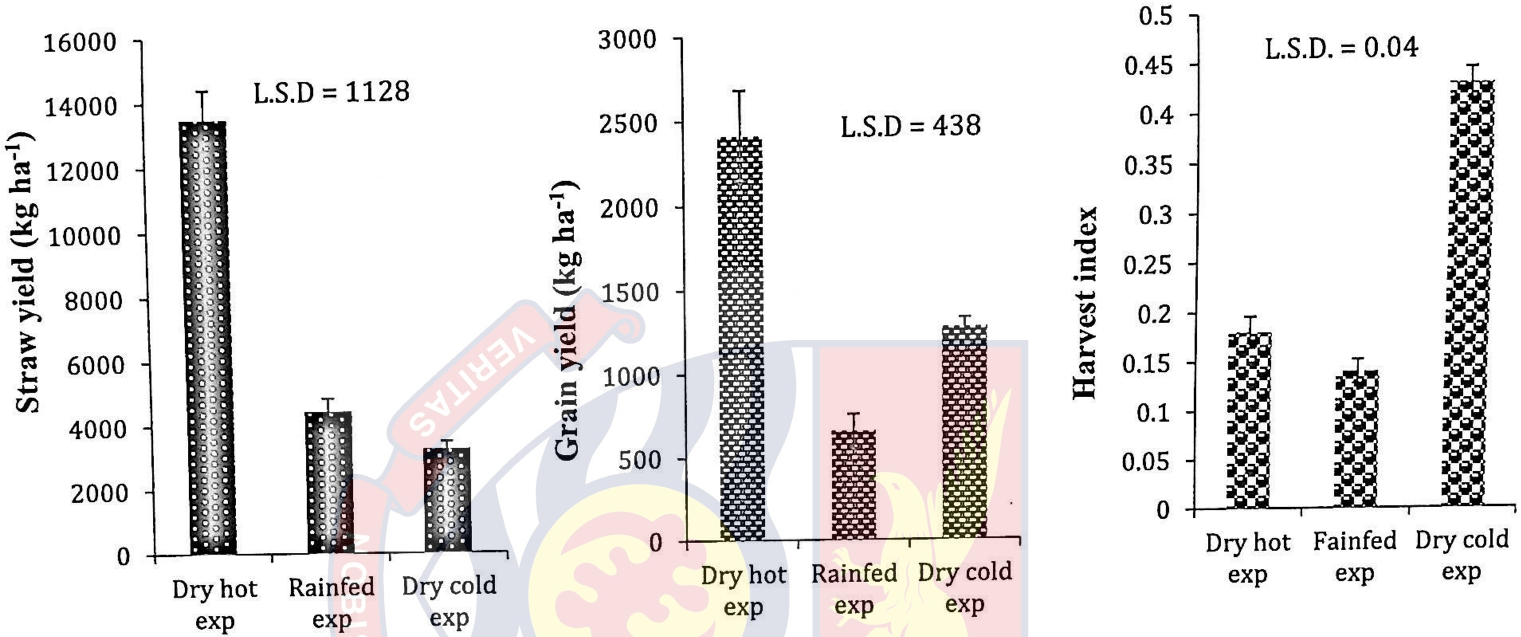


Figure 12: Sorghum straw, grain yield and harvest index as affected by growth conditions.

Effect of growth conditions on sorghum partial factor productivity and agronomic efficiency

To compare the productivity of dry season experiments (dry hot and cold experiments) with that of the rainfed experiment, the partial factor of productivity and the agronomy efficiency were assessed. The results on this assessment were noted in Table 10.

Table 10: *Sorghum partial factor of productivity and agronomy efficiency as affected by growth conditions*

Experiments	Partial factor productivity	Agronomy efficiency
Dry hot Experiment	38	13
Dry cold Experiment	20	6
Rainfed Experiment	11	4
L.S.D	8.8	4.6

Table 10 showed that the effect of growth conditions was significant on the partial factor of productivity (PFP) and the agronomy efficiency (AE). The difference between the three PFP of the three growth conditions was significant while for AE, there was no significant difference between AE from the rainfed and the dry cold experiments (Table 10). The analysis of variance revealed that the PFP in the dry hot experiment was 47% and 71% higher than those in the dry cold and rainfed experiments respectively. The PFP in the dry cold experiment was 45% higher than that of the rainfed experiment (Table 10).

The analysis of variance also revealed that the AE in the dry hot experiment was 54% and 77% higher than those in the dry cold and rainfed experiments respectively. In the dry cold experiment, even though there was no significant difference between the AE in the dry cold and rainfed experiments, the AE was 50% higher in the dry cold experiment than in the rainfed one (Table 10).

Effect of watering regimes on sorghum production

The effect of watering regimes was assessed on sorghum production under the three growth conditions. The following paragraphs present the results on the parameters studied regarding to sorghum production.

Effect of watering regimes on sorghum water use and nitrogen use efficiencies

The results presented in Table 11 analyzed first the effect of watering regimes on sorghum water use efficiency and then on nitrogen use efficiency. The effect of watering regimes was only assessed on the dry season experiments (dry hot and cold experiments). Water use efficiency (WUE) was found significantly influenced by the watering regimes (Table 11). In the dry hot and cold experiments, water use efficiency was improved in the well-watered conditions compared to that of the water stress condition.

Table 11: *Water use and nitrogen use efficiencies as affected by watering regimes*

Treatments	Dry hoot experiment	Dry cold experiment	Dry hoot experiment	Dry cold experiment
	WUE (kg ha^{-1} mm^{-1})		NUE (%)	
Watering regimes (WR)				
Water stress	2.01	3.24	7	15
Well – watered	3.23	4.66	6	16
L.S.D (0.05) main effect of WR	0.58	1.11	NS	NS

The analysis of variance showed that under, well-watered condition, WUE was 38% and 30% more improved in the dry hot and dry cold experiments respectively (Table 11).

With regards to nitrogen use efficiency, in the two dry hot and cold experiments, nitrogen use efficiency was not significantly influenced by watering regimes.

Effect of watering regimes on sorghum root growth

Assessing the effect of watering regimes on sorghum root growth in the two dry irrigated experiments (dry hot and dry cold experiments), it was found that root growth was significantly influenced only in the dry cold experiment (Table 12). It was also noticed that the root numbers, root length and root length density were greater in the water stress condition (using 50% of PET) than in the well-watered one (using 100% of PET). The analysis of variance showed that in the water stress condition, root numbers was 43% higher than in the well-watered condition.

Table 12: *Sorghum root growth as affected by watering regimes*

Treatments	Dry hot exp.	Dry cold exp.	Dry hot exp.	Dry cold exp.	Dry hot exp.	Dry cold exp.
Watering regimes (WR)	Root numbers		Root length (cm)		Root length density (cm cm^{-3})	
Water stress	24	21	94	82	0.7	0.7
Well - watered	32	12	124	45	1	0.4
L.S.D (0.05) main effect of WR	NS	7.81	NS	23.82	NS	0.19

Effect of watering regimes on sorghum reproductive cycle

Assessing the effect of watering regimes on sorghum reproductive cycle, it was found that only the maturity days in the dry cold experiment was significantly influenced (Table 13). The water stress condition (using 50% of PET) recorded the highest number of the maturity days. Under water stress, sorghum reproductive cycle was therefore lengthened up to 13 days.

Table 13: *Sorghum reproductive cycle as affected by watering regimes (in days)*

Treatments	Beginning of flowering	50% of Flowering	maturity
Watering regimes (WR)			
Water stress	58	79	101
Well - watered	56	72	88
L.S.D (0.05) main effect of WR	NS	NS	9.74

Effect of watering regimes on sorghum straw and grain yields and harvest index

Assessing the effect of watering regimes on sorghum production, Figure 13 showed significant effect of the watering regimes on sorghum straw and grain yields and harvest index. In the two dry experiments (dry hot and dry cold experiments), the well-watered condition (using 100% of PET) presented the highest straw and grain yields and harvest index.

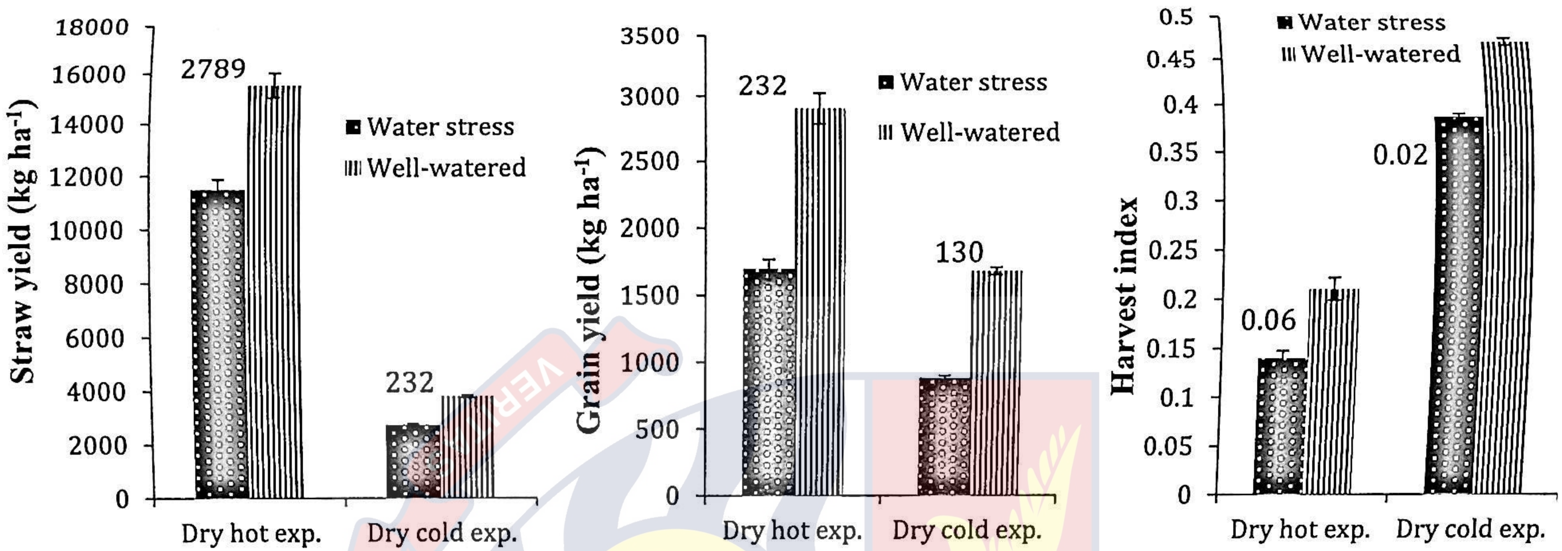


Figure 13: Sorghum straw and grain yields and harvest index as affected by watering regimes.

Compared to water stress condition, sorghum straw yield was improved by 26% and 28% in the dry hot and dry cold experiments respectively under well-watered condition (Figure 13). Under the same well-watered condition, grain yield was also improved by 29% and 47% in the dry hot and dry cold experiments respectively. Well-watered condition contributed then to improve sorghum harvest index by 33% and 23% in the dry hot and dry cold experiment respectively compared to that under water stress condition.

Effect of watering regimes on sorghum partial factor of productivity and agronomy efficiency

The effect of watering regimes was assessed on sorghum partial factor of productivity and agronomy efficiency in the two dry hot and dry cold experiments.

Table 14: *Partial factor of productivity and agronomy efficiency as affected by watering regimes*

Treatments	Dry hot exp.	Dry cold exp.	Dry hot exp.	Dry cold exp.
Watering regimes (WR)	Partial factor productivity		Agronomy efficiency	
Water stress	32	14	19	4
Well - watered	49	26	21	7
L.S.D (0.05) main effect of WR	6	2.8	NS	NS

Table 14 showed that watering regimes influenced significantly sorghum partial factor of productivity (PFP). The highest values of PFP were found in the well-watered condition (using 100% of PET). The analysis of variance showed that compared to water stress condition (using 50% of PET), well-watered condition contributed to improve sorghum PFP by 35% and 46% in the dry hot and dry cold experiments respectively.

Effect of nitrogen levels and genotypes on sorghum production

The effect of nitrogen levels and sorghum genotypes was assessed on the parameters of sorghum production. The results are noted in the following paragraphs.

Effect of nitrogen levels and genotypes on sorghum water use efficiency

Assessing the effect of the combined effect of nitrogen levels and genotypes on sorghum water use efficiency, no significant effect was found. However, Table 15 showed that the main effects of nitrogen levels and genotypes were significant on water use efficiency in the dry hot and dry cold experiments.

With regards to nitrogen levels, no significant main effect on water use efficiency was noted in the rainfed experiment. But the main effect of genotypes was observed in the entire experiments (dry hot, rainfed and dry cold experiments) (Table 15).

Table 15: *Water use efficiency as affected by nitrogen levels and genotypes*

Genotypes (G)	*Kapelga*			*Sariaso* 14		
Nitrogen levels (NL)	Dry hot exp.	Rainfed exp.	Dry cold exp.	Dry hot exp.	Rainfed exp.	Dry cold exp.
0 kg ha^{-1}	1.11	0.41	2.14	3.24	0.84	4.66
60 kg ha^{-1}	2.01	0.66	3.08	4.03	1.41	5.05
L.S.D (0.05) of NL * G:			NS			

The main effect of genotypes revealed that the improved genotype *Sariaso* 14 contributed to improve sorghum water use efficiency compared to that of the local genotype *Kapelga*. Therefore, Sorghum genotypic performance significantly affected water use efficiency (Table 15). The analysis of variance revealed that water use efficiency was more improved by *Sariaso* 14 by 66%, 51% and 54% in the dry hot, rainfed and dry cold experiments respectively.

It was also observed in Table 15 that in the irrigated experiments (dry hot and dry cold experiments), the two sorghum genotypes (*Sariaso* 14 and *Kapelga*) used water more efficiently than when they were in the rainfed experiment.

Effect of nitrogen levels and genotypes on sorghum nitrogen use efficiency

Assessing the interaction effect of nitrogen and genotypes on sorghum nitrogen use efficiency, Table 16 showed that the interaction effect was not significant in the entire experiments. However, the main effect of nitrogen on sorghum nitrogen use efficiency was significant in the entire experiments. Table 16 showed that under the three growth conditions, the application of the 60 kg ha^{-1} contributed significantly to the low nitrogen use efficiency. This situation was more expressed in the dry hot and rainfed experiment respectively.

Assessing the main effect of genotypes on sorghum nitrogen use efficiency, it was found that in the two dry irrigated experiments (dry hot and cold experiments) there was no significant influence (Table 16). But in the rainfed experiment, nitrogen use efficiency was influenced by the genotypic performance.

Table 16: *Nitrogen use efficiency as affected by nitrogen levels and genotypes*

Genotypes (G)	*Kapelga*			*Sariaso* 14		
	Dry hot	Rainfed	Dry cold	Dry hot	Rainfed	Dry cold
Nitrogen levels (NL)	exp.	exp.	exp.	exp.	exp.	exp.
0 kg ha^{-1}	22	70	55	21	39	45
60 kg ha^{-1}	4	8	10	3	5	9
L.S.D (0.05) of NL * G	NS	NS	NS	NS	NS	NS

The local genotype (*Kapelga*) was found to improve more NUE up to 44% and 38% under the control (0 kg ha^{-1}) and the 60 kg ha^{-1} conditions respectively (Table 16).

Effect of nitrogen levels and genotypes on sorghum root growth

Assessing the effect of nitrogen levels and sorghum genotypes on sorghum root growth under the three growth conditions, it was shown in Table 17 a significant effect of nitrogen levels and genotypes only in the dry cold experiment.

Table 17: *Sorghum root growth as affected by nitrogen levels and genotypes*

Genotypes (G)	*Kapelga*			*Sariaso* 14		
Nitrogen levels (NL)	Dry hot exp.	Rainfed exp.	Dry cold exp.	Dry hot exp.	Rainfed exp.	Dry cold exp.
0 kg ha^{-1}	23	36	17	17	38	12
60 kg ha^{-1}	31	35	21	20	34	16
L.S.D (0.05) of NL * G:	NS	NS	4.2	NS	NS	4.2

In the dry cold experiment, the highest number of roots was recorded under the application of 60 kg ha^{-1} of nitrogen by genotype Kapelga (Table 17). The increase in root numbers due to the application of the 60 kg ha^{-1} of nitrogen where the local genotype Kapelga was sown was 24% in this dry cold experiment. The main effect of nitrogen levels and genotypes was also found significant only in the dry cold experiment.

Effect of nitrogen levels and genotypes on sorghum reproductive cycle

The effect of nitrogen levels and sorghum genotypes was assessed on sorghum reproductive cycle under the dry cold growth conditions. Significant effect of the interaction on sorghum reproductive cycle is noted in Table 18.

Table 18: *Sorghum reproductive cycle as affected by nitrogen levels and genotypes (in days)*

Genotypes (G)	*Kapelga*		*Sariaso* 14	
Nitrogen levels (NL)	50% flowering	Maturity	50% flowering	Maturity
0 kg ha^{-1}	84	101	73	91
60 kg ha^{-1}	82	99	70	86
L.S.D (0.05) of NL * G:		6.33		

The lower number of the 50% of flowering and maturity days was observed in the 60 kg ha^{-1} by the improved genotype *Sariaso* 14 (Table 18). Therefore, the application of the 60 kg ha^{-1} of nitrogen where the improved genotype *Sariaso* 14 was sown contributed to shorten sorghum reproductive cycle by 29 days for the 50% of flowering and 13 days for the maturity. The main effect of nitrogen and genotypes was also found significant on sorghum 50% of flowering and on maturity days.

Effect of nitrogen levels and genotypes on sorghum straw and grain yields and the harvest index

Assessing the effect of nitrogen levels and genotypes on sorghum straw and grain yields and harvest index, Table 19 showed a significant effect in the rainfed and dry cold experiments with regards to the straw yield. Concerning grain yield and harvest index, the effects were significant in the three growth conditions (dry hot, rainfed and dry cold experiments).

For grain yield and harvest index, the highest values were noted in the 60 kg ha^{-1} by genotype *Sariaso* 14 treatments. These treatments were the most improving grain yield and harvest index. Grain yield was improved by 62%, 61% and 53% in the dry hot, rainfed and dry cold experiments respectively.

Table 19: *Sorghum straw and grain yields and harvest index as affected by nitrogen levels and genotypes*

Straw yield (kg ha^{-1})

Genotypes (G)	*Kapelga*			*Sariaso* 14		
Nitrogen levels (NL)	Dry hot exp.	Rainfed exp.	Dry cold exp.	Dry hot exp.	Rainfed exp.	Dry cold exp.
0 kg ha^{-1}	8641	4713.6	2423.7	12345.5	2834.3	3470.3
60 kg ha^{-1}	15669.2	6506.3	3041.5	17298.7	3748.3	4141.5
L.S.D (0.05) of NL * G:	NS	1424.03	575.93	NS	1424.03	575.93

Table 19: *Sorghum straw and grain yields and harvest index as affected by nitrogen levels and genotypes (cont'd)*

Grain yield (kg ha^{-1})

Genotypes (G)	*Kapelga*			*Sariaso* 14		
Nitrogen levels (NL)	Dry hot exp.	Rainfed exp.	Dry cold exp.	Dry hot exp.	Rainfed exp.	Dry cold exp.
0 kg ha^{-1}	956.9	265.9	614	2952	883.1	1587.3
60 kg ha^{-1}	1586.3	415.4	926.5	4155.1	1069	1989.9
L.S.D (0.05) of NL * G:	605.42	338.71	200.06	605.42	338.71	200.06

Table 19: *Sorghum straw and grain yields and harvest index as affected by nitrogen levels and genotypes* (cont'd)

Harvest index

Genotypes (G)	*Kapelga*			*Sariaso* 14		
Nitrogen levels (NL)	Dry hot exp.	Rainfed exp.	Dry cold exp.	Dry hot exp.	Rainfed exp.	Dry cold exp.
0 kg ha^{-1}	0.08	0.09	0.18	0.23	0.16	0.62
60 kg ha^{-1}	0.13	0.11	0.21	0.27	0.19	0.7
L.S.D (0.05) of NL * G:	0.05	0.04	0.05	0.05	0.04	0.05

Regarding the harvest index, it was improved by 52%, 42% and 70% in the dry hot, rainfed and dry cold experiments respectively.

Concerning the main effects, Table 19 showed that the main effects of nitrogen were significant on grain yield and harvest index in the two dry experiments but not in the rainfed experiment. Significant effect of the genotypes was observed on straw and grain yields and harvest index in the entire experiments.

Concerning the main effect of nitrogen levels, the analysis of variance revealed in Figure 14 that the application of the 60 kg ha^{-1} of nitrogen contributed to improve sorghum grain yield by 32% and 25% in the dry hot and dry cold experiments respectively. The harvest index was improved up to 25% and 11% in the dry hot and dry cold experiments respectively.

Regarding the main effect of genotype, Figure 15 also revealed that compared to the local genotype *Kapelga*, the improved genotype *Sariaso* 14 contributed to improve grain yield by 64%, 65% and 57% in the dry hot, rainfed and dry cold experiments respectively. Also, this genotype *Sariaso* 14 contributed to improve harvest index by 56%, 44% and 71% in the dry hot, rainfed and dry cold experiments respectively. It was noted that genotype Sariaso 14 developed secondary tillers that formed grains during grain filling stage.

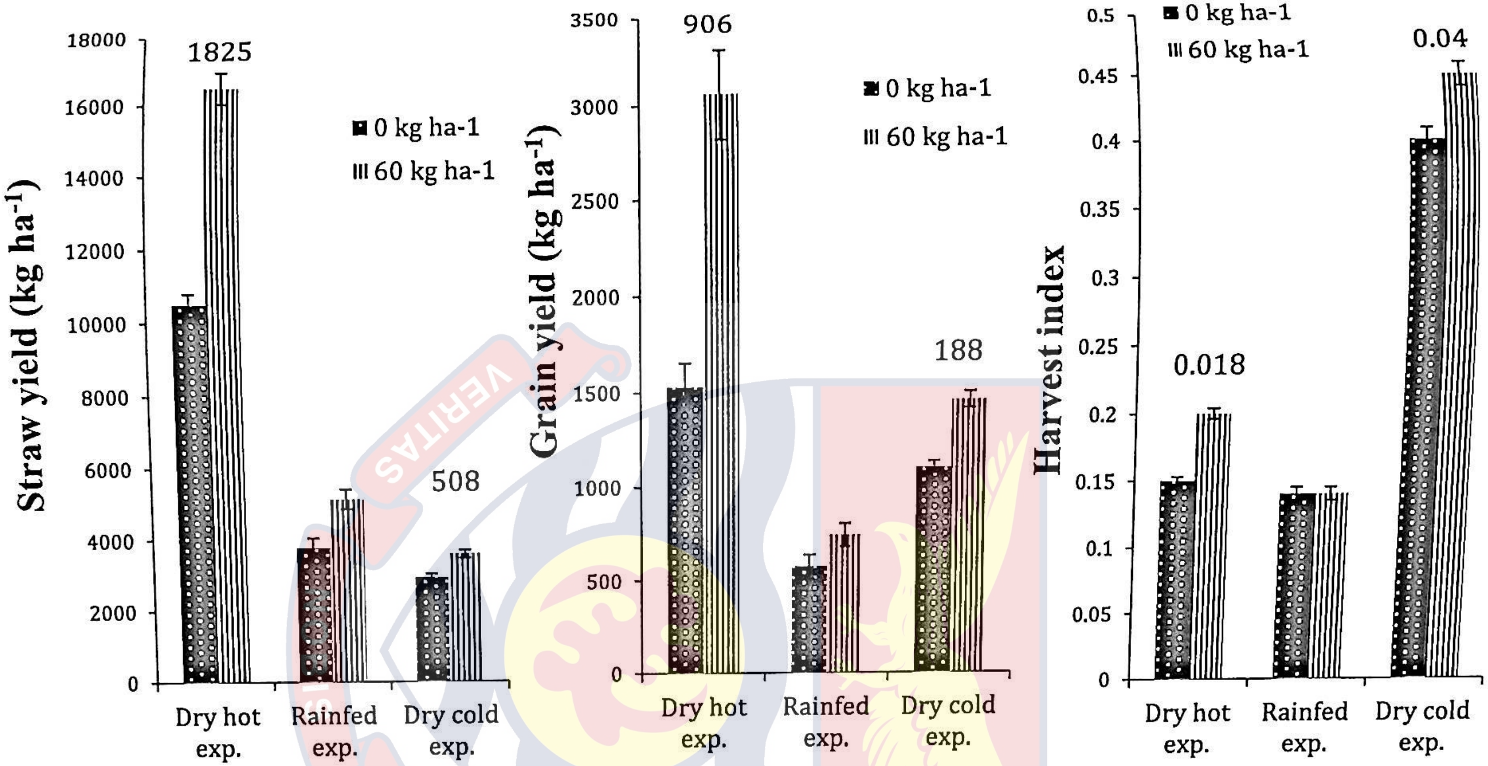


Figure 14: Sorghum straw and grain yields and harvest index as affected by nitrogen levels.

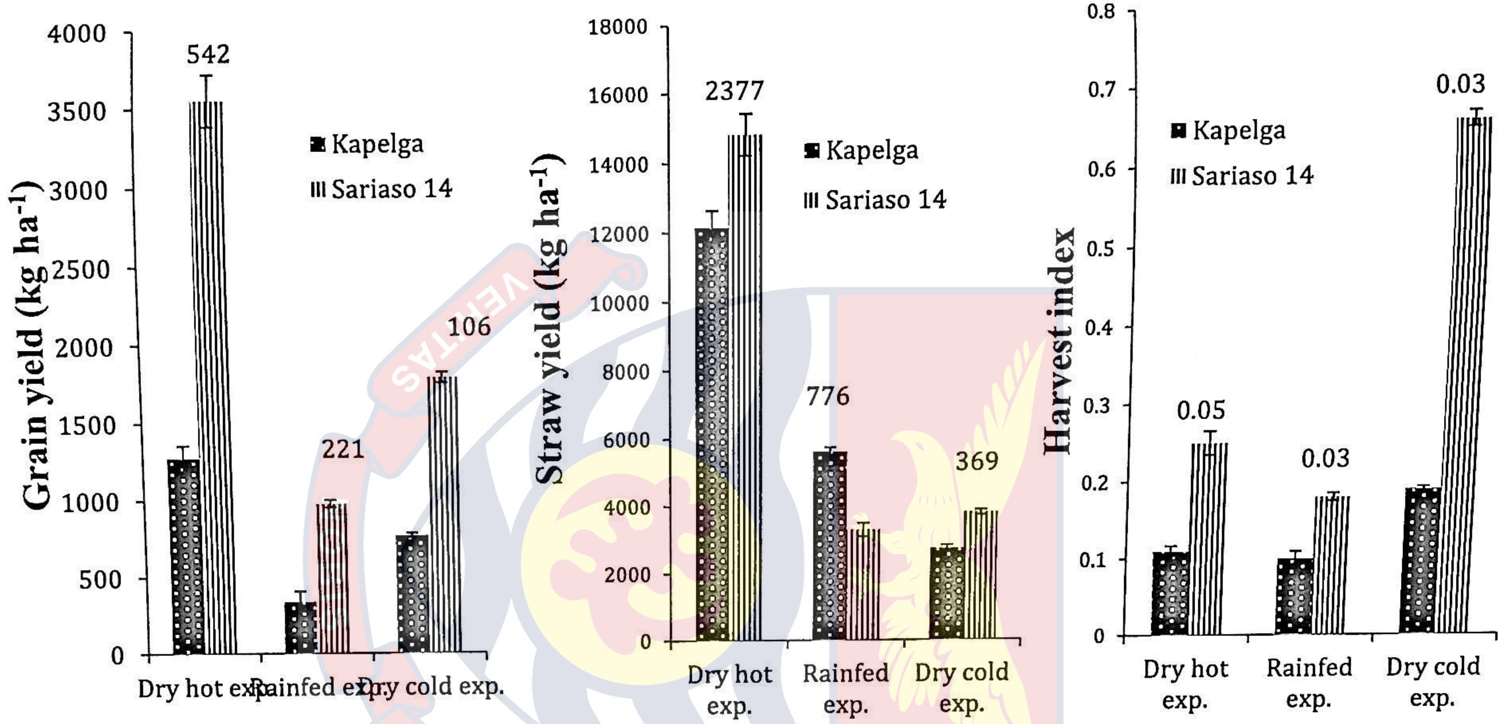


Figure 15: Sorghum straw and grain yields and harvest index as affected by genotypes performance.

Interaction effect of watering regimes, nitrogen levels and genotypes on sorghum production

The interaction effect of the three factors (watering regimes, nitrogen levels and genotypes) was assessed in the two dry conditions (dry hot and dry cold experiments). Table 20 showed that the interaction effect of the three factors was significant on water use efficiency (WUE) in the two dry experiments while for gain yield, this interaction was only significant in the dry cold experiment.

Table 20 also showed that WUE and grain yields were improved under the two dry experiments combined with the two watering regimes, the two nitrogen levels and the genotype *Sariaso* 14 (improved genotype). It was also found in these dry experiments that WUE and grain yield were more improved under well-watered by the 60 kg ha^{-1} of nitrogen (urea) and by the two genotypes treatments.

The highest WUE and grain yield in the two dry experiments were obtained under the WW * 60 NL * GS treatment. Genotype *Sariaso* 14 contributed so to improve more sorghum production than genotype *Kapelga*. For WUE, the improvement induced by *Sariaso* 14 was 59% and 64% in the dry hot and dry cold experiments respectively. For grain yield, the improvement induced was 30% and 35% in the dry hot and dry cold experiments respectively.

Table 20 also showed a decrease in grain yield in the treatment WS * 60 NL * GK. In water stress condition, the application of 60 kg ha^{-1} of nitrogen contributed to reduce the production of genotype *Kapelga* by 6% in the dry cold experiment.

Table 20: *Sorghum water use efficiency and grain yield as affected by the interaction of watering regimes, nitrogen levels and genotypes*

Treatment		WUE (kg ha^{-1} mm^{-1})		Grain yield (kg ha^{-1})	
Water regimes (WR)	NL * G	Dry hot exp.	Dry cold exp.	Dry hot exp.	Dry cold exp.
Water stress	0N * GK	0.74	1.41	536.2	350.9
	0N * GS	2.12	3.34	1395.9	1202.8
	60N * GK	1.62	1.86	1307.5	328.2
	60N * GS	4.39	4.62	3538.3	1647.4
Well - watered	0N * GK	1.19	2.03	1273.1	877.1
	0N * GS	3.41	4.80	2910.7	1971.9
	60N * GK	2.60	2.68	3042.6	1524.8
	60N * GS	6.31	7.42	4376.4	2332.3
L.S.D. (0.05) for WR * NL * G		0.58	0.92	NS	680.76

Effect of growing sorghum under three different growth conditions, watering regimes, nitrogen fertilization and sorghum genotype on soil fertility

Initial soil pH, soil physical and chemical properties

The laboratory analysis presented the following results in Table 21 and 22 on soil pH, physical and chemical properties before starting the experiments.

Table 21: *Initial soil physical properties*

Experiments	Clay%	Silt	Sand	Texture
Initial 1	14.2	23.33	39.65	Sandy loam
Initial 2	20.33	24.37	34.36	Sandy loam
Initial 3	18.51	23.75	35.55	Sandy loam

The analysis shows and acidic sandy loam soil with low levels of total N and P, and available P, low organic carbon, low exchangeable bases and low cation exchange capacity (Table 21 and 22).

Table 22: *Initial soil pH and chemical properties*

Experiments	Horizons	pH	P	K	C	N	Pavail	C/N	Ca^{2+}	Mg^{2+}	CEC
				g kg $^{-1}$			mg kg^{-1}			cmol$_c$ kg^{-1}	
Initial 1	0-20 cm	4.66	0.13	0.39	4.25	0.23	6.48	19	0.86	0.43	3.57
	20-40 cm	4.6	0.08	0.44	3.55	0.2	4.17	18	0.94	0.42	4.55
	Average	4.63	0.105	0.415	3.9	0.215	5.325	18.5	0.9	0.425	4.06
Initial 2	0-20 cm	4.55	0.08	0.42	3.50	0.21	4.17	17	1.27	0.51	4.38
	20-40 cm	5.04	0.07	0.54	3.74	0.23	1.85	16	2.16	1.00	7.25
	Average	4.795	0.075	0.48	3.62	0.22	3.01	16.5	1.715	0.755	5.815
Initial 3	0-20 cm	4.62	0.08	0.37	3.21	0.20	5.56	16	1.19	0.45	4.62
	20-40 cm	5.77	0.07	0.53	3.41	0.23	1.85	15	2.84	1.10	7.29
	Average	5.195	0.075	0.45	3.31	0.215	3.705	15.5	2.015	0.775	5.955

Soil chemical properties at the end of the experiments

At the end of the three experiments, an analysis of variance and a correlation analysis were done to study the impacts of growing sorghum under different growth conditions on soil fertility. The impacts of watering regimes, nitrogen levels and the genotypes on soil pH and certain chemical properties were assessed.

Soil pH and chemical properties were more or less affected by the conditions of laying out the experiments (Table 23). Soil N, P, P available, K, and C/N ratio contents were significantly affected by the temperature. The correlation showed a positive impact of temperature on soil K and C/N whereas N, P and available P were negatively affected by the temperature. Concerning the other nutrients such as organic C, Ca^{2+}, Mg^{2+} CEC and pH content, the impact of temperature was positive but not significant (Table 23).

The potential evapotranspiration affected positively and significantly soil K, C, CEC and C/N. However this potential evapotranspiration affected negatively and significantly soil pH, N, P and available P whereas on Ca^{2+} and Mg^{2+} contents, the impact was slightly positive (Table 23).

The results also showed that with regards to watering regimes, no significant correlation was found for soil pH and chemical properties. However, a slight positive impact of watering regimes was noted on soil P, available P, K, Ca^{2+}, Mg^{2+}, and CEC contents. Watering regimes were found to decrease but not significantly organic C and C/N contents (Table 23).

Nitrogen fertilization was noted to affect negatively and significantly soil pH and Mg^{2+}. Also, a slight negative impact of nitrogen fertilization was reported on N, available P, K, organic C, Ca^{2+}, Mg^{2+} and CEC contents. The impact of nitrogen fertilization was also found to be slightly positive on soil P and C/N ratio content (Table 23).

A positive significant impact of sorghum genotype was noted in available P and organic C contents. On soil N, P, Ca^{2+} and C/N ratio contents, sorghum genotype had positive but not significant effects. The genotypic effect was slightly negative on pH, K Mg^{2+} and CEC contents (Table 23).

Table 23: *Correlation among growth conditions, watering regimes, nitrogen levels, sorghum genotypes and soil properties*

Variables	Ho	T °C	PET	WR	N level	Genotypes	pH	N	P	Avail P	K	C	C/N	Ca^{2+}	Mg^{2+}	CEC
Ho	**1**															
T °C	0.000	**1**														
PET	0.000	**0.922**	**1**													
WR	0.000	0.000	0.000	**1**												
N level	0.000	0.000	0.000	0.000	**1**											
Genotypes	0.000	0.000	0.000	0.000	0.000	**1**										
pH	**0.184***	0.014	**-0.223**	0.114	**-0.164**	-0.149	**1**									
N	0.079	**-0.263**	**-0.214**	-0.037	-0.037	0.077	-0.044	**1**								
P	-0.010	**-0.283**	**-0.200**	0.150	0.022	0.144	**-0.171**	**0.430**	**1**							
Avail P	0.020	**-0.267**	**-0.347**	0.148	-0.053	**0.161**	**0.247**	0.010	**0.366**	**1**						
K	**0.334***	**0.160**	**0.333**	0.051	-0.005	-0.012	**-0.262**	**0.185**	0.127	**-0.235**	**1**					
C	-0.028	0.108	**0.178**	-0.063	-0.043	**0.200**	-0.123	**0.588**	**0.298**	-0.080	0.127	**1**				
C/N	-0.106	**0.409**	**0.453**	-0.012	0.011	0.133	-0.129	**-0.386**	-0.108	-0.104	-0.024	**0.500**	**1**			
Ca^{2+}	**0.163***	0.039	0.051	0.103	-0.068	0.029	**0.236**	**0.262**	-0.154	**-0.410**	**0.177**	0.137	-0.117	**1**		
Mg^{2+}	**0.190**	0.099	0.123	0.088	**-0.245**	-0.044	**0.259**	**0.405**	0.043	**-0.246**	**0.246**	**0.226**	**-0.165**	**0.702**	**1**	
CEC	0.154	0.127	**0.286**	0.038	-0.012	-0.061	**-0.169**	**0.306**	0.101	**-0.281**	**0.357**	**0.259**	-0.005	**0.451**	**0.523**	**1**

The bold values indicate that the correlation is significant at the 0.05 level (2-tailed test) Ho: horizon

Effect of growth conditions on soil fertility

Before setting up and at the end of the three experiments, the analysis of variance was performed on soil chemical properties to see whether or not the different treatments applied had an impact on soil chemical properties. Table 24 presented the results.

The analysis of variances showed that all the growth conditions (dry hot, dry cold and rainfed experiments) affected more or less soil pH and the chemical properties contents dosed in this study. It was found that the three growth conditions did not have a significant effect on soil organic Carbon.

Studying soil fertility under the dry hot condition, it was found that soil pH and certain chemical properties were more or less affected by this dry hot condition. Soil pH and Phosphorus (P) contents were not significantly affected. However, compared to the contents dosed before the experiment, the dry hot condition had significant and negative impact on the content of soil P available (Table 24). Then, soil P, N, C/N, Ca^{2+}, Mg^{2+} and CEC contents were found to be significantly positively increased into the soil in this dry hot condition.

In the rainfed experiment, soil pH and all the chemical properties dosed were significantly influenced at the end of the implementation. The analysis of variance showed a significant decrease in soil pH i.e. soil acidity has increased. A significant decrease was also noted in soil K, Ca^{2+}, Mg^{2+}, and CEC contents. However, under this growth condition, there was a significant increase of P available, P and N contents into the soil (Table 24).

Under the dry cold condition, apart from soil pH and C, all the chemical properties dosed were significantly influenced (Table 24). It was observed that soil available P, P, N and C/N contents were increased into the soil while the contents of K, Ca^{2+}, Mg^{2+}, and CEC decreased into the soil.

Table 24: *Soil pH and some chemical properties as affected by the growth conditions*

Experiments	pH	Pav	P	K	N	Ct	C/N	Ca^{2+}	Mg^{2+}	CEC
		mg kg^{-1}		g kg^{-1}					cmol kg^{-1}	
Initial 1 sample	4.63	5.33	0.11	0.42	0.22	3.9	18.5	0.9	0.43	4.06
Dry hot exp.	4.65	2.25	0.10	0.50	0.24	3.83	16.5	1.53	0.71	5.25
L.S.D.	NS	0.28	NS	0.06	0.02	NS	1.20	0.08	0.04	0.22
Initial 2 sample	4.80	3.01	0.08	0.48	0.22	3.62	16.5	1.72	0.76	5.81
Rainfed exp.	4.65	5.14	0.13	0.42	0.28	3.56	12.74	1.47	0.63	4.54
L.S.D.	0.11	1.29	0.014	0.039	0.02	NS	0.78	0.12	0.05	0.67
Initial 3 sample	5.20	3.71	0.08	0.45	0.22	3.31	15.5	2.02	0.78	5.96
Dry cold exp.	5.14	5.41	0.11	0.31	0.25	3.38	13.54	1.46	0.63	3.46
L.S.D.	NS	1.115	0.008	0.02	0.02	NS	0.64	0.15	0.08	0.39

Effect of watering regimes on soil fertility

The watering regimes were assessed under the two dry conditions (dry hot and dry cold conditions). The analysis of variance showed that the effect of these watering regimes on soil pH and certain soil properties was found significant only on soil pH and P in the dry hot condition. All the other properties were not significantly influenced by watering regimes. Soil P content and pH were increased under well-watered condition (Table 25). This well-watered condition contributed therefore to reduce soil acidity under the dry hot condition.

At the end of the two dry experiments compared to the beginning, it was noted a decreased in soil available P content and an increase in the Ca^{2+}, Mg^{2+}, and CEC content due to well-watered condition in the dry hot experiment . In the dry cold experiment, under well-watered condition, there was a decrease in Ca^{2+}, Mg^{2+}, and CEC contents while an increase was noted in available P content (Table 25).

Table 25: *Soil pH and some chemical properties as affected by watering regimes*

Soil properties	Treatments / Watering regimes	Initial 1 sample	Dry hot exp.	Initial 3 sample	Dry cold exp.
pH	Water stress	4.63	4.58	5.20	5.10
	Well-watered	4.63	4.71	5.20	5.19
	L.S.D.		0.06		NS
P (g kg^{-1})	Water stress	0.11	0.098	0.08	0.10
	Well-watered	0.11	0.11	0.08	0.11
	L.S.D.		0.010		NS
P av (mg kg^{-1})	Water stress	5.33	2.17	3.71	4.70
	Well-watered	5.33	2.33	3.71	6.12
K (g kg^{-1})	Water stress	0.42	0.48	0.45	0.30
	Well-watered	0.42	0.51	0.45	0.32
N (g kg^{-1})	Water stress	0.22	0.24	0.22	0.25
	Well-watered	0.22	0.23	0.22	0.25
C (g kg^{-1})	Water stress	3.9	3.78	3.31	3.47
	Well-watered	3.9	3.88	3.31	3.29
C/N	Water stress	18.5	15.94	15.50	13.78
	Well-watered	18.5	17.07	15.50	13.30
Ca^{2+}	Water stress	0.9	1.43	2.02	1.41
	Well-watered	0.9	1.63	2.02	1.50
Mg^{2+}	Water stress	0.43	0.67	0.78	0.61
	Well-watered	0.43	0.74	0.78	0.65
CEC	Water stress	4.06	5.17	5.96	3.40
	Well-watered	4.06	5.34	5.96	3.53
	L.S.D.		NS		NS

Effect of nitrogen fertilization on soil fertility

The effect of nitrogen levels on soil pH and on certain soil chemical properties was studied in the three growth conditions. Table 26 showed that under these growth conditions, nitrogen levels affected more or less soil pH and chemical properties. No significant effect of nitrogen levels was noted on soil P available, K, N, C and C/N in the three growth conditions. However, comparing the contents of available P and C/N in the initial sample and at the end of the rainfed and dry cold experiments, it was observed under nitrogen fertilization, a great increase in soil available P and a great decrease in the C/N ratio. In the dry hot experiment, under nitrogen fertilization, there was a great difference between the content of available P at the beginning and at the end of the experiment. With regards to the dry hot experiments, nitrogen levels had no significant influence on soil pH and chemical properties. But at the end of this experiment, a slight increase was noted in Ca^{2+}, Mg^{2+} and CEC contents (Table 26). Concerning the rainfed experiment, there was a significant positive effect of nitrogen levels on soil Ca^{2+}, Mg^{2+} and CEC contents and a significant negative effect on soil pH. Under nitrogen fertilization, soil pH decreased i.e. soil acidification increased in this rainfed condition (Table 26).

Assessing the effect of nitrogen levels on soil pH and chemical properties under the dry cold growth condition, apart from Mg^{2+}, no significant effect of nitrogen fertilization was noted on soil pH and chemical properties studied in this experiment. But comparing the contents of chemical properties at the beginning and at the end of the experiment, a decrease was noted in Ca^{2+}, Mg^{2+} and CEC.

Table 26: *Soil pH and some chemical properties as affected by nitrogen levels*

Soil properties	Treatments	Initial 1	Dry hot exp.	Initial 2	Rainfed exp.	Initial 3	Dry cold exp.
	Nitrogen levels						
pH	0 kg ha^{-1}	4.63	4.65	4.80	4.75	5.20	5.22
	60 kg ha^{-1}	4.63	4.64	4.80	4.55	5.20	5.07
	L.S.D.		NS		0.11		NS
P (g kg^{-1})	0 kg ha^{-1}	0.11	0.11	0.08	0.13	0.08	0.11
	60 kg ha^{-1}	0.11	0.10	0.08	0.12	0.08	0.11
P av (mg kg^{-1})	0 kg ha^{-1}	5.33	2.21	3.01	5.27	3.71	5.67
	60 kg ha^{-1}	5.33	2.29	3.01	5.01	3.71	5.15
K (g kg^{-1})	0 kg ha^{-1}	0.42	0.48	0.48	0.43	0.45	0.31
	60 kg ha^{-1}	0.42	0.52	0.48	0.40	0.45	0.31
N (g kg^{-1})	0 kg ha^{-1}	0.22	0.24	0.22	0.29	0.22	0.25
	60 kg ha^{-1}	0.22	0.24	0.22	0.28	0.22	0.25
C (g kg^{-1})	0 kg ha^{-1}	3.90	3.85	3.62	3.63	3.3	3.41
	60 kg ha^{-1}	3.90	3.81	3.62	3.49	3.3	3.36
C/N	0 kg ha^{-1}	18.50	16.55	16.5	12.61	15.50	13.51
	60 kg ha^{-1}	18.50	16.46	16.5	12.87	15.50	13.57
	L.S.D.		NS		NS		NS
Ca^{2+}	0 kg ha^{-1}	0.90	1.52	1.72	1.59	2.02	1.48
	60 kg ha^{-1}	0.90	1.54	1.72	1.34	2.02	1.44
	L.S.D.		NS		0.15		NS
Mg^{2+}	0 kg ha^{-1}	0.43	0.70	0.76	0.69	0.78	0.71
	60 kg ha^{-1}	0.43	0.71	0.76	0.562	0.78	0.55
	L.S.D.		NS		0.07		0.09
CEC	0 kg ha^{-1}	4.06	5.34	5.81	5.05	5.96	3.30
	60 kg ha^{-1}	4.06	5.18	5.81	4.02	5.96	3.63
	L.S.D.		NS		0.70		NS

Effect of sorghum genotypes cultivation on soil fertility

The genotypes performance was assessed in the three growth conditions. This assessment showed that apart from soil pH that was significantly affected by the genotypic effect in the dry hot experiment, all the other pH and soil chemical properties were not affected by the genotype (Table 27).

At the genotypic level, it was found that in the dry hot experiment, soil available P content decreased greatly while Ca^{2+}, Mg^{2+} and CEC contents were more improved at the end of the dry hot experiment compared to available P and Ca^{2+}, Mg^{2+} and CEC contents at the beginning of the experiment.

In rainfed and in dry cold experiments, under genotypes, soil Ca^{2+}, Mg^{2+} and CEC contents decreased more at the end of the experiments compared to the beginning of the experiments (Table 27).

Table 27: *Soil pH and chemical properties as affected by genotypes performance*

Soil properties	Treatments	Initial 1	Dry hot exp.	Initial 2	Rainfed exp.	Initial 3	Dry cold exp.
	Genotypes						
pH	*Kapelga*	4.63	4.68	4.80	4.68	5.20	5.22
	Sariaso 14	4.63	4.62	4.80	4.62	5.20	5.07
	L.S.D.		0.03		NS		NS
P (g kg^{-1})	*Kapelga*	0.11	0.10	3.01	4.25	0.08	0.10
	Sariaso 14	0.11	0.11	3.01	6.02	0.08	0.11
P av (mg kg^{-1})	*Kapelga*	5.33	2.23	3.01	4.25	3.71	4.82
	Sariaso 14	5.33	2.27	3.01	6.02	3.71	6.00
K (g kg^{-1})	*Kapelga*	0.42	0.48	0.48	0.44	0.45	0.31
	Sariaso 14	0.42	0.51	0.48	0.39	0.45	0.31
N (g kg^{-1})	*Kapelga*	0.22	0.23	0.22	0.30	0.22	0.24
	Sariaso 14	0.22	0.24	0.22	0.27	0.22	0.26
	L.S.D.		NS		NS		NS
C (g kg^{-1})	*Kapelga*	3.90	3.76	3.62	3.67	3.31	3.11
	Sariaso 14	3.90	3.90	3.62	3.45	3.31	3.65
	L.S.D.		NS		NS		0.17
C/N	Kapelga	18.5	16.59	16.5	12.47	15.5	12.97
	Sariaso 14	18.5	16.42	16.5	13.01	15.5	14.11
Ca^{2+}	*Kapelga*	0.9	1.55	1.72	1.56	2.02	1.40
	Sariaso 14	0.9	1.50	1.72	1.37	2.02	1.52
Mg^{2+}	*Kapelga*	0.425	0.70	0.76	0.68	0.78	0.63
	Sariaso 14	0.425	0.71	0.76	0.58	0.78	0.63
CEC	*Kapelga*	4.06	5.30	5.81	4.67	5.96	3.57
	Sariaso 14	4.06	5.21	5.81	4.41	5.96	3.36
	L.S.D.		NS		NS		NS

Interaction effect of watering regimes and nitrogen levels on soil fertility

The interaction effect between watering regimes and nitrogen levels was found in the two dry conditions (Table 28). The interaction watering regimes by nitrogen levels had significant effect on soil nitrogen content in the dry hot experiment while this interaction effect was significant on soil K in the dry cold experiment.

Under water stress by 0 kg ha^{-1} of urea, soil N content was much improved in the dry hot experiment while under well-watered by 60 kg ha^{-1} of urea, soil N content was most improved in this dry hot experiment (Table 28).

In the dry cold experiment, under well-watered by 0 kg ha^{-1} of urea, soil K content was much improved. It was also more improved under water stress by 60 kg ha^{-1} of urea (Table 28).

Table 28: *Soil N and K as affected by the interaction of watering regimes by nitrogen levels*

		0 kg ha^{-1}		60 kg ha^{-1}		0 kg ha^{-1}		60 kg ha^{-1}	
	Treatment	Initial 1 sample	Dry hot exp.	Initial 1 sample	Dry hot exp.	Initial 3 sample	Dry cold exp.	Initial 3 sample	Dry cold exp.
N (kg ha^{-1})	Watering regimes								
	Water stress	0.22	0.26	0.22	0.23	0.22	0.25	0.22	0.26
	Well-watered	0.22	0.22	0.22	0.24	0.22	0.26	0.22	0.24
	L.S.D.			0.026			NS		
K (kg ha^{-1})	Water stress	0.42	0.51	0.45	0.42	0.45	0.28	0.45	0.32
	Well-watered	0.42	0.44	0.59	0.42	0.45	0.34	0.45	0.29
	L.S.D.			NS			0.03		

Interaction effect of watering regimes and genotypes on soil fertility

The interaction effect between watering regimes and genotypes was noted and significant on soil organic carbon (C) in the dry cold experiment. The interaction water stress by genotype *Sariaso* 14 contributed to improve more soil C (Table 29).

Table 29: *Soil C as affected by the interaction of watering regimes by genotypes*

	Kapelga		*Sariaso* 14		*Kapelga*		*Sariaso* 14	
Treatment	Initial 1 sample	Dry hot exp.	Initial 1 sample	Dry hot exp.	Initial 3 sample	Dry cold exp.	Initial 3 sample	Dry cold exp.
Watering regimes								
WS	3.90	3.72	3.90	3.83	3.31	3.03	3.31	3.91
WW	3.90	3.81	3.90	3.96	3.31	3.19	3.31	3.39
L.S.D.			NS			NS		0.44

CHAPTER FIVE

GENERAL DISCUSSION

The study sought to study the effect of some climatic parameters on long term sorghum grain yield and find out whether or not cropping sorghum under irrigation in dry season is feasible.

Climate change and its effect on long term sorghum trials yields in Saria: Adaptation strategies

In the study, it was found some variations in the climatic parameters studied. Rainfall, rain days and temperature increased with time at Saria but potential evapotranspiration decreased. The slope of the increase in rainfall was greater (y = 3.83) than the slope in the increase of rainy days (y = 0.25), temperature (y = 0.0008) and the potential evapotranspiration (y = -0.85). The increase in temperature was therefore low to influence potential evapotranspiration. More rains have contributed to cool down the ambient atmosphere leading to a slight reduction in the potential evapotranspiration. The increase in the annual rainfall may be due to earlier rains observed these last years.

The study also revealed a large decrease in sorghum grain yields over 32 years. This decrease in sorghum grain yield may be due to the low fertility level of soil on which sorghum is produced in Saria during the 32 years. In addition, the application of nitrogen fertilizer years to years may lead to soil acidification. A study conducted by Barak, Job, Krueger, Peterson and Laird. (1997) showed that the use of nitrogen fertilizers without lime or without organic matter input would over time significantly degrade soil quality.

The decrease in sorghum yield may be also due to the variation in the climatic parameters studied and especially to the increase in the maximum temperature as it was found in this study. This result asserted the global concerns on climate change especially in the rising temperature that affect hugely food crop production (Lobell, Schlenker and Costa, 2011). This result was also similar to that of Lobell et al. (2012) who reported a decrease in sorghum yield due to a continuous increase of the temperature over the years.

Effect of growth conditions on sorghum production

The study showed that the growth conditions were the most affecting sorghum production. They had great influence on sorghum reproductive cycle, on root growth, on WUE and NUE, on straw and grain yields, on harvest index and on the partial factor of productivity and agronomy efficiency.

Under the dry hot condition (dry hot experiment sown on March 17th under temperature > 35° C and potential evapotranspiration = 7 mm day^{-1} m^{-2}), sorghum reproductive cycle was lengthened especially that of the local genotype *Kapelga*. This may be due to the sensitivity of the local genotype to photoperiod. The length of this dry hot experiment contributed to increase sorghum plant growth and therefore the increase in the straw yield. During this dry hot experiment, the improved *Sariaso* 14 flowered when the temperature was about

38 °C. No significant length was found in this improved genotype *Sariaso* reproductive cycle. However the panicles that flowered were not filled of grain leading to many empty panicles. The panicles may not be able to form grains and this situation may be linked to the rising temperature occurred at the flowering period. This result corroborated with those of Hatfield and Prueger (2015), Singh et al. (2015) and (Song, et al., 2015) who reported that high temperature (> 38 °C) can prevent fertility in sorghum and can also increase risk to sorghum productivity by reducing grain yield. Despite the heat stress effect that prevented panicle fertility, at the end of this dry hot experiment, grain yield assessment was found higher than those of the dry cold and rainfed experiments. This was due to the grains formed by the secondary panicles developed when the rainy season started. The result agreed with Alam et al. (2014) study where they showed that tillers can increase grain yield by increasing the number of panicles. Despite the high grain yield, adopting this practice will be difficult given the length of the reproductive cycle (especially for genotype *Kapelga* that reproductive cycle was more lengthened). In addition, nitrogen use efficiency was low in this dry hot experiment though the amount of water used was high (871 mm). The low nitrogen use efficiency noted in this dry hot experiment may be due to the conditions under which the experiment was led (temperature > 35 °C, higher evaporative demand PET between 6 and 7 mm day^{-1} mm^{-2}). Nitrogen may be lost by evaporation (Bonzi, 2002).

The rainfed experiment used more water (878 mm) and produced high root growth. However, WUE, NUE, straw and grain yield, harvest index and therefore the productivity and agronomy efficiency were lower under this rainfed condition. The low productivity of the rainfed experiment was due to its low water use efficiency. This experiment, experienced many drought spells and a part of rain water was lost by runoffs, drainage, percolation, evaporation etc. The high root growth in this experiment may be explained by the fact that rain water by infiltration brought down soil nutrients and that roots had to grow more and at deeper soil layer in order to uptake nutrient into the deep soil layer to fill plant's needs. The finding agreed with that of Mirza, Shabbir and Gary (2013) who linked the low productivity in rainfed agriculture to nutrient losses by deep drainage.

Under the dry cold condition (dry cold experiment, sown under temperature < 35 °C and potential evapotranspiration = 3 mm day^{-1} m^{-2}), sorghum reproductive cycle was shorter than the two other experimental reproductive cycles. In addition, water use efficiency, nitrogen use efficiency, the number of full panicle, panicle yield, grain yield, harvest index and therefore the partial factor of productivity and agronomy efficiency were higher in this experiment than in the two other experiments. The early maturation in the dry cold experiment may be due to the sensitivity of sorghum to day length. The days were more shortened in the improved genotype *Sariaso* 14 compared to that of the local *Kapelga*. The high water use and nitrogen use efficiencies in this experiment may be due to the fact that the lower temperature prevented high evaporative demand

and thus water which was supplied did not evaporate and has been profitable for sorghum plant. This was the opposite in the first dry season experiment conducted under higher temperature and higher evaporative demand. The result was in accordance with the conclusions of Blum (2009) and Fixen et al. (2015) according to which sorghum production was linked to the two factors (WUE and NUE). The high grain yield and harvest index under this growth condition may be also due to the earlier flowering and maturity allowing the dry cold experiment to be more productive than in rainfed experiment. This result contrasted that of Ouma and Akuja (2013) who found that earlier flowering and maturity decreased sorghum grain yield. The positive results induced on yield and yield components by the irrigated dry cold experiment underscored the positive effect of growing sorghum under irrigation in dry cold season. This contrasted Grossi, Flávio, Ávila, and Andrade (2015) results according to which sorghum yield was more positively influenced by rainfall than by irrigation.

Effect of irrigation (watering regimes) on sorghum production

Assessing the effect of watering regimes on sorghum production in the two dry irrigated experiments (dry hot and dry cold experiments), it was found that after growth condition, watering regimes was the second factor to influence more sorghum production. The well-watered using 100% of the rate of the potential evapotranspiration contributed to improve significantly sorghum WUE, grain and straw yields, harvest index and therefore the partial factor of productivity than the water stress condition using 50% of the rate of the potential evapotranspiration.

The high WUE obtained was due to the fact that in the well-watered condition, water was permanently around root zones and those roots were able to use efficiently water and nutrients available around those root zones to fill plant's needs. Similar results were reported by Clavel, Drame, Roy-Macauley, , Braconnier and Laffray (2005) who found that water use efficiency is improved under well-watered condition. In the same way, Boutraa, Akhkha, Abdulkhaliq and Al-Shoaibi (2010), Rahimi et al. (2013) reported greater decrease in water use efficiency due to water stress condition. The current result was in contrast to Liu et al. (2012) and Webber et al (2006) findings in which, high water use efficiency was obtained under water deficit condition. The difference in these results may be linked to the growing season and conditions under which the experiments were laid out. The result also highlighted the importance of irrigation in improving sorghum yield. Therefore, increasing the irrigated areas may contribute to enhance sorghum production. This assumption goes along with that of Cassman (2016).

Under dry cold condition (dry hot experiment), the amount of water used was 63% lower (316 mm) than that of the dry hot experiment (using 871 mm of water). In this dry cold experiment, the numbers of roots and root length were higher under the water stress treatments than under that of the well-watered. This may be due to the insufficiency of water around root zones, and roots are obliged to grow more widely and deeply in order to access to more nutrients for plant's needs. This may be also the way used by sorghum root to resist to drought stress as it was known as the drought resistant crop (Sultan et al., 2014). This may be also the reason why there was no significant difference between NUE in the well-watered and in the water stress treatments. The high root numbers in the water stress condition were able to go deep into the soil to seek for nutrients, and those nutrients were used efficiently as it was in the well-watered treatments. The ability of roots to go deep into the soil to look for nutrients, highlighted the importance of deep and high root numbers in soil nutrients uptake. The result corroborated with those of Wasson, Richards, and Watt (2012), Babar Atta, Mahmood, and Trethow (2013) who noted the importance of deep root system in extracting efficiently water and nutrient from the soil and make them available to the crops.

Under watering regimes, sorghum reproductive cycle was shorter in the well-watered treatment. Moreover, the straw yield, grain yield and harvest index were more improved in these well-watered treatments. This underscored the importance of available water for sorghum production. Similar results were noted by Boyer (1985) who defended the fact that yield reduction due to water deficit was greater than yield reduction due to other any environmental stresses. To reduce the effect of drought stress on sorghum yield, the irrigation would be necessary (Wasige , 2009).

Effect of genotypes on sorghum production

After the growth conditions and watering regimes, the genotypes performance was found significant on sorghum production. Apart from NUE and root growth that were greater in the local genotype *Kapelga* treatments, all the other variables like WUE, straw and grain yields, harvest index and the partial factor of productivity were much improved in the improved genotype *Sariaso* 14 treatments in the entire experiments (dry hot, rainfed and dry cold experiments). Moreover, the reproductive cycle was more reduced in *Sariaso* 14 treatments. Genotype *Sariaso* 14 may have some genetic characters which allow it to be more performance regarding WUE. In addition, the genetic character of Sariaso 14 may allow it to develop some productive secondary tillers. These tillers formed grains and therefore contributed to improve grain yield. The results are consistent with those of Mutava, Prasad, Tuinstra and Kofoid (2011) and Haussmann et al. (2012) who reported significant variations among sorghum genotypes contributing to more or less production. The result also goes along with those of El Naim, Mohammed, Ibrahim, and Suleiman (2012), Aml Tag, Eatemad and Ali, (2012), Mahama, Vara, Mengel and Tesfaye (2014) and Amare, Habtamu and Bultosa (2015) who reported that the high productivity of improved genotypes sorghum was linked to their ability to shorten their reproductive cycle.

Effect of nitrogen fertilization on sorghum production

Among the factors used to assess their effect on sorghum production (growth conditions, watering regimes, nitrogen level and genotypes), nitrogen levels were found to have the lowest effect on sorghum production. However, the application of 60 kg ha^{-1} of nitrogen (urea) contributed to improve sorghum WUE, root growth, straw and grain yield and harvest index and also contributed to reduce sorghum reproductive cycle in the dry irrigated conditions (dry hot and dry cold experiments). Similar results were observed by Rahimi et al. (2013) where nitrogen supply significantly increased WUE and therefore grain yield from 0 N to 120 N application but no significant differences between 60 N and 120 N applications. The finding also was in accordance with those of Kraiser et al. (2011), Mueller et al. (2012), Liu et al. (2013) and Lassaletta, Billen, Grizzetti, Anglade and Garnier (2014) who found that nitrogen application increased grain yield.

Under rainfed condition, the application of 60 kg ha^{-1} of nitrogen contributed to the better root growth. However, water use efficiency, grain yield and harvest index were low. The low water use efficiency may be due to water losses by runoffs, drainage, percolation and evaporation etc. and the low grain yield observed may be linked to the low water use efficiency noted in this rainfed experiment. The result agreed with Mirza et al. (2013) finding according to which the low productivity in rainfed agriculture was linked to nutrient losses by deep drainage. The finding also goes along with that of Blum (2009) and Fixen (2015) who noted that sorghum productivity depended on WUE and NUE.

Contrary to the findings of Reynolds et al. (2007), Wasson et al. (2012), Babar, Mahmood and Trethow (2013) and Kristensen and Kirkegaard (2016) who linked water use efficiency to better root growth, it was found in this study that WUE and NUE were not linked to root growth. They were found to be influenced by the availability of water around root zones.

Though nitrogen application contributed to improve water use efficiency, it contributed also to the low nitrogen use efficiency in the entire experiments (dry hot, rainfed and dry cold experiments). The values were below 70% where 60 kg ha^{-1} of nitrogen was applied. Overall, according to Brentrup and Pallière (2010), the 70% represented the threshold for nitrogen losses. The low NUE values showed therefore nitrogen losses. And these losses may be due to the type of nitrogen that was applied. Overall, it was noted by Bonzi (2002), that using urea as the source of nitrogen in crop production especially in dry conditions, contributed to its losses by evaporation. Bonzi noted that there was a risk to lose 30% of nitrogen by volatilization during dry season experiments. Similar results were found by Ceesay (2004), who demonstrated the gradual decrease of nitrogen use efficiency according to the amount of nitrogen applied; nitrogen use efficiency decreased when the amount of nitrogen applied increased. Nitrogen application is important for crop production (Palé, Mason and Taonda, 2009; Shamme, Raghavaiah, Balemi and Hamza, 2016). However, applying it in bad condition, it may be harmful to the environment (Lassaletta et al., 2014).

Interaction effect of growth conditions, watering regimes, nitrogen levels and genotypes

The interaction effect induced by the three factors under the three growth conditions allowed drawing the following conclusions:

The first growth condition (dry hot experiment grown under temperature > 35 °C and potential evapotranspiration = 7 mm day^{-1} m^{-2}) was not appropriate for sorghum production because this condition contributed to the panicles abortion that reduced the panicle yield and therefore harvest index. This practice would not be possible for achieving food security issues.

The second growth condition representing the rainfed experiment was subjected to natural environmental stresses as in usual rainfed agriculture. By this growth condition, the lowest grain yield was obtained. Alone, this practice would not be possible to reach food security as erratic rainfall and natural stresses will continue to impact negatively on rainfed agriculture.

The third growth condition representing the dry cold experiment grown under temperature < 35 °C and potential evapotranspiration = 3 mm day^{-1} m^{-2} was found to use much less water to produce high grain yield, high harvest index. In addition under this growth condition, sorghum reproductive cycle was much reduced. The importance of appropriate climatic conditions to grow high performance sorghum genotype was therefore highlighted in this experiment. The highest response of sorghum was obtained under the well-watered x 60 kg ha^{-1} N x genotype *Sariaso* 14. Similar results were found by many researchers on diverse crops and that optimum growth condition is one of the important factors that influenced yield appreciably (Zafar et al., 2010 and Rao et al., 2013). According to Ashofteh, et al. (2011), the high productivity of maize crop was due to the conditions under which it was cropped. Sanjana et al. (2014) observed that the appropriate growth period induced more variations (58 to 94%) into sugar yield.

Assessing the effect of growth conditions, watering regimes, nitrogen fertilization and sorghum genotypes on soil fertility

Effect of growth conditions on soil pH and on some soil chemical properties

The three growth conditions under which these experiments were carried out contributed to decrease in pH, N, P, and available P. Soil K, organic C, Ca^{2+}, Mg^{2+} and CEC contents were more or less improved in all experiments.

Soil fertility is a determinant yielding factor in sorghum production. Many environmental stresses constrain its production in Sub-Saharan Africa, but at the same time, the conditions in which the sorghum crop is produced can negatively affect the environment including soil fertility itself (Reynolds et al., 2015). In the current study, the soil on which sorghum was grown during the first dry season experiment (dry hot experiment) and the rainfed experiment were more negatively affected by nutrients depletion than the soil on which sorghum was produced during the second dry season experiment (dry cold experiment). This decrease in soil chemical properties contents due to the temperature > 35 °C and to other natural stresses increases the concerns on the impact of climate change on sorghum production, as temperature is expected to increase over the years, and therefore will affect soil fertility and food security (i.e. that climate change is expected to affect soil fertility and sorghum crop yield). Climate change is expected to increase drought conditions in the Sahelian Africa (Urama and Ozor, 2010) like Burkina Faso. Under more droughts, soil can have large negative impacts on soil microorganisms that allow the decomposition of soil organic matter from plant residue and animal manure. Once decomposed, it enriches soil and plants with improved water holding capacity and nutrients enabling the soil to better support crop growth (Frazer, 2009). Wang, Wei, Wang, Ma and Ma,. (2011) and Brevik (2013) reported that increased temperature contributed to decline in the amount of carbon into the soil. According to Brady and Weil (2008), a soil with poor organic matter is also poor in carbon and nitrogen since these two elements are major components of soil organic matter. In addition, a deficiency of soil organic matter reduces the capacity of soil to hold water, decrease soil CEC and hence leads to poor soil structure and poor nutrient supply to the soil ecosystem (Brevik, 2013).

Through climate change, rainfed agriculture is expected to experience many droughts, floods, and violent winds (Sivakumar, 2011). Some simulations done in arid areas showed that water runoff would increase significantly up to 5 times more than the increase in rainfall (Chiew, Whetton, McMahon & Pittock., 1995). A study by García-Fayos and Bochet (2009) reported a strong correlation between climate change and soil erosion. According to them, climate change is likely to negatively affect soil aggregate stability, bulk density, water holding capacity, pH, organic matter, total N and soluble P. This decrease in soil fertility is the major problem to food security especially in Africa (St. Clair & Lynch, 2010). However, adopting best growth conditions could contribute to increase soil fertility.

In this study, sorghum cropped during the dry cold irrigated experiment grown under temperature < 35 ^{o}C and potential evapotranspiration = 3 mm day^{-1} m^{-2} with nitrogen fertilization improved more soil chemical properties such as N, P, available P, C, Ca^{2+}, and Mg^{2+}. According to Lal (2004), in Argentina, cereal grain yield improved up to 40 kg ha^{-1} due to the application of 1 t ha^{-1} of organic material. In West Africa, Tan et al. (2010) asserted that an application of 30-60 kg ha^{-1} of nitrogen fertilizer could prevent soil organic carbon losses and hence improve biomass production and therefore enriches soil residues. In Sahel West Africa especially in Burkina Faso and Niger, soil fertility increased due to stone bunds techniques. Zougmoré et al. (2014) and Bationo et al. (2014) reported that stone bunds techniques could contribute to increase crop yield up to 2-5 times more than crop yield on soil without these techniques. In Saria, sorghum grain yield improved (about 142%) due to the combination of stone bunds with an application of compost (Zougmoré, et al., 2004). Other cropping systems such as crop rotation and intercropping improved fertilizer use efficiency by increasing biological nitrogen fixation (Bationo et al., 2014). These authors noted that locally available phosphate rock could be used to improve soil phosphorus that is usually deficit in the soil of West Africa, especially that of Burkina Faso.

Effect of irrigation on some soil chemical properties

In this study, the irrigation system applied, especially in the dry cold irrigated experiment, contributed to slightly improve soil chemical properties over the other season it was monitored. The pH slightly decreased compared to the pH dozed at the beginning of the experiments. In addition, C/N ratio decreased more in this irrigated experiment from 17 at the beginning of the implementation to 13 after harvesting in the dry cold irrigated experiment.

Overall, C/N ratio determines the decomposability of soil organic matter. It is also often considered as a sign of soil nitrogen mineralization capacity (Wu et al., 2001). According to Shunfeng, Haigang, Mengmeng and Yuanmao (2013), C/N ratio was used to indicate soil quality and to assess the carbon and nitrogen nutrition balance of soils. According to them, C and N reflected the soil fertility level and explained the regional ecological system evolution. High C/N ratios slowed down the decomposition rate of organic matter and organic nitrogen (Wu et al., 2001). Once the decomposition rate is slowed down, soil microbial activity is limited. Low C/N ratios was indicated by Wu et al. (2001) to be the best as it accelerated the process of microbial decomposition of organic matter and nitrogen. In the study, the decrease of C/N ratio from 17 to 13 in the dry cold irrigated experiment underscored the fact that soil N and C improved in this experiment. The growth condition of dry cold irrigated experiment combined with the irrigation system allowed the improvement of soil fertility. This situation indicates that under climate change, appropriate crop management practices could help to deal with these climatic problems.

Lobell et al. (2008) also found that the adaptation of agricultural practices would be the best way to face the negative impact of climate change. According to Torriani, Calanca, Schmid, Beniston and Fuhrer (2007), and Lehmann, Finger, & Klein (2011), the adjustment in sowing dates and fertilization intensity could help to abate the negative impact of climate change. The irrigation system was suggested by Rosenzweig and Parry (1994) while Araus, Slafer, Royo and Serret (2008) and Campos, Cooper, Habben, Edmeades and Schussler (2004) suggested the use of drought tolerant cultivars to deal with climate change.

Effect of nitrogen fertilization on soil pH and on some soil chemical properties

A correlation analysis done on the impact of nitrogen application on soil chemical properties in the three experiment showed that nitrogen application decreased soil pH, N, available P, C, K Ca^{2+}, Mg^{2+} and CEC. However, according to Lust et al. (2016) and Shamme et al. (2016), nitrogen is the main determinant nutrient for soil to produce high grain yield. Nitrogen fertilizer was a way to restore soil fertility level in Kenya (Ngome, Becker, Mtei and Mussgnug, 2011) and to increase sorghum yield (Kebeney, Msanya, Semoka, Ngetich & Kipkoech, 2015). It is one of the most limiting nutrients in lowland rice production in Iran (Tayefe, Gerayzade, Amiri and Zade, 2011). In Cameroun, its application contributed to increase crop yield but it was found by Tsozué, Nghonda and Mekem (2015) as a nutrient difficult to manage in fertilization. Naudin, Gozé, Balarabe, Giller and Scopel (2010) reported that nitrogen with phosphorus application could stimulate crops growth and productivity, however, Novara, Gristina, Guaitoli, Santoro and Cerdà (2013) found that their excess use could increase their noxiousness to the environment.

In this study, nitrogen application decreased significantly soil pH, K and Mg^{2+} and decreased less N, P, C. Ca^{2+} and CEC, and this was counter-productive for soil fertility. This result is in agreement with that of Jones (1976) who supported that the continuous use of nitrogen was damaging since it led to the rapid soil acidification indicated by the decrease in soil pH. In Burkina Faso, according to Savadogo et al. (2011) and Ouedraogo et al. (2012), to prevent soil acidification by nitrogen, its excess use should be avoided in the areas with low rainfall. These authors showed the amount of nitrogen to be used in each agro-climatic zone. That way, 60 kg ha^{-1} of nitrogen is advised in the areas with rainfall below 600 mm (case of the current study area). In addition, long terms 14 years (Czarnecki and Düring, 2015) and 40 years (Cakmak, Saljnikov, Perovic, Jaramaz & Mrvic, 2010) experiments were respectively laid out in Germany and Cambisol on soil pH as in this study. These authors also noted an increase in soil C and CEC contents. Our finding also is in accordance with that of Cakmak et al. (2010) who reported a decrease in Mg^{2+} content in their study.

Effect of genotypes on soil pH and chemical properties

The correlation analysis showed that sowing the genotype *Sariaso* 14 in the dry cold experiment contributed to improve slightly soil available P, P, C, N, Ca^{2+} and Mg^{2+}contents. This improvement of soil chemical properties in this dry cold experiment, in addition to the improvement of yield, underscored the importance with regards to the choice of improved seed varieties and the choice of appropriate time of production. With the events of climate change affecting crop productivity, more adoption of cropping these improved varieties is expected to be beneficial to farmers.

CHAPTER SIX

CONCLUSIONS, RECOMMENDATIONS AND FUTURE OUTLOOK

Conclusions

Variations in the climatic parameters decreased sorghum trials yields in Saria over 32 years.

Growth conditions strongly influenced sorghum production followed by watering regimes, genotypes and nitrogen levels.

In the dry hot experiment, sorghum reproductive cycle was shortened, while water use efficiency, nitrogen use efficiency, panicles yield and harvest index were low.

In the rainfed experiment, root growth was high but water use efficiency, grain yield, harvest index and the partial factor of productivity were low.

With the dry cold experiment, sorghum reproductive cycle was shortened and water use efficiency, nitrogen use efficiency, grain yield, harvest index and the partial factor of productivity were high.

The well-watered condition improved sorghum yield more than the water stress condition (by 30%).

The application of 60 kg ha^{-1} of nitrogen contributed to low nitrogen use efficiency in the three experiments.

In the rainfed experiment, the application of 60 kg ha^{-1} of nitrogen had no significant effect on sorghum production.

In the irrigated dry hot and dry cold experiments, the application of 60 kg ha^{-1} of nitrogen was appropriate for sorghum yield.

For the genotypic differences, *Sariaso* 14 was superior to *Kapelga*.

The interaction effect among watering regimes, nitrogen levels and genotypes (WW * 60 N * GS) improved sorghum WUE and grain yield from 30% to 64% in the dry hot and dry cold experiments respectively.

Comparing the rainfed experiment and the dry cold experiment, sorghum production was 34% more improved in the dry cold experiment than in the rainfed.

Regarding soil fertility, the temperature > 35 °C affected negatively soil pH, N, P and available P contents.

The application of 60 kg ha^{-1} of nitrogen affected negatively soil pH, N, available P, K, organic C, Ca^{2+}, Mg^{2+} and CEC contents.

In the dry cold experiment, growing the genotype *Sariaso* 14 contributed to improve soil N, P and available P, organic C, Ca^{2+} and C/N ratio.

Recommendations and future outlook

a) The State or government should ensure more water storage which would be used judiciously in the dry season by the bulk of rural farmers.

b) Farmers should also find some water harvesting techniques to collect water from rains that could be used to irrigate their crops.

c) Research institutions could look at repeating this study over three or four years (long term experiments) by varying water regimes (± 50% PET) and nitrogen levels (± 60 kg N ha^{-1}).

For future outlook

i. Future study should concentrate on Integrated Soil Fertility Management strategies (integration of organic matter and crop residues).

ii. Future study should also concentrate on the development of crop models for cropping sorghum under irrigation. Simulations should be done in order to identify the impact of water regimes, nitrogen levels, amount of organic matter and the system of straw mulching to identify optimum factors for sustainable sorghum production.

iii. The cost-benefit analysis should be done in order to find whether or not cropping sorghum under irrigation in dry season would be beneficial to farmers.

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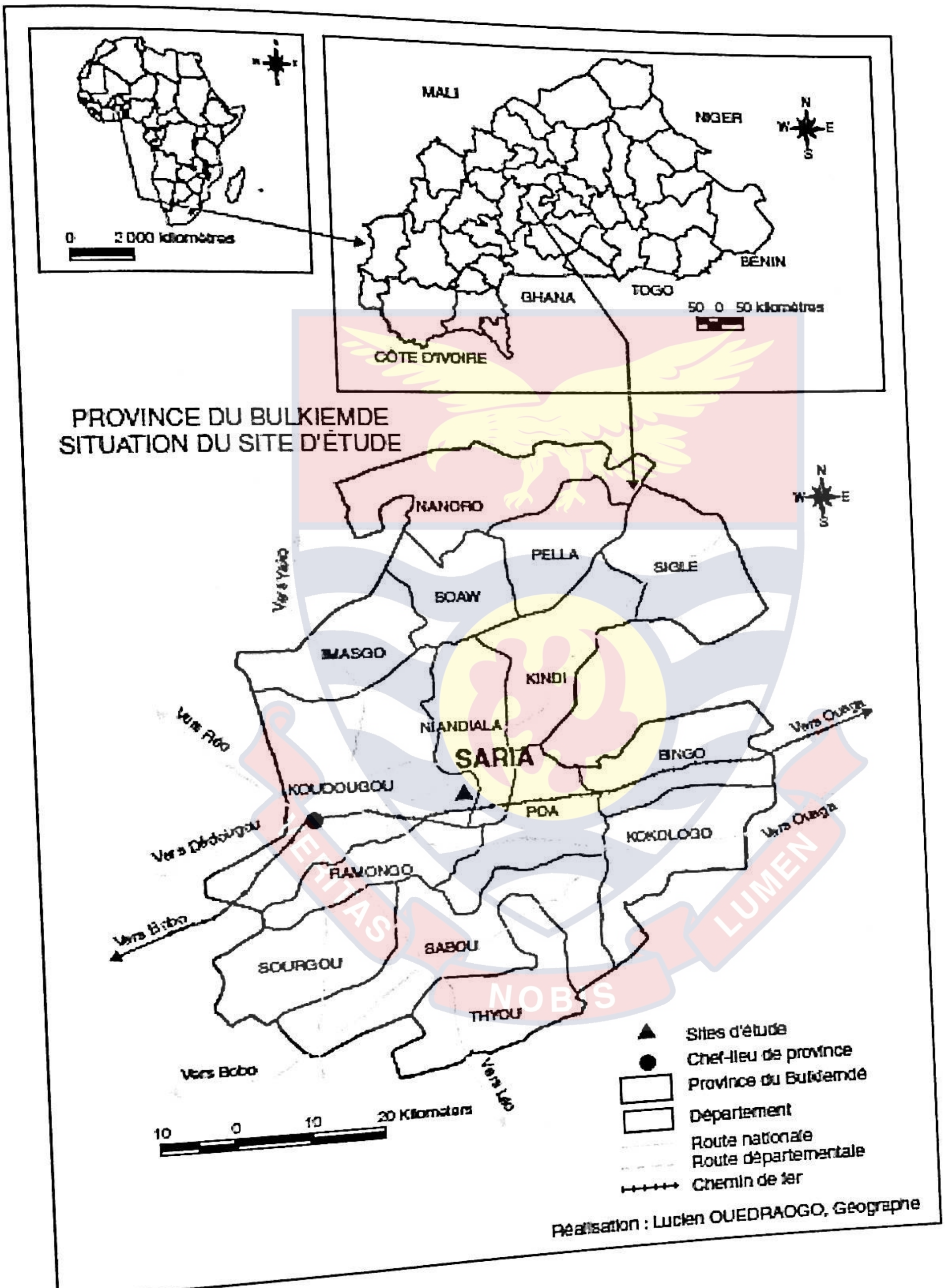
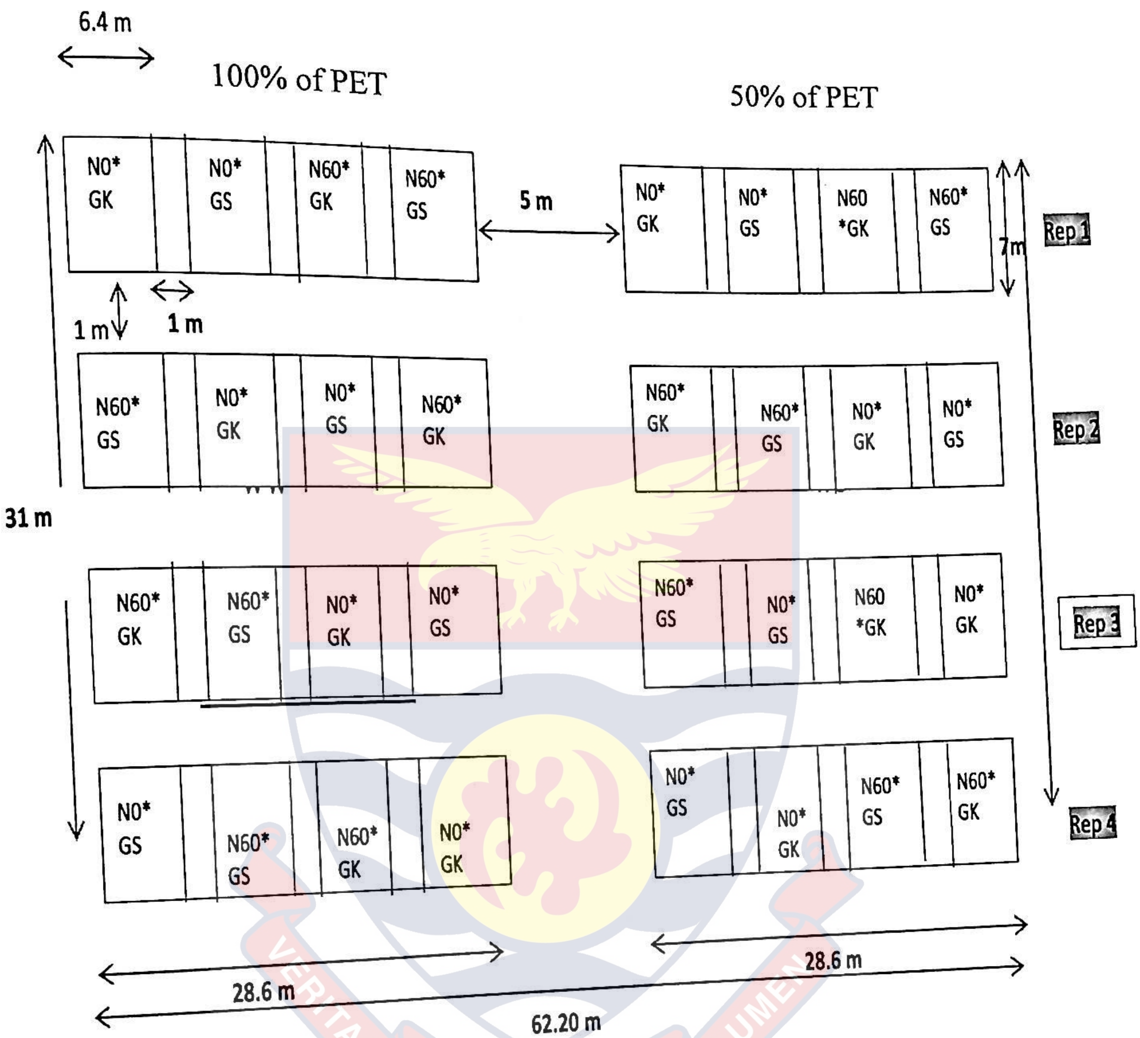
APPENDICES

Appendix A: *Location of the study site (Saria)*



Source: from Lucien Ouedraogo, geographer

Appendix B: *Experimental design*



Appendix C: *Soil water content measurement*

Second dry season experiment

Appendix D: *Sorghum root profile*

Picture from the first dry season experiment

Appendix E: *Some pictures showing the amount of biomass per experiment*

Genotype *Kapelga* (local variety) Genotype *Sariaso* 14 (improved variety)

Experiment 1: first dry season experiment sown 17 March 2014:

Appendix E: *Some pictures showing the amount of biomass per experiment* (cont'd)

Genotype *Kapelga* (local variety)

Genotype *Sariaso* 14 (improved variety)

Experiment 2: rainfed experiment sown 5 July 2014

Appendix E: *Some pictures showing the amount of biomass per experiment* (cont'd)

Genotype *Kapelga* (local variety) **Genotype *Sariaso* 14 (improved variety)**

Experiment 3: second dry season experiment sown 20 October 2014

Appendix F: *Estimation of the amount of water used during the three experiments*

Mean water used by	Dry hot exp.		Rainfed exp.	Dry cold exp.	
watering regimes	WW	WS	Rains	WW	WS
Irrigation (mm)	369	306	0	300	212
Rains	517	517	870.6	0	0
SW	13	19	7	60	60
Total water used	899	842	877.6	360	272

Dry hot irrigated experiment sown 17 March 2014

Rainfed experiment sown 5 July 2014

Dry cold irrigated experiment sown 20 October 2014

Appendix G: *ANOVA tables on the parameters studied during the three experiments: dry hot, rainfed and dry cold experiments*

Variate: WUE (kg ha^{-1} mm^{-1})			Dry hot 2014		
Source of variation	Df.	Sum of Squares	Mean Squares	Variance	F pr.
Blocks stratum	3	1937.5	645.8	2.35	
Blocks.Water stratum					
Water	1	6313.9	6313.9	22.99	0.017
Residual	3	823.9	274.6	0.34	
Blocks.Water.N_level stratum					
N_level	1	13343	13343	16.61	0.007
Water.N_level	1	2855	2855	3.55	0.108
Residual	6	4818.9	803.1	0.83	
Blocks.Water.N_level.Genotype stratum					
Genotype	1	45044.3	45044.3	46.38	<.001
Water.Genotype	1	2992	2992	3.08	0.105
N_level.Genotype	1	245.7	245.7	0.25	0.624
Water.N_level.Genotype	1	852.5	852.5	0.88	0.367
Residual	12	11655.7	971.3		
Total	31	90882.3			

Variate: WUE (kg ha^{-1} mm^{-1})	Dry cold experiment				
Source of variation	Df.	Sum of Squares	Mean Squares	Variance	F pr.
Blocks stratum	3	66.61	22.2	1.2	
Blocks.Water stratum					
Water	1	545.62	545.62	29.57	0.012
Residual	3	55.35	18.45	1.91	
Blocks.Water.N_level stratum					
N_level	1	268.24	268.24	27.75	0.002
Water.N_level	1	0.08	0.08	0.01	0.929
Residual	6	57.99	9.67	0.85	
Blocks.Water.N_level.Varieties stratum					
Varieties	1	1469.56	1469.56	129.34	<.001
Water.Varieties	1	71.39	71.39	6.28	0.028
N_level.Varieties	1	1.84	1.84	0.16	0.695
Water.N_level.Varieties	1	117.21	117.21	10.32	0.007
Residual	12	136.34	11.36		
Total	31	2790.24			

Variate: NUE (%)		Dry hot and dry cold experiments			
Source of variation	Df.	Sum Sq.	Mean Sq	Variance	F pr.
Replications stratum	3	311.4	103.8	13.79	
Replications.Water_regime stratum					
Water_regime	1	0	0	0	0.994
Residual	3	22.6	7.5	0.25	
Replications.Water_regime.N_level stratum					
N_level	1	12936.9	12936.9	429.77	<.001
Water_regime.N_level	1	3.1	3.1	0.1	0.758
Residual	6	180.6	30.1	0.97	
Replications.Water_regime.N_level.Genotypes stratum					
Genotypes	1	153	153	4.94	0.046
Water_regime.Genotypes	1	8	8	0.26	0.621
N_level.Genotypes	1	60	60	1.94	0.189
Water_regime.N_level.Genotypes	1	26.4	26.4	0.85	0.374
Residual	12	371.9	31	0.29	
Replications.Water_regime.N_level.Genotypes.*Units* stratum					
Growth conditions	1	4610.4	4610.4	42.86	<.001
Water_regime. Growth conditions	1	26.5	26.5	0.25	0.624
N_level. Growth conditions	1	1841.1	1841.1	17.12	<.001
Genotypes. Growth conditions	1	62.8	62.8	0.58	0.452
Water_regime.N_level. Growth conditions	1	16.5	16.5	0.15	0.698
Water_regime.Genotypes. Growth conditions	1	213.6	213.6	1.99	0.172
N_level.Genotypes. Growth conditions	1	61.5	61.5	0.57	0.457
Water_regime.N_level.Genotypes. Growth conditions	1	238.9	238.9	2.22	0.149
Residual	24	2581.8	107.6		
Total	63	23727.1			

Variate: Root numbers		Dry hot experiment			
Source of variation	Df.	Sum of Squares	Mean Squares	Variance	F pr.
Block stratum	3	39.84	13.28	0.1	
Block.Water stratum					
Water	1	371.28	371.28	2.9	0.187
Residual	3	383.59	127.86	3.15	
Block.Water.N_level stratum					
N_level	1	215.28	215.28	5.3	0.061
Water.N_level	1	0.78	0.78	0.02	0.894
Residual	6	243.69	40.61	0.73	
Block.Water.N_level.Genotype. stratum					
Genotypes	1	552.78	552.78	9.92	0.008
Water.Genotypes	1	195.03	195.03	3.5	0.086
N_level.Genotypes	1	42.78	42.78	0.77	0.398
Water.N_level.Genotype	1	140.28	140.28	2.52	0.139
Residual	12	668.62	55.72		
Total	31	2853.97			

Variate: Root length (cm)	Dry hot experiment				
Source of variation	Df.	Sum of Squares	Mean Squares	Variance	F pr.
Block stratum	3	617.7	205.9	0.1	
Block.Water stratum					
Water	1	5724.5	5724.5	2.9	0.187
Residual	3	5924.5	1974.8	3.15	
Block.Water.N_level stratum					
N_level	1	3325.2	3325.2	5.3	0.061
Water.N_level	1	12	12	0.02	0.895
Residual	6	3765	627.5	0.73	
Block.Water.N_level.Genotypes. stratum					
Genotypes	1	8528.2	8528.2	9.92	0.008
Water.Genotypes	1	3014.8	3014.8	3.51	0.086
N_level.Genotypes	1	658.8	658.8	0.77	0.399
Water.N_level.Genotypes	1	2168.1	2168.1	2.52	0.138
Residual	12	10319.8	860		
Total	31	44058.6			

Variate: Root length density (cm cm-3)		Dry hot experiment			
Source of variation	Df.	Sum of Squares	Mean Squares	Variance	F pr.
Block stratum	3	0.03625	0.01208	0.09	
Block.Water stratum					
Water	1	0.36125	0.36125	2.64	0.203
Residual	3	0.41125	0.13708	3.29	
Block.Water.N_level stratum					
N_level	1	0.18	0.18	4.32	0.083
Water.N_level	1	0	0	0	1
Residual	6	0.25	0.04167	0.74	
Block.Water.N_level.Genotypes stratum					
Genotypes	1	0.605	0.605	10.8	0.007
Water.Genotypes	1	0.18	0.18	3.21	0.098
N_level.Genotypes	1	0.06125	0.06125	1.09	0.316
Water.N_level.Genotypes	1	0.10125	0.10125	1.81	0.204
Residual	12	0.6725	0.05604		
Total	31	2.85875			

Variate: Root numbers	Dry cold experiment				
Source of variation	Df.	Sum Sq	Mean Sq	Variance	F pr.
Replications stratum	3	453.53	151.18	0.65	
Replications.Water_regime stratum					
Water_regime	1	3436.89	3436.89	14.8	0.031
Residual	3	696.83	232.28	1.57	
Replications.Water_regime.N_level stratum					
N_level	1	570.02	570.02	3.85	0.097
Water_regime.N_level	1	400	400	2.7	0.151
Residual	6	887.98	148	1.59	
Replications.Water_regime.N_level.Sorghum_genotypes stratum					
Sorghum_genotypes	1	1156	1156	12.45	0.004
Water_regime.Sorghum_genotypes	1	435.77	435.77	4.69	0.051
N_level.Sorghum_genotypes	1	40.64	40.64	0.44	0.521
Water_regime.N_level.Sorghum_genotypes	1	1.56	1.56	0.02	0.899
Residual	12	1114.53	92.88	2.36	
Replications.Water_regime.N_level.Sorghum_genotypes.*Units* stratum					
Layers	7	54188.88	7741.27	196.3	<.001
Water_regime.Layers	7	3404.48	486.35	12.33	<.001
N_level.Layers	7	509.36	72.77	1.85	0.082
Sorghum_genotypes.Layers					
Water_regime.N_level.Layers					
Water_regime.Sorghum_genotypes.Layers	7	507.86	72.55	1.84	0.083
N_level.Sorghum_genotypes.Layers	7	52.73	7.53	0.19	0.987
Water_regime.N_level.Sorghum_genotypes.Layers	7	35.06	5.01	0.13	0.996
Residual	168	6625.12	39.44		
Total	255	76997.75			

Variate: Root length (cm)	Dry cold experiment				
Source of variation	Df.	Sum Sq.	Mean Sq.	Variance	F pr.
Replications stratum	3	6999.7	2333.2	0.65	
Replications.Water_regime stratum					
Water_regime	1	53043.8	53043.8	14.8	0.031
Residual	3	10754.6	3584.9	1.57	
Replications.Water_regime.N_level stratum					
N_level	1	8797.4	8797.4	3.85	0.097
Water_regime.N_level	1	6173.5	6173.5	2.7	0.151
Residual	6	13704.9	2284.1	1.59	
Replications.Water_regime.N_level.Sorghum_genotypes stratum					
Sorghum_genotypes	1	17841.3	17841.3	12.45	0.004
Water_regime.Sorghum_genotypes	1	6725.5	6725.5	4.69	0.051
N_level.Sorghum_genotypes	1	627.2	627.2	0.44	0.521
Water_regime.N_level.Sorghum_genotypes	1	24.1	24.1	0.02	0.899
Residual	12	17201.3	1433.4	2.36	
Replications.Water_regime.N_level.Sorghum_genotypes.*Units* stratum					
Layers	7	836333.4	119476.2	196.3	<.001
Water_regime.Layers	7	52543.7	7506.2	12.33	<.001
N_level.Layers	7	7861.3	1123	1.85	0.082
Sorghum_genotypes.Layers	7	31451.9	4493.1	7.38	<.001
Water_regime.N_level.Layers	7	6831.3	975.9	1.6	0.138
Water_regime.Sorghum_genotypes.Layers	7	7838.1	1119.7	1.84	0.083
N_level.Sorghum_genotypes.Layers	7	813.9	116.3	0.19	0.987
Water_regime.N_level.Sorghum_genotypes.Layers	7	541.1	77.3	0.13	0.996
Residual	168	102250	608.6		
Total	255	1188358			

Variate: Root length density (cm cm^{-3})	Dry cold experiment				
Source of variation	Df.	Sum Sq	Mean Sq	Variance	F pr.
Replications stratum	3	0.44798	0.14933	0.65	
Replications.Water_regime stratum					
Water_regime	1	3.39481	3.39481	14.8	0.031
Residual	3	0.6883	0.22943	1.57	
Replications.Water_regime.N_level stratum					
N_level	1	0.56304	0.56304	3.85	0.097
Water_regime.N_level	1	0.3951	0.3951	2.7	0.151
Residual	6	0.87711	0.14619	1.59	
Replications.Water_regime.N_level.Sorghum_genotypes stratum					
Sorghum_genotypes	1	1.14184	1.14184	12.45	0.004
Water_regime.Sorghum_genotypes	1	0.43043	0.43043	4.69	0.051
N_level.Sorghum_genotypes	1	0.04014	0.04014	0.44	0.521
Water_regime.N_level.Sorghum_genotypes	1	0.00154	0.00154	0.02	0.899
Residual	12	1.10088	0.09174	2.36	
Replications.Water_regime.N_level.Sorghum_genotypes.*Units* stratum					
Layers	7	53.52534	7.64648	196.3	<.001
Water_regime.Layers	7	3.3628	0.4804	12.33	<.001
N_level.Layers	7	0.50312	0.07187	1.85	0.082
Sorghum_genotypes.Layers	7	2.01292	0.28756	7.38	<.001
Water_regime.N_level.Layers	7	0.43721	0.06246	1.6	0.138
Water_regime.Sorghum_genotypes.Layers	7	0.50164	0.07166	1.84	0.083
N_level.Sorghum_genotypes.Layers	7	0.05209	0.00744	0.19	0.987
Water_regime.N_level.Sorghum_genotypes.Layers	7	0.03463	0.00495	0.13	0.996
Residual	168	6.544	0.03895		
Total	255	76.05492			

Variate: Heading to maturity (days)	Dry cold experiment				
Source of variation	Df.	Sum Sq	Mean Sq	Variance	F pr.
Blocks stratum	3	8379.38	2793.13	0.69	
Blocks.Water_regime stratum					
Water_regime	1	140184.1	140184.1	34.66	0.01
Residual	3	12133.36	4044.45	2.1	
Blocks.Water_regime.N_level stratum					
N_level	1	31535.84	31535.84	16.35	0.007
Water_regime.N_level	1	15660.19	15660.19	8.12	0.029
Residual	6	11571.56	1928.59	1	
Blocks.Water_regime.N_level.Genotype stratum					
Genotype	1	194480.5	194480.5	100.77	<.001
Water_regime.Genotype	1	71610.75	71610.75	37.11	<.001
N_level.Genotype	1	10790	10790	5.59	0.036
Water_regime.N_level.Genotype	1	6037.56	6037.56	3.13	0.102
Residual	12	23158.42	1929.87	41.49	
Blocks.Water_regime.N_level.Genotype.*Units* stratum					
Dates	53	1829618	34521.09	742.16	<.001
Water_regime.Dates	53	63305.85	1194.45	25.68	<.001
N_level.Dates	53	14881.48	280.78	6.04	<.001
Genotype.Dates	53	82984.11	1565.74	33.66	<.001
Water_regime.N_level.Dates	53	13280.38	250.57	5.39	<.001
Water_regime.Genotype.Dates	53	36757.81	693.54	14.91	<.001
N_level.Genotype.Dates	53	6842.69	129.11	2.78	<.001
Water_regime.N_level.Genotype.Dates	53	2617.13	49.38	1.06	0.358
Residual	1272	59166.29	46.51		
Total	1727	2634995			

Variate: Straw yield (kg ha^{-1})	Dry hot and dry cold experiments				
Source of variation	Df.	Sum Sq	Mean Sq	Variance	F pr.
Blocks stratum	3	2.78E+07	9.26E+06	2.69	
Blocks.Water_regime stratum					
Water_regime	1	1.03E+08	1.03E+08	29.83	0.012
Residual	3	1.03E+07	3.44E+06	2.45	
Blocks.Water_regime.N_level stratum					
N_level	1	1.76E+08	1.76E+08	125.48	<.001
Water_regime.N_level	1	7.83E+05	7.83E+05	0.56	0.483
Residual	6	8.42E+06	1.40E+06	0.3	
Blocks.Water_regime.N_level.Genotype stratum					
Genotype	1	1.02E+07	1.02E+07	2.17	0.167
Water_regime.Genotype	1	3.54E+06	3.54E+06	0.76	0.402
N_level.Genotype	1	4.53E+06	4.53E+06	0.97	0.345
Water_regime.N_level.Genotype	1	2.46E+06	2.46E+06	0.52	0.483
Residual	12	5.63E+07	4.69E+06	0.98	
Blocks.Water_regime.N_level.Genotype.*Units* stratum					
Growth conditions	1	1.67E+09	1.67E+09	349.57	<.001
Water_regime.Growth conditions	1	3.49E+07	3.49E+07	7.29	0.012
N_level.growth conditions	1	1.14E+08	1.14E+08	23.92	<.001
Genotype.Growth conditions	1	5.60E+07	5.60E+07	11.71	0.002
Water_regime.N_level.Growth conditions	1	2.17E+06	2.17E+06	0.45	0.507
Water_regime.Genotype.CampaignGrowth conditions	1	1.61E+06	1.61E+06	0.34	0.568
N_level.Genotype.Growth conditions	1	4.09E+06	4.09E+06	0.86	0.364
Water_regime.N_level.Genotype.Growth conditions	1	2.43E+06	2.43E+06	0.51	0.482
Residual	24	1.15E+08	4.78E+06		
Total	63	2.40E+09			

Variate: Gain yield (kg ha^{-1})	Dry hot and dry cold experiment				
Source of variation	Df.	Sum Sq	Mean Sq	Variance	F pr.
Blocks stratum	3	452511	150837	0.39	
Blocks.Water_regime stratum					
Water_regime	1	10382424	10382424	26.82	0.014
Residual	3	1161423	387141	2.88	
Blocks.Water_regime.N_level stratum					
N_level	1	6489829	6489829	48.35	<.001
Water_regime.N_level	1	100327	100327	0.75	0.42
Residual	6	805310	134218	0.5	
Blocks.Water_regime.N_level.Genotype stratum					
Genotype	1	43567266	43567266	161.38	<.001
Water_regime.Genotype	1	705338	705338	2.61	0.132
N_level.Genotype	1	440625	440625	1.63	0.226
Water_regime.N_level.Genotype	1	2153264	2153264	7.98	0.015
Residual	12	3239558	269963	0.92	
Blocks.Water_regime.N_level.Genotype.*Units* stratum					
Growth conditions	1	20544780	20544780	69.81	<.001
Water_regime. Growth conditions	1	2061	2061	0.01	0.934
N_level. Growth conditions	1	1248663	1248663	4.24	0.05
Genotype. Growth conditions	1	6386300	6386300	21.7	<.001
Water_regime.N_level. Growth conditions	1	72542	72542	0.25	0.624
Water_regime.Genotype. Growth conditions	1	326270	326270	1.11	0.303
N_level.Genotype. Growth conditions	1	234017	234017	0.8	0.381
Water_regime.N_level.Genotype. Growth conditions	1	508112	508112	1.73	0.201
Residual	24	7063305	294304		
Total	63	1.06E+08			

Variate: Harvest Index		Dry hot and dry cold experiments			
Source of variation	Df.	Sum Sq	Mean Sq	Variance	F pr.
Blocks stratum	3	0.021178	0.007059	3.42	
Blocks.Water_regime stratum					
Water_regime	1	0.118249	0.118249	57.22	0.005
Residual	3	0.006199	0.002066	0.88	
Blocks.Water_regime.N_level stratum					
N_level	1	0.010471	0.010471	4.47	0.079
Water_regime.N_level	1	0.005373	0.005373	2.29	0.181
Residual	6	0.014067	0.002344	1.69	
Blocks.Water_regime.N_level.Genotype stratum					
Genotype	1	1.473676	1.473676	1065.19	<.001
Water_regime.Genotype	1	0.023151	0.023151	16.73	0.001
N_level.Genotype	1	0.002783	0.002783	2.01	0.182
Water_regime.N_level.Genotype	1	0.009372	0.009372	6.77	0.023
Residual	12	0.016602	0.001383	0.31	
Blocks.Water_regime.N_level.Genotype.*Units* stratum					
Growth conditions	1	1.001081	1.001081	227.13	<.001
Water_regime.Growth conditions	1	0.006048	0.006048	1.37	0.253
N_level.Growth conditions	1	0.012721	0.012721	2.89	0.102
Genotype.Growth conditions	1	0.428309	0.428309	97.18	<.001
Water_regime.N_level.Growth conditions	1	0.002394	0.002394	0.54	0.468
Water_regime.Genotype.Growth conditions	1	0.011778	0.011778	2.67	0.115
N_level.Genotype.Growth conditions	1	0.000483	0.000483	0.11	0.743
Water_regime.N_level.Genotype.Growth conditions	1	0.000915	0.000915	0.21	0.653
Residual	24	0.10578	0.004407		
Total	63	3.27063			

Variate: Partial Factor Productivity	Dry hot and dry cold experiments				
Source of variation	Df.	Sum of Squares	Mean Squares	Variance	F pr.
Blocks stratum	3	478.46	159.49	16.96	
Blocks.Water stratum					
Water	1	1695.19	1695.19	180.24	<.001
Residual	3	28.21	9.4	0.34	
Blocks.Water.N_level.Genotype stratum					
Genotype	1	2781.67	2781.67	100.41	<.001
Water.Genotype	1	155.96	155.96	5.63	0.055
Residual	6	166.22	27.7	0.36	
Blocks.Water.N_level.Genotype.*Units* stratum					
Growth conditions	1	3321.54	3321.54	42.96	<.001
Water.Growth conditions	1	45.01	45.01	0.58	0.46
Genotype.Growth conditions	1	184.67	184.67	2.39	0.148
Water.Genotype.Growth conditions	1	17.67	17.67	0.23	0.641
Residual	12	927.83	77.32		
Total	31	9802.44			

Variate: Agronomy efficiency	Dry hot and dry cold experiments				
Source of variation	Df.	Sum of Squares	Mean Squares	Variance	F pr.
Blocks stratum	3	1151.6	383.9	9.98	
Blocks.Water stratum					
Water	1	50.4	50.4	1.31	0.335
Residual	3	115.4	38.5	0.51	
Blocks.Water.N_level.Genotype stratum					
Genotype	1	103.2	103.2	1.36	0.287
Water.Genotype	1	453.8	453.8	6	0.05
Residual	6	454.1	75.7	0.53	
Blocks.Water.N_level.Genotype.*Units* stratum					
Growth conditions	1	1768.5	1768.5	12.45	0.004
Water.Growth conditions	1	1.2	1.2	0.01	0.927
Genotype.Growth conditions	1	94.1	94.1	0.66	0.431
Water.Genotype.Growth conditions	1	97.3	97.3	0.69	0.424
Residual	12	1704.6	142		
Total	31	5994.2			

Variate: WUE (kg ha^{-1} mm^{-1})			Rainfed experiment		
Source of variation	Df.	Sum of Squares	Mean Squares	Variance	F pr.
Blocks stratum	3	0.28869	0.09623	1.52	
Blocks.N_level stratum					
N_level	1	0.14312	0.14312	2.25	0.23
Residual	3	0.19054	0.06351	1.61	
Blocks.N_level.Genotypes stratum					
Genotypes	1	2.0704	2.0704	52.64	<.001
N_level.Genotypes	1	0.00238	0.00238	0.06	0.814
Residual	6	0.23599	0.03933		
Total	15	2.93112			

Variate: NUE (%)		Rainfed experiment			
Source of variation	Df.	Sum of Squares	Mean Squares	Variance	F pr.
Replications stratum	3	496.98	165.66	1.77	
Blocks.N_level stratum					
N_level	1	9223.53	9223.53	98.82	0.002
Residual	3	280	93.33	1.05	
Blocks.N_level.Genotypes stratum					
Genotypes	1	1168.36	1168.36	13.08	0.011
N_level.Genotypes	1	812.43	812.43	9.1	0.024
Residual	6	535.84	89.31		
Total	15	12517.13			

Variate: Straw yield (kg ha^{-1})		Rainfed experiment			
Source of variation	Df.	Sum of Squares	Mean Squares	Variance	F pr.
Blocks stratum	3	5342901	1780967	1.95	
Blocks.N_level stratum					
N_level	1	7326384	7326384	8.01	0.066
Residual	3	2744353	914784	2.28	
Blocks.N_level.Varieties stratum					
Genotype	1	21503607	21503607	53.51	<.001
N_level.Varieties	1	772071	772071	1.92	0.215
Residual	6	2410953	401826		
Total	15	40100269			

Variate: Grain yield (kg ha^{-1})	Rainfed experiment				
Source of variation	Df.	Sum of Squares	Mean Squares	Variance	F pr.
Blocks stratum	3	236870	78957	1.62	
Blocks.N_level stratum					
N_level	1	112473	112473	2.31	0.226
Residual	3	145952	48651	1.49	
Blocks.N_level.Varieties stratum					
Varieties	1	1615228	1615228	49.51	<.001
N_level.Varieties	1	1322	1322	0.04	0.847
Residual	6	195743	32624		
Total	15	2307587			

Variate: Harvest index	Rainfed experiment				
Source of variation	Df.	Sum of Squares	Mean Squares	Variance	F pr.
Blocks stratum	3	0.00769	0.002563	6.54	
Blocks.N_level stratum					
N_level	1	0.000127	0.000127	0.32	0.61
Residual	3	0.001177	0.000392	0.5	
Blocks.N_level.Varieties stratum					
Varieties	1	0.021094	0.021094	26.71	0.002
N_level.Varieties	1	0.001994	0.001994	2.52	0.163
Residual	6	0.004739	0.00079		
Total	15	0.03682			

Appendix 1: Publications

1. Coulibaly, P. J. A., Okae-Anti, D., Ouattra, B., Gaiser, T. & Sedogo, P. M. (2016). Effect of two watering systems on sorghum productivity in Burkina Faso, West Africa. *International Journal of Innovation and Applied Studies, 19* (4), 806-812.

2. Cropping sorghum under irrigation, a strategy to mitigate climate change induced effect in Burkina Faso, West Africa. Publication under review