INFLUENCE OF RIDGING AND INTERCROPPING ON SORGHUM PRODUCTIVITY IN ARID AND SEMI-ARID LANDS

BY

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DECLARATION

Declaration by the candidate

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To my Parents Mr John Musyimi and Mrs Scolastica Ndunge Kilonzo, and my mentors Dr. Clement Kamau Karari, Prof. Beatrice Were and Prof. Samuel Gudu for their Inspiration, support and value towards my education.

ABSTRACT

Sorghum is a staple food crop and essential for food security in Arid and Semi-Arid Lands (ASALs). The crop is one of the major sources of livelihood in Kenya's Eastern, Western and Rift Valley regions. Sorghum productivity has however been on a decline due to soil moisture deficit owing to erratic and erratically distributed rainfall and elevated temperatures experienced in the ASALs. It was therefore critical to explore the effects of moisture conservation practises and intercropping of sorghum with common beans on sorghum productivity, an area that has received limited research attention. The objective of this study was to evaluate the effect of ridging and intercropping on soil moisture conservation, sorghum productivity and land productivity in ASALs. The study was carried out at Agricultural Mechanization Research Institute, Kiboko sub-centre, under controlled irrigation. The experimental design was a randomized complete block design in split plot arrangement. The treatment structure constituted ridging techniques; 1) no ridging, 2) open ridging 3) tie ridging under the main plot and intercropping; sole sorghum and sorghum-bean intercropping with two bean varieties *KAT Bean 1* and *KAT X56* under the subplot. Soil moisture content was monitored gravimetrically. Moisture data, sorghum yield and bean yield data were collected and subjected to analysis of variance (ANOVA) using GENSTAT (version 20.1) and means were separated by fisher's protected LSD. Soil moisture content was found to increase by 25-26% and 11-13% due to tie-ridging and open-ridging respectively relative to no ridging. On the other hand, moisture content decreased by 10%-11% due to Sorghum-*KAT B1* intercropping and 5-8% due to sorghum *Kat X56* intercropping relative to sole sorghum. Sorghum grain yield was found to increase by 29-33% due to tie ridging and 0-28% due to open ridging relative to no ridges. Sorghum-bean intercropping was found to decrease sorghum grain yield by 34% due to sorghum-*KAT B1* and 36% due to sorghum-*KAT X56* intercropping. There was no significant interaction between ridging and intercropping. Ridging exhibited increase in soil moisture content, sorghum yield and sorghum equivalent yield. Intercropping sorghum and bean (additive system) exhibited a decrease in soil moisture content and component sorghum yield. Interestingly, intercropping exhibited an increase in sorghum equivalent yield ($p \leq 0.05$). The study recommends **1.** the use of tie ridging for improved soil moisture content and sorghum yield. **2.** Integration of ridging and sorghum-bean intercropping (additive system) for increased water use efficiency and land productivity.

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LIST OF ABBREVIATIONS AND ACRONYMS

ANOVA:	Analysis of Variance
ASALs:	Arid and Semi-Arid Lands
CA:	Conservation Agriculture
CS:	Cropping System
EABL:	East Africa Breweries Limited
FAOSTAT:	Food and Agriculture Organization Corporate Statistical Database
GENSTAT:	General statistics software
ICRISAT:	International Crops Research Institute for the Semi-Arid Tropics
KALRO:	Kenya Agriculture and Livestock Research Organization
LSD:	Least Significance Difference
MT:	Metric Tons
PET:	Potential Evaporation Rate
SEY:	Sorghum Equivalent Yield
SMC:	Soil Moisture Conservation
SVI:	Seedling Vigor Index
THVC:	Traditional High- Value Crop

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CHAPTER ONE

INTRODUCTION

1.1 Overview

This chapter explains the purpose and significance of the study. It elaborates the gaps and opportunities in sorghum cultivation and production in ASALs. It indicates the importance of filling those gaps and utilising the opportunities for optimum sorghum yield. Plausible strategies and focus of the study are outlined.

1.2 Background

Sorghum is the fifth most important staple food crop in the world, and is widely grown in semi-arid tropics (SAT) which are disposed to precipitation deficiencies and drought hazards (Oyier *et al.* 2016). Sorghum is essential in Africa, second to maize as the staple crop from millions of people (Mundia *et al.*, 2019). Sorghum is the only cereal crop indigenous to Kenya (Kilambya and Witwer, 2013). The crop ranks third in importance after maize and wheat; however, the later perform well in high potential agricultural areas, whereas sorghum performs well in mid to low potential agricultural areas (Njagi *et al.*, 2019). More than 80% of Kenya land mass is categorized as arid and semi-arid lands (ASALs) (Kathuli and Itabari, 2015). Therefore, sorghum is mainly relied as a staple livelihood source in Kenya’s south-western and south-central counties within the former Eastern, Nyanza, Western and Rift Valley provinces (Mailu and Mulinge 2016).

Sorghum has vast untapped potential which can be harnessed in poverty alleviation, employment creation, and in reducing malnutrition in the country (Njagi *et al.*, 2019).

Sorghum is adapted in a wide range of altitudes ranging from sea level to 2,500 meters above sea level and requires a minimum annual rainfall of 250 mm and a minimum temperature of upto10°C (Kilambya and Witwer, 2013). The crop is highly resilient to harsh environmental conditions and produces in areas where maize fail to reach physiological maturity (Karanja *et al.*, 2006; Ogeto *et al.*, 2013). Cultivation of sorghum has been on the rise due to promotion of the crop by the Kenyan government to boost food and nutritional security and increase rural income (Ogeto *et al.*, 2013; Chepng'etich *et al.*, 2014; FAOSTAT, 2019). Sorghum productivity has however stagnated despite increase in area under production (Egesa *et al.*, 2016). Low crop productivity is attributed to both biotic and abiotic factors including: drought, pest, diseases and poor agronomic practices (Karanja *et al.*, 2014). Advancement in crop breeding has led to development of high yielding, drought, pest and disease tolerant sorghum cultivars. Use of fungicide and pesticides has been effective in managing most ASALs pest and disease incidences and their severity to low levels (Karanja *et al.* 2006). Sorghum drought tolerance has however not been without decline in the crop yield and productivity and drought is categorized as the major production constraint in the ASALs (Ogeto *et al.*, 2013).

Naturally, drought occurs after a prolonged period of deficient precipitation which causes loss of soil moisture content (Ogecha *et al*. 2016). Soil moisture deficit or agricultural drought occur when soil moisture content in plants root zone is at, or below, the permanent plant wilting percentage. ASALs suffer moisture deficit attributed to heavy but short period stormy and erratically distributed rains, which causes runoff and inter-seasonal dry spells respectively (Kwena, 2015); poor soils which are mainly loamy sandy with significant surface crusting and sealing, hard pan formation, low organic matter content and unstable structure characterized by surface run off during the rainy season (Karuma *et al.*, 2014); and high temperatures and diurnal temperature range which contribute to water loss through evaporation (Zuberi *et al.* 2013). Agricultural drought gives rise and exacerbates other production constraints including; marketing channels due to low production, soils nutrients circulation and absorption and instances of pests and diseases (Kilambya and Witwer, 2013). It is the major yield-limiting factor in ASALs and further affects crops response to applied soil nutrients. Majority of ASALs residents depends on market food supplies during dry seasons due to inadequate crop yield caused by unrelenting drought and water scarcity (Gichure, 2017). This study was meant to come up with ways of mitigating the effect of water stress for optimum sorghum yield.

The degree in which drought affects agricultural productivity depends on the crop type and variety, soil type, temperature, geographical region and the available land management practices (Łabędzki, 2016). Increase in area under sorghum cultivation in ASALs with consistent low productivity inspired this study to determine how land management practises would be incorporated in the farmers' field to enhance sorghum yield and productivity in Lower eastern Kenya. The study hypothesized that combating rainwater loss would enhance sorghum yield and productivity, and this could be achieved through improved rainwater harvesting, management and increased crop water use efficiency (Kathuli and Itabari, 2015). Various soil and water conservation technologies such as stone lines, half-moons, contour hedgerows, rock bunds, filter walls, zaï, agroforestry, contour ridges, benches and no-tillage have been developed and found effective in reducing runoff and in improving water infiltration and soil moisture (Traore *et al.*, 2017).

The applicability of these techniques however depends on their availability, accessibility, affordability and ease of application. About 53% of the people who live in ASALs live below the poverty line (Titilola *et al.,* 2018) and only less demanding techniques such as ridging, mulching terracing, and intercropping can suitably be used to enhance on farm water harvesting and retention boosting crop production and productivity. Mulching for instance can be very expensive in ASALs due to high demand for crop stover as animal feed or purchase of synthetic mulch from the market (Kathuli and Itabari 2015). Terracing is labour intensive and wears with time (Karuku, 2018). With the above consideration, this study preferred ridging and intercropping as the most suitable techniques for application in ASALs of Makueni for optimum sorghum yield.

Tied ridges are furrows with barriers which transform the farm land into small pockets where rain water collects reducing surface run off, improving water infiltration and thus plant water contact time (Kathuli and Itabari 2015). Intercropping on the other hand is the growing of two or more crops in proximity to promote synergism for increased productivity. In intercrops plants accumulate biomass rapidly and attain higher ground cover which minimizes impact of erratic rainfall on bare soil and thus reduce rain water loss through surface run off and evaporation enhancing soil water recharge and withholding (Egesa *et al.,* 2016). Similar studies have shown these techniques to improve moisture content. For instance, Mutiso *et al.,* 2018 found ridging to improve moisture retention and overall productivity of pearl millet in ASALs of Makueni. Chimonyo *et al.,* (2016) found intercrops of sorghum and bottle gourd to increase soil moisture content and sorghum yield relative to sole crop. This study was therefore essential to establish how ridging and intercrops of beans (additive system) would affect the productivity of sorghum (var. *gadam*), a variety whose market demand is on the rise despite low productivity (Njagi *et al.,* 2019).

1.3 Statement of the problem

Sorghum is mainly grown in ASALs of Kenya which occupy 88% of the total land area and soil water deficit is ranked the single most limiting factor to successful crop growth, survival and productivity (Ogeto *et al*., 2013; Traore *et al.,* 2017). Relative decrease in the potential crop yields under ideal conditions associated with water deficit can reach up to 70% (Queiroz *et al.,* 2019). These regions are characterized by frequent crop failures (Kogo *et al.,* 2020). Sorghum productivity in Kenya has stagnated over the years despite availability of high yielding varieties, high market demand and increase in the planted area (FAOSTAT, 2019; Njagi *et al.*, 2019). Between 2000 and 2019, sorghum productivity in the country did not rise above 1 tha^{-1} except in 2005, productivity has always been ranging between 0.6 tha^{-1} to 0.9 tha^{-1} for cultivars with potential yield of 2 to 5 tha^{-1} (Kilambya and Witwer, 2013; FAOSTAT, 2019). Sorghum production is always inadequate for household demand notwithstanding the high market demand (Muui *et al.,* 2013). Kenya regularly imports more than one-third of its annual sorghum consumption from neighbour countries (Titilola *et al.,* 2018). Drought is a crippling hazard and occurs when is least expected and thus farmers' inability to cope or mitigate if no strategic water management practises are in place (Wellborn, 2018). Inefficient on farm rainwater harvesting, utilization and management is a major contributing factor to agricultural drought in ASALs (Ngetich *et al.,* 2014). The frequency and severity of agricultural drought has been aggravated by climate change and is projected to worsen (Kogo *et al.*, 2020).

1.4 Justification of the study

Sorghum yield is more dependent on rainfall or irrigation well distributed over the growing season depending on demand at each stage than on total water available throughout the growing season (Assefa *et al.,* 2010). It was therefore critical to explore how sorghum (Variety: *Gadam*) will perform under moisture conservation practises and intercropping with common beans. *Gadam* is a high demand white sorghum grown mainly in the ASALs (Njagi *et al.*, 2019). Intercropping and particularly cereal with legume is a sustainable and integrated soil fertility and moisture conservation practice in ASALs. It enhances water and light use efficiency causing an increase unit crop yield. Intercrop of cereal and legumes conserves soil moisture by reducing the land area exposed to sun radiation, evaporation and smothering weeds. For example, scholars have reported intercrop of maize-bean to have higher soil water holding capacity to sole maize due to early high leaf area index and higher leaf area and shading (Dahmardeh and Rigi, 2013). Root structure and organization in cereal-legume cropping system interact in a way to maximize utilization of the available soil moisture. Ridges create a barrier which reduces surface runoff and as a result increase soil water contact time boosting water infiltration, which in effect reduce risk of soil erosion, loss of soil nutrients and support exuberance crop. Effective moisture conservation techniques and high soil water potential increase plant nutrients uptake capacity and the ability of soils to supply nutrients hence enhancing overall crop yield.

1.5 Objectives of the study

1.5.1 Broad objective

- To contribute to increased sorghum productivity in ASALs

1.5.2 Specific objectives

- To determine the effect of ridging and intercropping on soil moisture conservation
- To determine the effects of ridging and intercropping on sorghum productivity

1.6 Research hypotheses (Ha)

- Ridging and intercropping improve soil moisture conservation in ASALs.

- Ridging and intercropping increase sorghum productivity in ASALs.

CHAPTER TWO

LITERATURE REVIEW

2.1 Overview

This chapter contains an elaborate discussion on the importance of sorghum cultivation and production trend in Kenya. Production constraints are outlined and drought which is categorized as the major productivity constraint in Arid and Semi-Arid lands. Opportunities for mitigation of agricultural drought and their setbacks are identified and discussed. The section also justifies the use of ridging and intercropping as the most suitable approach for moisture conservation in ASALs. The session also contains description and justification on the equipment used for data collection.

2.2 Sorghum production and yield statistics

Sorghum (*Sorghum bicolor* L. Moench) is the world's fifth most important cereal in terms of production and areas planted (Ogeto *et al.,* 2013). It has one of the largest crop germplasm collections, comprising more than 42,000 accessions and therefore this presents great opportunities for sustainable crop production, diversity in diet and supply of deficient micronutrients and provision of extra income (Muui *et al.,* 2013). Its cultivation is mainly practiced in developing countries with 90 percent of the cultivated area found in African and Asian countries, africa accounts for 61% of the area and 41% of production and Asia accounts for 22% of the area and 18% of production (Mundia *et al.,* 2019). USA is the chief producer of sorghum for animal feeds and India is the leading sorghum grain producer

(Oyier *et al.* 2016). Nigeria is the third largest producer after the United States and India and accounts for up to 40% of total sorghum production in Africa (Mundia *et al.*, 2019). A third of the total sorghum production in the world comes from Africa annually; productivity is however low with an average of 0.85 tha^{-1} (Muui *et al.*, 2013).

Sorghum production in Kenya ranks third after maize and wheat. Kenya is estimated to account for only 0.6 percent of Africa's sorghum production far behind major producers in Africa such as Nigeria, Burkina Faso and Sudan (Mailu and Mulinge, 2016). Sorghum productivity decreased from 1.2 tha^{-1} in 2005 and to 0.5 tha^{-1} in 2009 despite increase in the area under sorghum cultivation from 122,368ha in 2005 to 173,172ha in 2009 (Chepng'etich *et al.*, 2014). Between 2000 and 2018 there was an incessant increase in sorghum production driven by increases in area harvested, largely due to the promotion of sorghum as a Traditional High- Value Crop (THVC); drought resistant crop and attractive prices from growing consumption (Mailu and Mulinge, 2016; Njagi *et al.*, 2019). Sorghum productivity has however stagnated and the country still imports more than one-third of the total consumption (figure 1) (Njagi *et al.*, 2019)

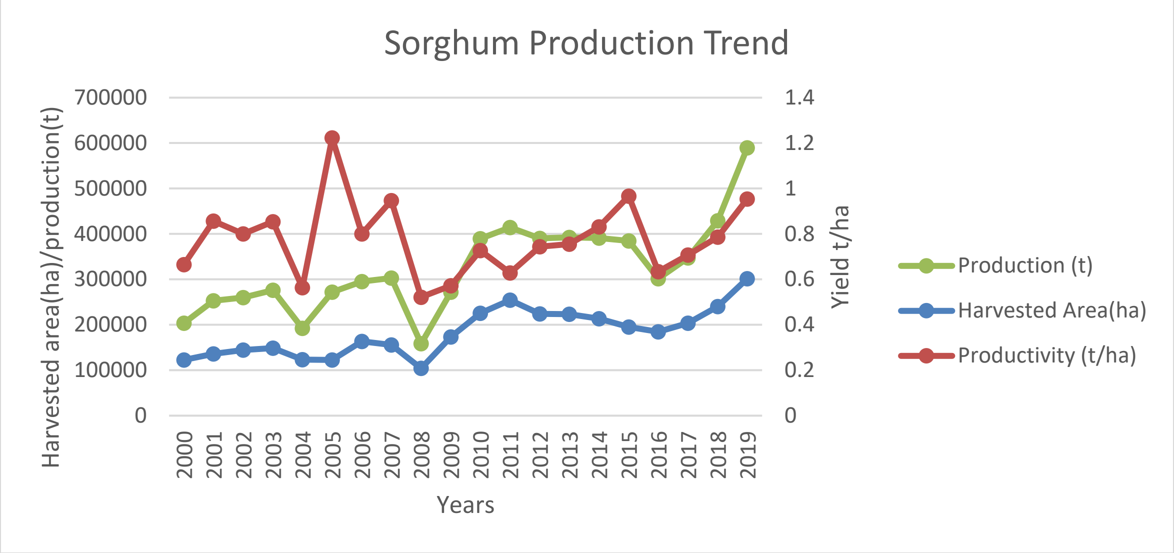

Figure 1: Sorghum production trend in Kenya between 1990-2018 (FAOSTAT, 2019)

2.3 Importance and utilization of sorghum

Sorghum has a short maturity period and the highest food production per unit of energy spent (Mundia *et al.*, 2019). The crop is a C4 physiology crop and has a wide agro-ecological adaptation, high resistance to water stress and high nutritional value (Restelatto *et al*., 2015). The crop is used by man for consumption, animal feeds and as a raw material in the brewing industry (Kilambya *and* Witwer 2013). In Kenya for instance, over 50 percent of the total sorghum production is annually consumed as food in the form of grain or flour (Titilola *et al.*, 2018). Farmers process the sorghum grain independently to sorghum flour or they blend with cassava to improve the flour quality. Sorghum is highly palatable and is used to produce a wide range of by-products. Grain sorghum is used to prepare; sorghum stew, sorghum pilau and sorghum green grams pilau, while sorghum flour makes: sorghum 'ugali', sorghum porridge, sorghum ginger biscuits, sorghum bread, sorghum queen cakes, sorghum cake, sorghum chapatti and sorghum beverage (Ogeto *et al*., 2013). Sorghum has higher concentrations of starch, proteins, unsaturated lipids, minerals and vitamins compared to other cereals. These nutrition components are also digested at a slower rate positively impacting on gut micro-organisms and issues related to obesity, diabetes, oxidative stress and hypertension (Sekoli and Morojele, 2016). Sorghum grain has high levels of iron (>70 ppm) and zinc (> 50 ppm) and thus important in the prevention of micronutrient malnutrition (Muui *et al.*, 2013). Sorghum is a favourite food crop for elderly people especially those with diabetic complications (Ogeto *et al.*, 2013).

As an essential fodder crop, Sorghum accumulates biomass quickly and contains high value calories which increase livestock milk production by over 60 percent (Oyier *et al*., 2016). As a result, the number of sorghum farmers cultivating the crop as a fodder doubled from 30% in 1990 to 60% in 2013 (Ogeto *et al.*, 2013). Sorghum grains make nutritious food for chicken while the leaves and stalks make silage and hay as dry season fodder and in the field as food for ruminants (Titilola *et al.*, 2018). Sorghum by-products in the processing industries make good animal feed (Kilambya and Witwer, 2013). The stem and foliage of the crop are used in extraction of molasses (Sekoli and Morojele, 2016). Molasses is a good source of iron, selenium, and copper, all of which help maintain healthy bones and hair, and prevent constipation in children and anaemia and is rich in antioxidants. At household level, sorghum stalks are used for fuel to complement the use of fire wood and in making temporary fencing material around household compound.

High carbohydrate content gives sorghum an added advantage to other cereal for ethanol and biodiesel production (Restelatto *et al*., 2015). And this had seen other countries such as Nigeria ban the use of barley for local sorghum in the brewing sector (Mailu and Mulinge, 2016). Twenty-four percent (24%) of the total sorghum produced in Kenya is annually used in the industrial sector (Kilambya and Witwer, 2013) to manufacture wax, starch, syrup, alcohol, dextrose agar, edible oils and gluten feed (Muui *et al.*, 2013). Sorghum demand in the brewery industry has increased over the years from 2,000 metric tons in 2009 to 27,000 metric tons (MT) for the 2017/2018 planting season (Titilola *et al.*, 2018). Today, demand for white sorghum (variety: *Gadam* and *Sila*) at East Africa Breweries Limited (EABL) stands at 60,000MT annually (Njagi *et al.*, 2019). Besides EABL, faces fierce competition from Unga limited and other feed, ethanol and syrup processing companies for the white sorghum variety (Njagi *et al.*, 2019).

2.4 Production constraints of sorghum

Sorghum production is affected by both biotic and abiotic factors. The biotic factors include head-smut disease, shoot flies and birds (Oyier *et al*., 2016). Sorghum (var: *Gadam*) is highly tolerant to stalk borers and shoot flies and common sorghum leaf diseases (KALRO, 2019). Small holder farmers control bird pest by avoiding off-season planting, mass planting and through bird scare. Seed dressing with a combination of fungicide and insecticide control major ASALs diseases including disease incidences and severity (Karanja *et al.* 2006). Aphids, maize stalk borer and boll warm are potential threats to the production of sorghum but are managed through integrated pest management practices

(Oyier *et al*., 2016). Abiotic factors include: marketing, soil fertility and drought. The demand for white sorghum is currently insatiable. Drought is the most devastating and complex constraint (Ogeto *et al.,* 2013). Drought can be defined as the absence of adequate moisture necessary for a plant to grow normally and complete its life cycle (Jabereldar *et al.,* 2017). Occurrence of drought is attributed to low and erratically distributed rainfall coupled with high temperatures and poor soil which drain and dry fast before crops attain optimal growth (Ngetich *et al.,* 2014).

2.5 Adaptation of sorghum to drought

Sorghum requires minimal annual rainfall of just above 250 mm, mild temperature of 20-25^o, low wind speed (< 2 m/sec) and high solar radiation, and a humid environment to attain optimal growth and higher yield (KALRO, 2019). Sorghum has a prolific root system, ability to maintain stomata opening at low levels of leaf water potential and high osmotic adjustment which helps the crop cope with water stress (Queiroz *et al.*, 2019). Sorghum is resilient to water logging, saline-alkaline conditions, soil infertility and high temperatures which accompany drought events (Muui *et al.*, 2013). Sorghum tolerates a range of soil pH from 5.0 - 8.5 and is more tolerant to salinity than maize (Njagi *et al.,* 2019). Besides, Sorghum leaves have a corky epidermis covered with a waxy bloom layer, which protects the leaf from desiccation (Muui *et al.,* 2013, Ogeto *et al.,* 2013). The crop has high chlorophyll content and chlorophyll fluorescence and high transpiration efficiency which enables it to withstand extended drought (Mundia *et al.,* 2019). Due to its ability to efficiently utilize photo-synthetically active radiation, sorghum is categorized as a C4 plant and normally has high photosynthetic rates, high growth rates, low photorespiration rates and water loss (Restelatto *et al.,* 2015). Moreover, under high levels of carbon dioxide (CO_2), plants categorized as C4 plants respond better to higher temperature and have better water utilization than C3 plants (Kogo *et al.*,2020). Sorghum has effective transpiration ratio of 1: 310, as the plant uses only 310 parts of water to produce one part of dry matter, compared with a ratio of 1: 400 for maize, and produces in areas where maize fail to reach physiological maturity in 5 out of every 8 seasons due to water stress (Karanja *et al.,* 2006). Sorghum partially closes its stomata under intermittent water stress to sustain reduced photosynthetic activity, which maintains a high and stable water use efficiency compared with other drought-susceptible cereals. Sorghum has a low leaf area index and the leaves normally roll under warm and dry weather condition to control evapo-transpiration rates (Hadebe *et al.,* 2017). The crops selectively ensure older leaves are senesced under drought stress, while the remaining young leaves retain turgor, stomatal conductance and assimilation as a result of high osmotic adjustment in the younger leaves (Hadebe *et al.,* 2017). Drought tolerance comes at expense of reduced yield due to reduced leaf area and number affecting photosynthetic rate.

2.6 Effect of drought on agriculture production

Agricultural productivity in Kenya has been characterized by performance below the global standards (Oyier *et al.,* 2016), this is associated with drought and high temperatures which are prevalent and pronounced in Semi-Arid Tropics (SAT) (Ogeto *et al.,* 2013). Devastating effect of agricultural drought on plant nutrients availability and transformations and soil biological activity negatively result to poor plant growth, survival and productivity (Estefan *et al*., 2013). The detrimental effects are however more severe when it coincides with various growth stages such as germination, establishment, and flowering (Queiroz *et al.*, 2019). Plants exposed to agricultural drought have low metabolic rate and are very susceptible to plant pest and diseases (Gichure, 2017). Globally, 25 percent of crops yield is annually lost to drought hazards (Bankole *et al*., 2017). In ASALs of Poland, the 1982–1983 drought events caused a 5% to 30% decrease in cereal crop yield across the country, and the 2015 drought led to 12% loss in cereals yield (Łabędzki, 2016). Besides, cereal crop production in SSA is projected to decline by a net 3.2 % by 2050 due to projected increase in incidence of drought and temperatures warming above global average (Hadebe *et al.*, 2017).

2.7 Implication of changing climate on drought

Arid and semi-arid regions are prone to drought events; Climate change predictions for SSA suggest rainfall reduction, variable distribution pattern, increased erratic rainfall, intra-seasonal dry spells, and incidences of flooding, high temperatures, corresponding increased evaporative demand and higher frequency of droughts (Hadebe *et al.*, 2017). The frequency and severity of drought have been exacerbated by climate change. For example, between the year 2007 and 2017, Kenya received poor and inadequate rainfall in which 7 of the years were affected by chronic drought events (Wellborn, 2018). Rainfall patterns have changed, and are now characterized by late rainfall onsets with mid-seasons dry spells and early offset, the rains are normally erratic and unequally distributed and accompanied by very high temperatures, which are further projected to rise by 2°C by the year 2050 due to global warming (KMD, 2015; Kwena, 2015; Kogo *et al.,* 2020).

2.8 Effects of agricultural drought in Kenya

Agricultural drought has far reaching consequences, including the rise of global food price instability and food insecurity (Łabędzki, 2016). It is mainly influenced by societal vulnerability at the time when drought occurs (Wilhelmi and Wilhite, 2002). Arid and semi-arid areas due to low rains and sandy like soil are more vulnerable to agricultural drought (Wilhelmi and Wilhite, 2002). Above 80% of the total land in Kenya is considered arid and semi-arid and is characterized by scarce, unreliable and erratic rainfalls (Kathuli and Itabari, 2015). Most of the ASALs residents live below the poverty line and are thus pre-disposed to agricultural drought (Titilola *et al.,* 2018). Majority of households in Eastern Kenya are dependent on market food supplies during dry seasons following seasonal crop failure attributed to water stress (Zuberi, *et al.,* 2013). In 2017, the government declared drought a national disaster for 23 of Kenya’s arid and semi-arid counties (Wellborn, 2018). Recurrent drought events have resulted in a significant portion of the country’s population regularly starving and heavily dependent on food aid, Kenya perennially remain on the global hunger index (Titilola *et al.,* 2018). Drought events have suppressed long-term growth of Kenya’s gross domestic product by 2.4% (KMD, 2015).

2.9 Mitigation measures of agricultural drought

Understanding the causes of agricultural drought is important when determining effective control strategies. Agricultural drought is a function of climate, soils, land use, and access to irrigation (Wilhelmi and Wilhite, 2002). Agricultural drought risk is a combination of the occurrence of drought hazards, their severity, and susceptibility of the affected crops (Łabędzki, 2016). Drought occurs naturally and sometime without farmers' awareness due to lack of sophisticated monitoring equipment (Kwena, 2015). Preparedness is normally the most effective way to mitigate drought impacts (Wilhelmi and Wilhite, 2002). Mitigation of agricultural drought is attained through:

2.9.1 Crop selection

Cultivation of drought resistance or tolerant cultivars reduce the risk of total crop failure or scanty harvests (Chepkemoi *et al.*, 2014). Overly, 70% or ASALs residents in lower eastern Kenya cultivate drought resistant crops obtained from dryland research centres (Gichure, 2017). The crops are said to mitigate famine alarms caused by water scarcity by up to 80%, the crop however produce low compared to their potential yield (Karanja *et al.*, 2006). Some of the crops are categorized as drought escaping, e.g., Maize (Variety: *Katumani composite*), this variety overcome drought by producing earlier in case of drought alarm, but when the weather conditions are optimal it delays maturity and yields higher (Karanja *et al.*, 2006).

2.9.2 Irrigation

Irrigation is the application of water in the farm to propagate a crop. It’s an important practice for ASALs areas where rainfall is normally inadequate and unpredictable. About 20% of the total land mass in Kenya receives sufficient rainfall for crop production, however only 2% of the country’s land is dedicated to irrigated agriculture (Wellborn, 2018). Irrigation in ASALs is inhibited by seasonality of rivers and dams and poor access to irrigation assets (Ogecha *et al.,* 2016). Surface water resources in ASALs are scarce, majorly influenced by deficient rainfall and high rate of evaporation in which the potential and available water resources for irrigation dry fast and thus most rivers are seasonal (KMD, 2015). In lower eastern Kenya only 8% of the residents and particularly from the well up families who have access to irrigation assets and other income sources use irrigation as an adaptive measure (Gichure, 2017). Through irrigation farmers only cope with a short-term drought conditions, however, in cases of severe droughts irrigation is costly as the cost of crop production increases due to increase in cost of water and energy used for irrigation (Wilhelmi and Wilhite, 2002).

2.9.3 Cover cropping and crop rotation

Cover crops is a term used to refer to crops planted with the aim of improving soil organic matter and soil structure for improved soil nutrients and soil moisture conservation (Clark., 2008). Cover crops contribute to moisture conservation through; suppression of weeds as smother crops that competes weeds for water and nutrients; improving infiltration of excess surface water, relieving compaction and improving structure of over tilled soil; holding soil in place through reduced soil crusting and erosion from direct effect of wind and rain (Clark., 2008; Aderunji *et al.,* 2020). Cover crops contribute to moisture retention through decay of the crop residues increasing water infiltration and decreasing soil water loss through evaporation (Clark., 2008). Crop rotation on the other hand is the growing of different crops on the same piece of land in a regular recurring sequence (Degani *et al.,* 2019). The use of crop diversity in a rotation increase crop resilience to drought and climate change. Crop rotation is essential in improving soil texture and structure, organic matter content, and biological activity, this factors combined improve actual availability of water to plants (Degani *et al.,* 2019).

2.9.4 Soil moisture conservation

Rainfall in arid and semi-arid areas is often erratic and characterized by surface runoff. Adoption of *in-situ* moisture conservation techniques can be used to delay the onset and occurrence of severe water stress by reducing the surface runoff for increased rain water harvesting, withholding and infiltration (Mutiso *et al.,* 2018). Soil water conservation structures increase soil water contact time facilitating water infiltration. Farmers who cultivate their crops without soil moisture conservation structures risk poor yield even in regions where the soils are adequately fertile. Moisture conservation in ASALs increase crop yield by 4–10 times (Kathuli and Itabari, 2015), and poor yield and food insecurity is mainly contributed by over reliance on traditional farming methods (Gichure, 2017).

2.10 Soil moisture conservation in ASALs

Soil moisture conservation involves on-farm water harvesting and withholding to make good use of rain water and/or irrigation water for plant growth and development (Łabędzki, 2016). This practise is important to augment the crop available soil moisture content as ASALs receive inadequate rainfall which is erratically distributed within the seasons accompanied by very high temperatures (Mutiso *et al.*, 2018; Zuberi *et al.* 2013). Moisture conservation improves crop productivity as rain water loss through evaporation and surface run off is curtailed (Kathuli and Itabari 2015). Some of the techniques used in soil moisture conservation in ASALs include; cover crops, conservation farming, contour farming, fanya juu terraces, bunds and ridges (Karuku, 2018).

2.10.1 Terraces

Contours terraces are moisture conservation techniques executed across sloping land. (Kathuli and Itabari, 2015). They are made by digging a ditch where the soil is thrown up the slope to form an earth bund. Terraces are used in water harvesting and withholding as they are made to trap runoff water. Contour terraces and ditches in eastern Kenya are found in upper midland agro-ecological zones where arable land is taken over due to high population density and infrastructure development. Over 70% of all cultivated land in Machakos County is terraced (Karuku, 2018). Contour terraces wear with time, besides construction and maintenance of this structures are labour intensive and thus adoption may be a challenge by low income farmers (Karuku, 2018).

2.10.2 Compost manure and mulching

Compost manure is a fermented mixture of animal dung and crop residue. This mixture when applied in the farm improves soil structure and soil organic matter which in effect boost soil water holding capacity. Soil rich with farm compost contains beneficial organisms such as earth worm and mycorrizha fungi which are essential for soil aeration and in absorption of soil water (Chepkemoi *et al.,* 2014). Mulching is a form of soil moisture conservation where organic or inorganic materials are used as soil surface cover to minimize soil-water loss through evaporation. Inorganic mulch constitutes porous black polythene material and organic mulch comprises; crop residues, plant leaves or wood chips. Mulching moderates' soil temperature reducing soil water evaporation and minimizes plant weed soil resource competition (Ngetich *et al*., 2014). In ASALs mulching is rarely practiced; Materials which could be used as organic mulch form rich diet for livestock (Kathuli and Itabari 2015). Besides, largest population of ASALs residents' lives below poverty level and access to wood chips and inorganic mulch material both physically and economically is a challenge (Titilola *et al.,* 2018).

2.10.3 Conservation agriculture

Conservation agriculture (CA) encompasses three principles; minimal soil disturbance, permanent soil cover and crop rotations (Ndoli *et al.,* 2018). A number of farms are practicing minimal tillage through precision farming such as Acacia farm in Athi River and Mr. Sessions' farm in Naro Moro (Karuku, 2018). Soils under CA tend to improve after applying the technology for several years. Ndoli *et al.,* 2018 found CA to adversely affect emergence, leaf area (LA), plant height, and yields of maize. Karuma *et al.,* 2014 found CA to be less effective to conventional tillage in arid and semi-arid lands where soil crust and soil hardpan formation is prevalent.

2.10.4 Ridging

Tied ridges comprise a long, narrow and elevated strips of land (a ridge) crossed by earth bands between the strips called ties. The ties create barrier for run off, improving water harvesting which facilitate infiltration and increase available soil moisture (Chimdessa *et al.,* 2017). Furrows between the soil bunds are tied in a pattern similar to that of bricks at a construction. The ties are lower than the soil bunds to prevent formation of water way and soil erosion. Tied ridges transform the farm land into small pockets of water and enables the crops to forego uncertain mid-season dry spells which prevail in arid and semi-arid regions (Ngetich *et al.,* 2014). Ridging is essential in combating the effect of farm water logging, reducing surface water losses and in enhancing on-farm soil water retention and infiltration (Tekle and Wedajo, 2015). Ridges augment the development of plant roots by increasing soil surface area (Chepkemoi *et al.,* 2014; Ngetich *et al.,* 2014). Chimdessa *et al.,* (2017) in a study on maize productivity reported ridging and furrow with ties to reduce surface runoff and thus increase soil water holding capacity. According to Kathuli and Itabari, (2015) in-situ moisture conservation summaries of ASALs, in corporation of manure and fertilizer coupled with tied ridges enhances crop yield by 100–359%. Ridging could be used to enhance soil moisture content and improve the productivity of sorghum (variety: *gadam*), a variety whose productivity has stagnated for years despite high demand.

2.10.5 Intercropping and moisture conservation

Intercropping is the growing of two or more crops in proximity to promote synergism for increased productivity and crop diversity (Assefa *et al.*, 2016). Intercropping is an old and widespread practice in the warm countries (Ogutu *et al.*, 2012). The success of an intercropping system depends on the interactions between the component species, the available management practices, and the environmental conditions. Therefore, selection of compatible crops maximizes positive interaction, minimizing crops competition and thus boosting their yield (Assefa *et al.*, 2016).

Intercropped systems are beneficial to sole crop due to increased overall productivity, provision of ecological services and high economic return (Egesa *et al.*, 2016). Intercropping enhances water and light use efficiency resulting to higher crop yield compared to yield of a monocrop (Ngetich *et al*, 2014). Biomass accumulated from legumes form mulch on the soil surface increasing soil water recharging and storage capacity (Mailu and Mulinge, 2016). Dahmardeh and Rigi, (2013) found Maize-green gram intercrops to form early high leaf area index and higher leaf area compared to sole maize, this resulted to reduced water loss by evaporation and higher soil moisture content which resulted to higher crop yield. In sorghum-cowpea intercropping a competitive interaction between the crops for space resulted to increased soil cover which reduced soil surface run off and soil loss (Egesa *et al.*, 2016).

Crop growth and performance in intercrops are influenced by the spread of the plant roots. Cereal-legumes intercropping systems improve water use efficiency as the varying roots lengths of component crops extract moisture from different soil horizons (Igbal *et al*., 2019). Cereals have long, fine and extensive root system compared to legumes (Ogutu *et al*., 2012). The root structures in an intercropping system harmonize water uptake and minimize competition for soil water by the plants (Dahmardeh and Rigi, 2013). A maize-peas cropping systems in china, the peas only extracted soil moisture in the shallow (top 20 cm) soil depths while the maize was found to make good use of moisture in the deeper soil layers (Chen *et al.,* 2018). Assefa *et al*., (2010) reported that 90% of the total water used by sorghum is extracted from a soil depth of 0 to 1.65 m. Cereals-Legume rooting in intercrop is ideal for breaking and prevention of soil hardpan formation, surface sealing and capping which enhances water infiltration for plant use (Kathuli and Itabari 2015).

Component crops cereal-legumes positively influence soil resource use efficiency. Legumes are not heavy consumers of soil nitrates and through their rhizobium activity they increase soil available nitrates (Dahmardeh and Rigi, 2013). Soil N rates influence the amount of soil P that the intercropped cereal crop exports (Egesa *et al.,* 2016, Restelatto *et al.,* 2015). Soil P facilitates plant root development. The root size, architecture and distribution influences the plants ability to access and absorb water for proper physiological functioning of shoots. Assefa *et al.,* (2016) reported the yield of cereal in an intercrop with legume to increase due to increased uptake of phosphorus mobilized by acidification of the rhizosphere via legumes root release of organic acids and protons. Intercropping cowpea with sorghum was reported to mobilize assimilates in production of sorbitol compounds that enhances osmotic potential of sorghum plant for water absorption in the dry soil and further help retain plant tissue integrity in low soil water levels (Egesa *et al.,* 2016). Igbal *et al.*, (2019) also reported legumes based intercropping systems to improve the absorption of macro and micronutrients from the soil along with nutrient use efficiency. Intercropping can enhance sorghum yield through moisture conservation and below ground plant root interaction.

2.11 Gravimetric method of moisture determination

Various techniques are used in soil moisture determination. The gravimetric Method was used in this study. It is a flexible and reliable moisture determination method and researchers take samples randomly in the net plot area (Estefan *et al.,* 2013). When using this method soil moisture is easily determined when one has access to soil auger, an oven for drying, and a scale for weighing. Other methods include: Tensiometers, electrical resistance blocks, neutron probes, and dielectric soil moisture sensors which encompass four other ways to measure soil moisture content. Each of the other four methods are very efficient and effective in reading soil moisture content for growers (Rowe, 2018). However, they utilize more complex processes and expensive instrumentation in order to conduct soil moisture content tests (Rowe, 2018).

CHAPTER THREE

MATERIALS AND METHODS

3.1 Overview

The planting material, study site, experimental design and procedure are described. It contains the description and justification on type of data and manner of collection and analysis procedures.

3.2 Planting materials

Gadam variety is a semi-dwarf small crop that grow 100-130 cm tall in the drier lowlands with an elevation of 50-1800 m above sea level and yield potential of 1.7 to 4.5 tha^{-1}. *Gadam* matures in 85-95 days, which is earlier to the other sorghum varieties making it an ideal variety for food deficient areas (KALRO, 2019). *Gadam* is highly tolerant to stalk borers and shoot flies and common sorghum leaf diseases (KALRO, 2019*). Gadam* contains about 75% carbohydrates as compared to 67% in barley making it a better source of fermentable sugars (Mailu and Mulinge, 2016). Due to the high demand, white sorghum (*Gadam*) offers farmers a ready market and reliable income source (Njagi *et al.*, 2019). *KAT B 1* and *KAT X56* are bean varieties which have determinate growth pattern, their height at maturity ranges between 35 and 40 cm and they both matures in 60-65 days. *KAT B1* is highly tolerant to heat and has a yield potential range of 1.4 to1.9 tha^{-1}, while *KAT X56* mature pods are tolerant to heavy rain and yields about 1.4 to 2 tha^{-1} under optimal condition (Karanja *et al.*, 2006). *KAT B1* however has high market demand and value compared to *KAT X56.* The two bean varieties have high preference in ASALs for their water use efficiency, high grain yielding capacity and high market demand hence ease for adoption (Johnson, 2018). Early maturity in the beans offer the component sorghum crop reduced competition for moisture at reproduction.

3.3 Study site

The experiment was conducted for two seasons at AMRI-Kiboko research site under regulated irrigation during the month of May to August 2019 and May to August 2020. Kiboko is located at 2°15’S latitude and 37°45’E longitude at an elevation of 975 m above sea level (Figure 2; CIMMYT, 2013).

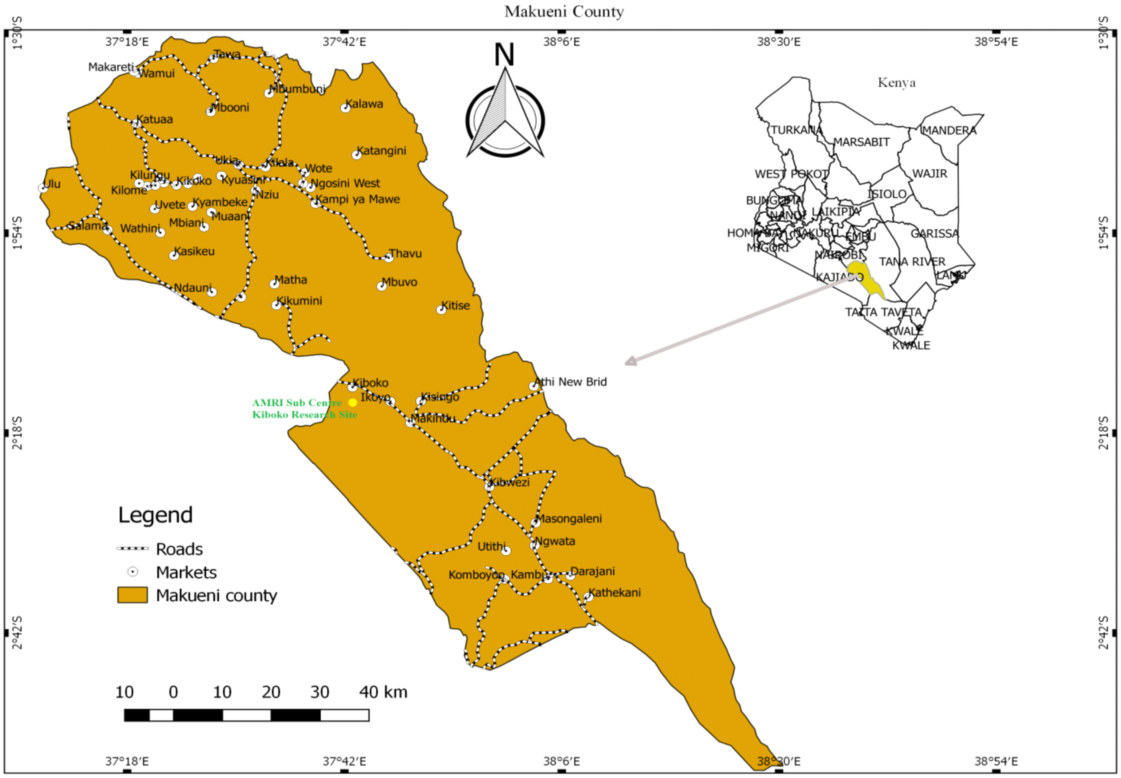

Figure 2: Topographical map of the research site (Source, Author 2019)

The site falls in agro-ecological zone VI and receives a bimodal type of rainfall with the long rains occurring from the month of March to May and the short rains from October to December (Mutiso *et al*, 2018). The rains are normally low and erratically distributed (545 - 629 mm) accompanied by very high temperatures (Mutiso *et al.*, 2018). The soils in the site are well drained, deep, dark reddish brown to dark red, friable sandy clay to clay (CIMMYT, 2013). During the first seasons, the total amount of rainfall received was 5.5mm and this was supplemented with 161.6mm of irrigation water. The second trial was set on May to August 2020, the total amount of rainfall received during the period was 26.5mm and 150.5mm of water was supplemented under irrigation. The mean average temperature during the first seasons was 22.3^{o}C and the mean minimum and maximum temperature were 15.14^{o}C and 29.5^{o}C respectively. In 2020, the mean minimum and maximum temperatures were 14.3^{o}C and 30.7^{o}C respectively. The rainfall and temperature real time data was collected from ICRISAT meteorological site in the vicinity of the trials. The temperature data agree with a report by Mutiso *et al,* (2018), who reported a high diurnal temperature range of between 14.5 to 31.5^{0}C annually in ASALs.

3.4 Experimental design

Treatments consisted of ridging (Tied ridging, Open ridging and No ridging) and Intercropping types (Sole Sorghum and Sorghum-bean intercropping) method of moisture conservation. Two bean varieties: *KAT X56* and *KAT B1* were grown in combination with sorghum (Variety: *Gadam*). A randomized complete block design in split plot arrangement was used as shown in figure 3. Ridging formed the main plot while sorghum-bean Intercropping formed the sub plot.

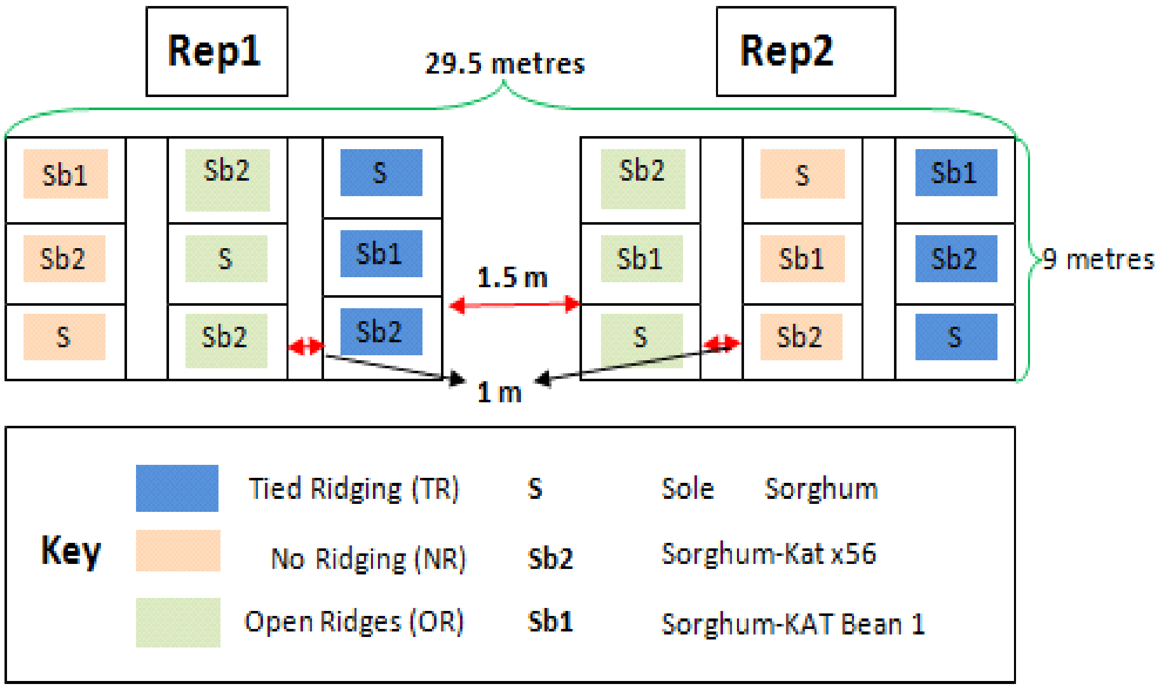

Figure 3: Experiment layout

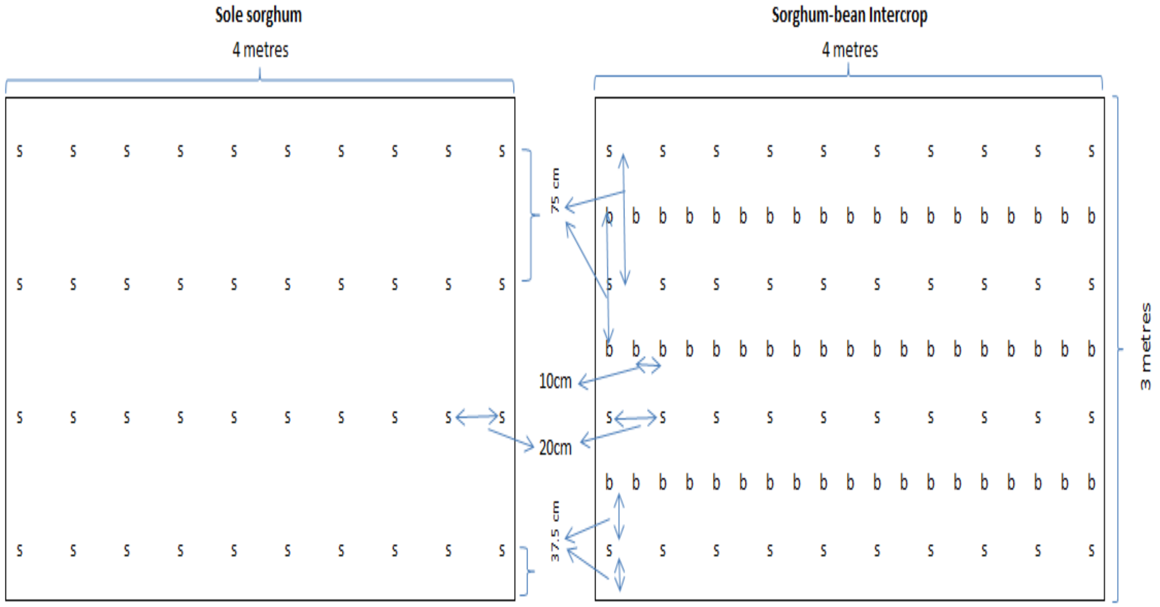

Figure 4: Crop spacing

3.5 Experimental procedures

Seedbed preparation was done using a mould bold plough. Ridges were prepared manually by erecting soil bunds across the farm gradient. The ridges were 15 cm high and 37.5 cm apart and cross tied with soil bunds after every 1m ridge length. The ridges were tied in a pattern similar to that of bricks at a construction, in that the tying was not perpendicular to prevent possible erosion. Certified seeds were obtained from Kenya Agricultural and Livestock Research Organization Seed Unit (KSU) at Katumani. Sorghum (Variety: *Gadam*) was planted as a sole crop and in combination with Beans (Varieties: *KAT X56* and *KAT B1*). Additive intercropping system was used in this study (figure 4). In additive intercropping another crop is added into a main crop resulting to increase in the final plant population relative to the main crop. Sorghum was the main crop and was sown at 100% of its recommended crop spacing (75 × 20 cm) in pure and in intercrops (KALRO, 2019). Beans varieties *KAT B 1* and *KAT X56* were used as component crops creating additional rows between the rows of sorghum. The seeds were planted on the side of the ridge at a depth of 3 cm. Di-ammonium phosphate (DAP) was applied as basal fertilizer at the rate of 100 kg/ha and sorghum was top dressed with calcium ammonium nitrate (CAN) fertilizer six weeks after emergence at the rate of 100 kg/ha (KALRO, 2019). 2-3 seeds were sown per hole and thinning was done three weeks later to retain only one healthy seedling per hole. The trial was monitored regularly to control weeds, insect pests, diseases and other probable sources of variation. Casual guards were engaged at sorghum milk, hardening and physiological maturity stage to scare bird pests. First weeding was done three weeks after emergence and second weeding was done three weeks later. The trials were mainly under sprinkler irrigation. Water was applied at variable intervals for either one or two-hour session simulating erratically distributed rainfall experienced in ASALs (figure 5). Furthermore, irrigation was curtailed deliberately at the onset of the sorghum reproduction stage (figure 5). Improvised measuring cylinders were installed systematically within the trial to collect total amount of water applied. The irrigation water was then converted into millimetres of water received per square metre according to FAO, (2019).

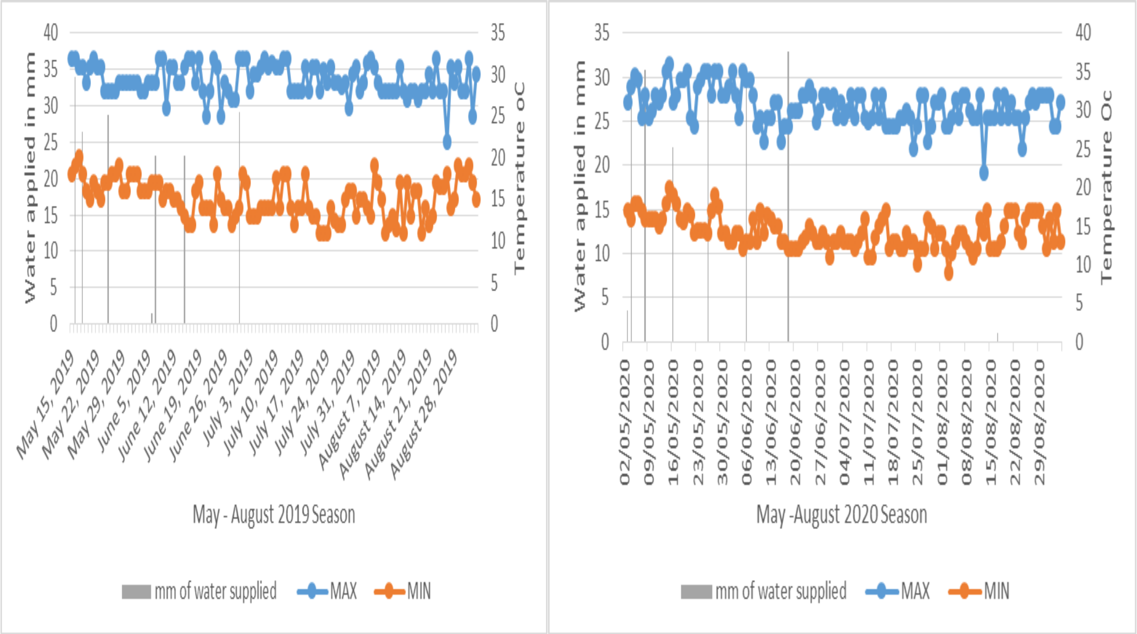

Figure 5: Irrigation Data and pattern

3.6 Sampling and parameters measured:

3.6.1 Soil moisture content (%) determination:

Soil sample were collected three times during the crop season using random sampling method and the gravimetric technique according to Shukla *et al.*, (2014). The samples were drilled in each and all plots using soil auger at a depth of 30 cm, collected samples were then mixed thoroughly and immediately sealed in plastic bags. In the lab the samples were put into air tight soil moisture boxes, weighed using digital weighing machine and oven dried at 105^{o}C for 24 hours. The soil moisture boxes were then re-weighed and weight of the wet soil samples, dry soil samples and the moisture boxes were determined and the percentage moisture content (% md) per sample computed using the formulae below according to (Traore *et al.*, 2017)

$$\%\mathrm{mc} = \frac{\text{wt of wet soil tare – wt of dry soil tare}}{\text{wt of dry soil tare – tare}} * 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. \text{(i)}$$

3.6.2 Seedling vigor index (SVI)

Sorghum seed germination and seedling establishment was examined under different levels of ridging and intercropping type. Seedling vigour was ranked using a score of 1 to 4: where 1 represented plots which had excellent seed germination (about 100%) and uniformity in seedling stand and 2 ranked plots with over 70% seed germination and uniformity in seedling stand. Seedling with over 50% seed germination and seedling uniformity were ranked 3 (fair), while seed with less than 50% seed germination and seedling uniformity were ranked number 4 (poor).

3.6.3 Plant height (cm)

This was measured as the length from the base of the plant to the tip of the panicle using a meter rule. The height was an average of six plants selected randomly within the net plot area in each and all plot.

3.6.4 Leaf area (cm^2)

Six sorghum plants were selected randomly within the net plot area, the third leaf width and leaf length were measured in centimetres using a metre rule. Average leaf length and width was then calculated in each and all plots and then used to compute leaf area in metres square according to Montgomery equation, which describes a proportional relationship between leaf surface area and the product of leaf length, width and a constant value (0.75) (He *et al.,* 2020).

A = cLW ....(ii)

Where A is the leaf area, L is the leaf length, W is the leaf width and c is the Montgomery parameter = 0.75.

3.6.5 Number of productive tillers (m^{-2})

Sorghum number of productive tillers were counted manually within the net plot area (4.8m^2) at when over 90% of the sorghum had reached physiological maturity stage i.e. the stage at which panicle loses their pigmentation and begin to dry. The tillers were then converted into number of productive tillers per square metres.

$$\text{Tillers/m2} = \frac{\text{Productive tillers}}{\text{harvested area(m2)}} \quad \text{...(iii)}$$

3.6.6 Days to 50% flowering

Days to 50% flowering were counted from sorghum crop emergence to when 50% of the sorghum panicles had flowered half way.

3.6.7 Stover yield (tha^{-1})

Sorghum stalks were cut within the net plot area (4.8 m^2), sundried for two weeks and then weighed in kilograms using an electronic balance. Sorghum dry panicle weight was determined in kilograms and the summation of stalk yield with the dry panicle yield constituted sorghum dry stover yield. The stover yield was then converted into tonnes per hectare.

$$\text{Stover yield}\left(\frac{\text{t}}{\text{ha}}\right) = \frac{\text{Yield of treatment(kg)} * 10000}{\text{Harvest area} * 1000} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(iv)}$$

Where harvest area = 4.8 m^2 and 10000 is equivalent to area of one hectare

3.6.8 Grain yield (tha^{-1})

Sorghum panicles were harvested at physiological maturity within the net plot area (4.8 m^2). They were then sun dried for one week until they were ready for threshing. The grains were winnowed and subjected to a weighing balance where the grain yield in kilograms was determined. The yield was then converted into tonnes per hectare (tha^{-1}) using the formula:

$$\text{Grain yield}\left(\frac{\text{t}}{\text{ha}}\right) = \frac{\text{Yield of treatment(kg)} * 10000}{\text{Harvest area} * 1000} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (v)$$

Where harvest area = 4.8 m^2 and 10000 is equivalent to area of one hectare

3.6.9 Harvest index

Sorghum stover and grain yield data collected was used to determine sorghum harvest index. Harvest index was determined as the ratio of sorghum grain yield to total above ground sorghum dry biomass yield.

$$\text{Harvest index} = \frac{\text{Grain yield (kg)}}{\text{Total above ground biomass yield(kg)}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{(vi)}$$

3.6.10 Sorghum equivalent yield (tha^{-1})

Sorghum grain yield data collected were used in combination with bean yield data to estimate Sorghum Equivalent Yield (SEY). SEY is the sum of sorghum yield in the intercrop system and the converted legume yield. Bean yield in intercrops were converted into sorghum yield by multiplying the legume yield with legume price kg-1/sorghum price kg-1 ratio according to Assefa *et al.,* (2016). The standard market price of sorghum and legume grain was obtained from the surrounding markets of Makueni, Machakos and Nairobi. The following formula was used to calculate SEY for the three ridging levels, i.e. No Ridges, Open Ridges and Tied Ridges:

$$\text{SEY} = \text{Ysl} + \left(\text{Yls} * \frac{\text{pl}}{\text{ps}}\right) \quad \text{(Assefa } \textit{et al.,} \text{ 2016).} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (vii)$$

Where; Ysl= intercrop sorghum grain yield kg/ha-1; Yls = intercrop legume grain yield kg/ha-1; pl = price of legume grain kg-1; ps = price of sorghum grain kg-1. NB: Prices at harvest were: Sorghum kg-1 = Ksh 30, KAT X56 kg-1 = Ksh 80 and KAT Bean 1 kg-1 = Ksh 100

3.7 Statistical model and data analysis

3.7.1 Fixed statistical model

$\gamma_{ijkl}=\mu+\beta_i+R_j+ƹ_{ij}+C_k+RC_{jk}+ƹ_{ijkl}$ ....(viii)

Where: Y_{ijkl}= Observations, μ = Grand mean, β_i= ith effect of blocking, R_j = jth effect of ridging, $ƹ_{ij}$= the error term due to ridging, C_k = kth effect of Intercropping type, RC_{jk}=jk interaction effect of ridging and Intercropping type, $ƹ_{ijkl}$= the error term due to ridging and blocking and Intercropping type.

3.7.2 Data analysis

Collected data on moisture content and sorghum yield and yield component was subjected to analysis of variance (ANOVA) to evaluate the treatment effects, and the means which were found to differ significantly were separated using Fisher's protected Least Significant Difference (LSD) at 5% level of significance using GENSTAT (Version 20.1). GENSTAT Multilinear correlations and regressions linear model output were used to establish the relationship between and among soil moisture content (%) and sorghum grain yield and yield components.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Overview

Effect of ridging and cropping system on soil moisture content (%), sorghum yield and component yield are presented and discussed in this chapter.

4.2 Effect of ridging technique and cropping system on soil moisture content (%)

Results on soil moisture content (%) are presented in table 1 and appendices I and 11. Ridging was found to influence moisture content (%) positively while intercropping type influenced moisture content (%) negatively. ANOVA results didn't show any significant interaction between ridging technique and intercropping type.

Ridging and cropping system influenced percentage soil moisture content. Soil moisture content (%) increased due to ridging, in both 2019 and 2020 however, the means on moisture content (%) did not show any significant ($p > 0.05$) difference (table 1, appendix I and II). Moisture content (%) was higher in plots with tie ridges to either open ridges or no ridges (table 1). Soil moisture content (%) increased progressively in the order NR<OR<TR regardless of the cropping system. Percentage Moisture content was +25% and +26% higher, under tie ridges and +13% and +11% under open ridging in the year 2019 and 2020 respectively (table 1). Moisture content was found to decrease under sorghum-bean intercropping. Plots with sorghum monocrop exhibited significantly ($p \leq 0.05$) higher soil moisture content (%) to those with intercrops of Sorghum-*KAT B1* in the

year 2019 and those with either Sorghum *KAT X56* intercropping or Sorghum *KAT B1* intercropping in the year 2020 (table 1, appendix I and II). The means on soil moisture content (%) between plots with sorghum mono and those with sorghum *KAT X56* intercropping did not show any significant ($p > 0.05$) difference in the year 2019 (table 1). Moisture content decreased by -11% and -10% due to sorghum *KAT B1* intercropping and -5% and -8% due to sorghum *KAT X56* intercropping in the year 2019 and 2020 respectively. Intercropped sorghum looked more stressed to sole sorghum when exposed to intra-season dry spells. In 2019 and 2020 mean moisture content (%) did not show any significant ($p >0.05$) difference between the variety of bean used in the intercrops (table 1). In both years, soil moisture content (%) decreased due to sorghum-bean intercropping in the order Sole sorghum > Sorghum *KAT X56* intercropping > Sorghum-*KAT B1*intercropping regardless of the ridging level (table 1). Intercrop of sorghum with *KAT X56* exhibited higher moisture content (%) to intercrops of sorghum *KAT B1* both in the year 2019 and 2020 (table 1). *KAT X56* was observed to accumulate above ground biomass faster than *KAT B1* which could have played an important role in minimising soil moisture loss through evaporation. Ridging and cropping system influenced moisture content (%) independently, there was no significant ($p >0.05$) interaction between the two treatments; ridging and cropping system (Appendix I and II). Moisture content (%) was found to be higher on treatment combination of sole sorghum under tie ridging (%) and lowest in treatment combination of Sorghum and *KAT B1* under no ridging in both the year 2019 and 2020 (table 1).

Consistent increase in soil moisture content (%) due to ridging was due to basin like structures formed between ridges which could withhold water extending its infiltration time. Mutiso *et al.*, (2018) observed ridging method of moisture conservation to delay onset and occurrence of plant water stress through extension of soil moisture availability to plants. The study results agree with those of Tekle and Wedajo (2015) who reported ridging to augment soil moisture content through formation of micro-basins like structures increasing water harvesting, infiltration and retention. Similar finding was reported by Chimdessa *et al.,* (2017) who reported 18% increase in moisture content under tie ridges over farmers practice and 10% higher moisture content under open ridges.

Table 1. Soil moisture content (%) as affected by ridging and cropping system

Factors	Treatments	Moisture content (%)	
		2019	2020
Ridging (R)	No ridging	7.7a	7.6a
	Open ridging	8.7a	8.8a
	Tied ridging	9.6a	9.6a
Cropping system (CS)	Sole Sorghum	9.2b	9.2b
	Sorghum/*KAT B1*	8.2a	8.3a
	Sorghum/*KAT X56*	8.7ab	8.5a
LSD $_{0.05}$ (R)		ns	ns
LSD $_{0.05}$ (CS)		0.8	0.6
LSD $_{0.05}$ (R*CS)		ns	ns
CV%		6.4	4.8

Means in a column bearing different letter (s) for each assessed treatment in a specific category of factors differ significantly ($p \leq 0.05$) and ns is not significant.

Besides, exhibiting higher surface ground cover, associated with low soil water evapotranspiration rate (Dahmardeh and Rigi, 2013), intercrops of beans with sorghum was found to decrease soil moisture content (%) in both the year 2019 and 2020 (table 1). The decrease in moisture content (%) under sorghum-bean intercropping was due to overexploitation resulting from increased root density among the component crops (Ghanbari *et al.,* 2010). Miriti *et al.,* (2012) on a study to determine effect of intercropping maize with cowpea on moisture retention found sole maize to retain more moisture by 10% to intercrop of maize and cowpea, and this the author attributed increased plant population density under intercrops resulting to greater soil water extraction. This study agrees and contradicts the finding of Chimonyo *et al.,* (2016) who in a similar study found sorghum intercropped with cowpea to exhibit low (−2.78%) water content relative to sole sorghum and higher (+2.11%) water content under sorghum bottle gourd intercropping. Chimonyo *et al.,* (2016) attributed decrease in relative content sorghum and cowpea roots extracting water in the same horizon. Nevertheless, other studies have shown intercrop of legumes to be effective in conserving soil moisture due to their cover nature; Ayele (2020) found intercrops of either maize and cowpea or maize and lablab to increase moisture retention over sole crop. In either of the planting seasons the author reported intercrop of maize-cowpea to retain more moisture than intercrop of maize-lablab (Ayele, 2020). This could therefore, mean that moisture conservation under legumes depends on the type or variety of legume used and maybe the spacing between component crops. This study showed adding a bean row within sorghum rows planted under the recommended spacing (75*20cm), had a competitive effect on percentage moisture content.

4.3 Effect of ridging and cropping system on sorghum agronomic yield

Results on sorghum yield and sorghum component yield are presented in tables 2 to 10 and in appendices III to XXI). The study exhibited ridging to affect seedling germination vigor due to seed water stress. At physiological maturity however, ridges were found to enhance sorghum plant height, leaf area, number of productive tillers, stover yield and grain yield which was attributed to higher moisture content (%). On the other hand, intercropping was shown to decrease sorghum agronomic yield in both the year 2019 and 2020 and this was associated with higher plant densities and competition for soil moisture content. The results did not exhibit any significant interaction between ridging and intercropping.

4.3.1 Seedling vigor index (SVI)

Sorghum seedling vigor (on a scale of 1-5) was found to decrease significantly at $p \leq 0.05$ due to open ridging in the year 2019 (table2; appendix III). The means were however not significantly ($p > 0.05$) different in the year 2020 (table2; appendix IV). Seedling vigor decreased in the order No ridges> Tie ridging>Open ridges. In either years, the seedlings were found to be more vigorous under no ridging to either tie ridging or open ridging (table 2). Seedling vigor between no ridging and tie ridging did not show any significance ($p > 0.05$) difference in either 2019 or 2020 (table 2). The seedling vigor were however found to decrease by 20% and 14% under open ridging and 10% and 10% under tie ridging in the year 2019 and 2020 respectively. Intercropping did not show any significant effect on seedling germination vigor (table 2, appendix III and IV).

Table 2. Sorghum seedling vigor index as affected by ridging and cropping system

Factors	Treatments	Sorghum seedling vigor	
		2019	2020
Ridging (R)	No ridging	1.2a	1a
	Open ridging	2.2b	1.7a
	Tied ridging	1.7ab	1.5a
Cropping system (CS)	Sole Sorghum	1.5a	1.5a
	Sorghum/*KAT B1*	1.8a	1.3a
	Sorghum/*KAT X56*	1.7a	1.3a
LSD $_{0.05}$ (R)		0.6	ns
LSD $_{0.05}$ (CS)		Ns	ns
LSD $_{0.05}$ (R*CS)		Ns	ns

Means in a column bearing different letter (s) for each assessed treatment in a specific category of factors differ significantly ($p \leq 0.05$) and ns is not significant.

Decline in seedling vigor under ridges could have been due to seedling-water stress as the raised soil bunds drained water into the furrows leaving the planted seeds with insufficient moisture to support germination. According to Queiroz *et al.*, (2019), water availability and movement play a very important role in stimulating seed germination, root growth, shoot elongation and establishment of uniform plant stand. Germination starts with seed imbibition, and the seeds should reach a satisfactory hydration level to allow reactivation of seed metabolic processes, and in precise seed water content of cereal crops must reach at least 35 to 45% of seed dry mass for the germination process to occur (Queiroz *et al.*, 2019). Chimonyo *et al.*, 2016 found low soil water availability in the 0-0.1m layer at planting to affect sorghum seedling emergence. Seedlings under tie ridging performed better than on open ridging this could be due to the fact that the cross ties formed basin like structures and hence higher water harvesting and withholding, which could be accessible to the germinating seedling through capillary action. The study results concur with mwende *et al.,* (2019) finding in that low seedling germination vigor was found to occur on seed planted on ridges to flatbed (no ridges) method. In either years, influence of intercropping on seedling germination vigor was non-significant, this could mean the germinating bean seedling were minute to affect component cereal crop and also there is no record of allelopathy effect on the variety of bean used, which could have hindered germination of component crops.

4.3.2 Plant height (cm)

Plant height was influenced by ridging and cropping system in both 2019 and 2020. Plant height was found to increase significantly ($p \leq 0.05$) due to tie ridging than either open ridges or no ridges (table 3; appendix V and VI). Plant height increased by 5% and 3% due to tie ridging over no ridging i.e. convectional method in the year 2019 and 2020 respectively. On the other hand, intercropping exhibited significant ($p \leq 0.05$) decrease in plant height in the year 2019; however, in the year 2020 the means on plant height did not show any significant ($p > 0.05$) difference (table 3; appendix V and VI). In both years, sorghum plant height was found to decrease by 4% and 1.3% under intercrops of sorghum-*KAT B 1* and by 3% and 1.9% under intercrops of Sorghum *KAT X56* in the year 2019 and 2020 respectively. The variety of bean used did not show any significant difference on the plant height; the heights were taller under intercrops of sorghum *KAT X56* in the year 2019 and taller under intercrops of sorghum *KAT B1* in the year 2020 (table 3).

Table 3: Influence of ridging and cropping system on sorghum plant height

Factors	Treatments	Sorghum plant height (cm)	
		2019	2020
Ridging (R)	No ridging	124.3^{a}	120.8^{a}
	Open ridging	124.5^{a}	123.5^{ab}
	Tied ridging	130.7^{b}	124.6^{b}
Cropping system (CS)	Sole Sorghum	129.3^{b}	124.3^{a}
	Sorghum/*KAT B1*	124.3^{a}	122.7^{a}
	Sorghum/*KAT X56*	125.8^{a}	122.0^{a}
LSD $_{0.05}$ (R)		5.3	2.7
LSD $_{0.05}$ (CS)		2.2	ns
LSD $_{0.05}$ (R*CS)		Ns	ns
CV%		1.2	2

Means in a column bearing different letter (s) for each assessed treatment in a specific category of factors differ significantly ($p \leq 0.05$) and ns is not significant.

The results did not show any significant ($p > 0.05$) interaction between ridging and cropping system (appendix V and VI). The highest plant height was found on sole sorghum in plots with tie ridging in both the year 2019 and 2020, while the least plant height was on Sorghum *KAT X56* intercropping in plots with no ridges in the year 2019, and on sorghum *KAT B 1* intercropping under no ridges in the year 2020. Increase in plant height under ridges could have been due to higher soil moisture content (%). Regression results showed plant height to positively correlate ($R^2 = 0.49$) with soil moisture content (%). Increase in moisture content (%) caused a significant ($p \leq 0.05$) increase in sorghum plant height (Appendix XXII; figure 6).

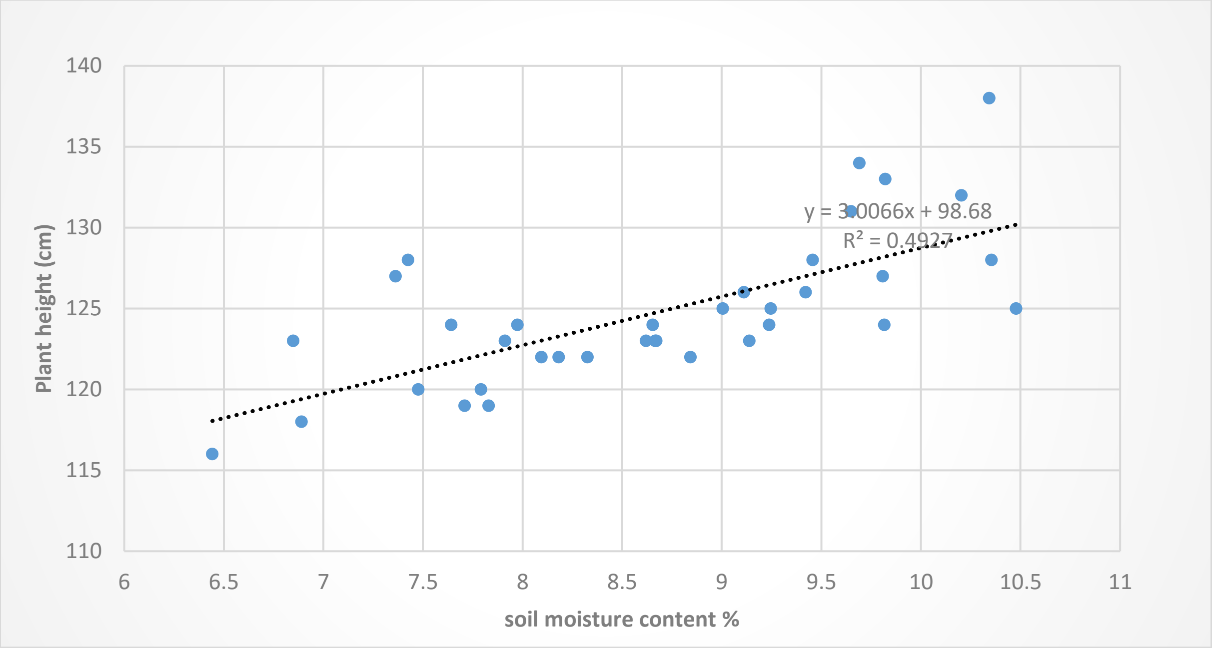

Figure 6: Correlation scatter graph between moisture content (%) and plant height (cm)

Plant height is a measure of vegetative growth and a reflection of the amount of moisture available for crops (Karuma *et al.*, 2014). Decrease in plant height under no ridges could have been due to crops exposure to water stress which resulted to low photosynthesis and hence low plant growth (Okiyo *et al.*, 2008). The study finding agrees with the finding of Gano *et al.*, (2021). The authors on a study to determine the effect of water stress on sorghum found plant height to decrease by 15-23%. On the other hand, decline in plant height under Intercrops could have been due to smothering effect of the intercropped beans, hence low sorghum plant height. The results of this study are in line with those of Karanja *et al.*, (2014), the authors found intercropped sorghum to produce the lowest plant height in sorghum-cowpea Intercropping due to higher competition for soil moisture, nutrients and solar radiation. Arshad *et al.*, 2020 found sorghum plant height to decrease under soybean intercropping by (-4%) to (-8%) and increase under mung-bean intercropping by (+4) to (+20%). Adesoji *et al.*, (2018) reported sorghum plant height to increase as a result of incorporation of lablab and cowpea and decrease as a results of incorporation of mucuna. This could therefore mean that the type of legume used in intercropping and the cereal legume spacing determines the response of the cereal crop in terms of height. The plant height of sorghum (var. *gadam*) increased due to ridging but decreased due to bean intercropping (additive system).

4.3.3 Leaf area (cm^2)

Ridging positively influenced sorghum leaf length and width and hence leaf area. Although the means on leaf area did not show any significance ($p>0.05$) difference in both years (appendix VII and VIII), Leaf area was found to increase by 5% and 10% due to tie ridging over convectional method (no ridging) in the year 2019 and 2020 respectively (table 4). Conversely, Intercropping exhibited significant ($p\leq0.05$) decrease on sorghum leaf area in 2019 (appendix VII). In the year 2020, the reduction in leaf area was only significant ($p\leq0.05$) when sorghum was intercropped with *KAT X56*. Intercrops of sorghum with *KAT B1*, did not show any significant ($p>0.05$) difference on leaf area (appendix VIII). This could have been due to the fact that, during the year 2020, *KAT B1* was affected by leaf blight which could have reduced the legume vigor and hence it competitive ability. The leaf area was found to decrease by 12% and 4% due to sorghum/*KAT B1* intercropping and 13% and 12% due to sorghum/*KAT X56* intercropping in the year 2019 and 2020 respectively. Decrease in leaf area could have been due smothering effect of the intercropped beans on the growing sorghum. There was no significant ($p>0.05$) interaction between ridging and intercropping (appendix VII and VIII). Sorghum mono was found to produce the highest leaf area (cm^2).

Table 4: Influence of ridging and cropping system on leaf area

Factors	Treatments	Leaf area (cm^2)	
		2019	2020
Ridging (R)	No ridging	181.3a	176.8a
	Open ridging	180.2a	173.7a
	Tied ridging	190.1a	196.0a
Cropping system (CS)	Sole Sorghum	200b	192.2b
	Sorghum/*KAT B1*	176.9a	184ab
	Sorghum/*KAT X56*	174.8a	169.3a
LSD $_{0.05}$ (R)		ns	ns
LSD $_{0.05}$ (CS)		11.77	16
LSD $_{0.05}$ (R*CS)		ns	ns
CV%		4.5	6.2

Means in a column bearing different letter (s) for each assessed treatment in a specific category of factors differ significantly ($p\leq0.05$) and ns is not significant.

Increase in sorghum leaf area from no ridges to tie ridges and decrease in sorghum leaf area under intercropping could be ascribed to moisture content (%). Regression analysis showed a positive correlation between moisture content (%) and sorghum leaf area. The effect of moisture content on sorghum leaf area was however not significant ($p>0.05$) (Appendix XXIII; figure 7).

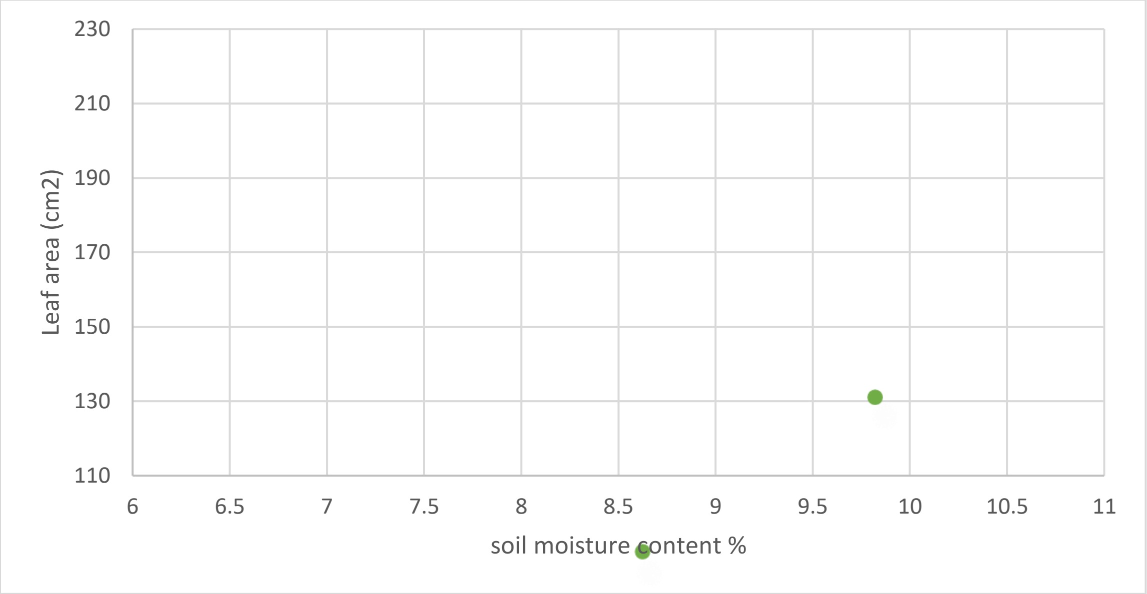

Figure 7: Correlation graph between moisture content (%) and sorghum leaf area (cm^2)

Increase in sorghum leaf area under ridging was due to increased soil moisture content. According to Gano *et al.*, (2021) when plants have adequate water supply their leaf size increases as the plants assimilate sufficient amount of water increasing the leaves turgor pressure. Further, higher soil moisture improves absorption of nutrients enhancing photosynthetic efficiency and leaf dry matter accumulation and production (Okiyo *et al.*, 2008). Other studies have shown drought stress to induce decrease in leaf appearance, transpiration and photosynthesis as a drought avoidance strategy to reduce water loss which end up inhibiting cell division and leaf growth (Gano *et al.*, 2021). Zhang *et al.*, (2019) found water-deficit to inhibit vegetative growth of sorghum and lower green leaf area. These results are in agreement with those of Okiyo *et al.*, 2008 who reported the length of sorghum flag leaf to reduce by 10.2% under water stress to well-watered crops. Assefa *et* *al.,* (2016), also reported on sorghum- cowpea intercropping leaf area index to decline due to increased competition for soil moisture content (%) and growth resources. This studies agrees with the finding of Arshad *et al.*, (2020). The authors found the Leaf area index (LAI) of sweet sorghum to reduce due to mung bean intercropping (-11%) and soybean intercropping (-2%). Moisture content influence size of sorghum (variety; *Gadam*) leaf area. Sorghum leaf area increased under ridging and decreased under intercropping.

4.3.4 Number of productive tillers per metre square (m^{-2})

The study showed ridging to significantly ($p \leq 0.05$) influence the number of productive tillers per square metres both in the year 2019 and 2020 (table 5; appendix IX and X). The number of tillers increased progressively due to ridging in the order NR<OR<TR. Tied ridging had the highest number of tillers with an average of four (4) tillers in every square metre (table 5).

Table 5: Influence of ridging and cropping system on number of productive tillers

Factors	Treatments	Tillers (m^2)	
		2019	2020
Ridging (R)	No ridging	2.6^a	2.0^a
	Open ridging	3.0^a	3.0^a
	Tied ridging	4.0^b	3.3^b
Cropping system (CS)	Sole Sorghum	4.1^b	3.5^b
	Sorghum/*KAT B1*	2.6^a	2.5^a
	Sorghum/*KAT X56*	2.8^a	2.2^a
$LSD_{0.05}$ (R)		0.44	0.56
$LSD_{0.05}$ (CS)		0.6	0.8
$LSD_{0.05}$ (R*CS)		ns	ns
CV%		12.4	16.8

Means in a column bearing different letter (s) for each assessed treatment in a specific category of factors differ significantly ($p \leq 0.05$) and ns is not significant.

The number of productive tillers however decreased significantly ($p \leq 0.05$) due to intercropping (table 5; appendix IX and X). The tillers decreased by 37% and 29% due to sorghum *KAT B1* intercropping and 32% and 37% due to sorghum *KAT x56* intercropping in the year 2019 and 2020 respectively.

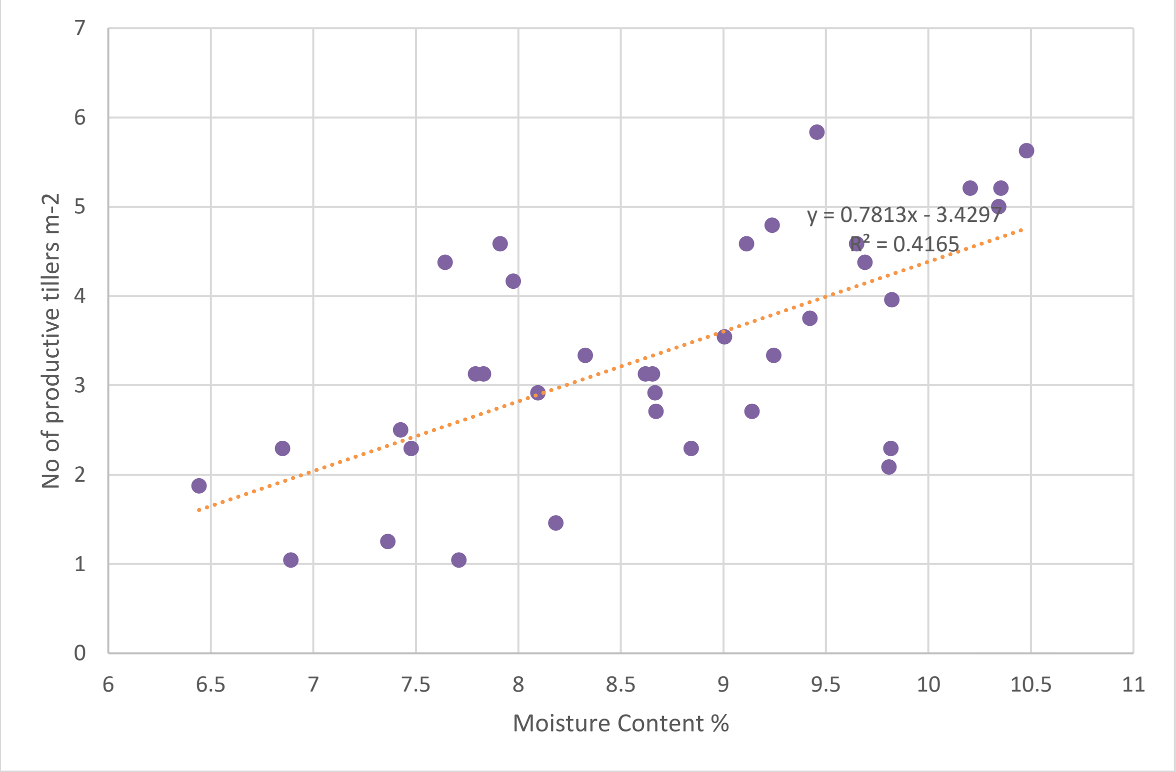

Figure 8: Correlation graph between moisture content (%) and number of productive tillers

Increase in number of tillers under ridging could be due to higher soil moisture content (%). Regression results showed soil moisture content (%) to positively ($R^2=0.4$) influence number of sorghum productive tillers (figure 8). The number of productive tillers increased significantly ($p \leq 0.05$) with increase in soil moisture content (%) (Appendix XXIV; figure

8). Increase in number of tillers with ridges could therefore be attributed with moisture content (%). The study finding concurs with those of Tekle and Wedajo (2015), where tied ridges was found to produce the highest number of productive tillers per plant, which was due to high moisture retention and use efficiency compared to conventional method. This study is in line with those of Chimonyo *et al.,* 2016. The authors found the number of sorghum tillers to increase under sorghum bottle gourd intercropping which also exhibited higher moisture content relative to sole crop and decrease under intercrop of sorghum cowpea which also exhibited low moisture content relative to sole crop. Ridging led to increase in number of tillers while sorghum-bean intercropping (additive design) led to decrease in number of tillers.

4.3.5 Days to 50% flowering

Number of days from emergence to half bloom did not differ significantly ($p>0.05$) either under ridging or sorghum-bean cropping system in the year 2019 and 2020 (table 6; appendix XI and XII).

Table 6: influence of ridging and cropping system on number of days to 50% flowering

Factors	Treatments	Days to 50% flowering	
		2019	2020
Ridging (R)	No ridging	50.7^a	51.2^a
	Open ridging	51.5^a	51.3^a
	Tied ridging	51.2^a	51.7^a
Cropping system (CS)	Sole Sorghum	51.3^a	51.5^a
	Sorghum/*KAT B1*	51.2^a	51.3^a
	Sorghum/*KAT X56*	50.8^a	51.3^a
$LSD_{0.05}$ (R)		ns	ns
$LSD_{0.05}$ (CS)		ns	ns
$LSD_{0.05}$ (R*CS)		ns	ns
CV%		1.5	1.3

Means in a column bearing different letter (s) for each assessed treatment in a specific category of factors differ significantly ($p \leq 0.05$) and ns is not significant.

The means on number of days to 50% flowering under ridging technique were however found to increase in the order NR<OR<TR; the highest number of days to 50% flowering was recorded on tie ridges while the lowest number of days were recorded on no ridges (table 6). Sorghum mono was shown to delay flowering compared to when planted together with either of the bean varieties (table 6).

Regression results did not show any significant ($p > 0.05$) effect of moisture content (%) on days to 50% flowering; the results exhibited a weak positive correlation ($R^2=0.02$) (Appendix XXV). The effect of Moisture content (%) on number of days to 50% flowering was therefore negligible. Delayed floral initiation under ridging could therefore be due to delayed emergence, Chimonyo *et al.,* 2016 found low soil water availability in the 0–0.10 m layer at planting to delay sorghum seedling emergence and establishment, end of juvenile stage and floral initiation. Water deficit at the end of the growing season was reported to hasten crop growth and development (Chimonyo *et al.,* 2016). Meaning that because no ridging was found to exhibit the lowest amount of moisture content relative to tie ridging, earlier floral initiation could have been due to moisture stress hastening the crop development. Other studies, have shown sorghum planted on tie ridging to significantly ($p \leq 0.05$) increase in number of days to maturity (Sibhatu *et al.,* 2017). Mesfin *et al.,* (2009) found sorghum to flower 4–7% days earlier under traditional farming practice to tied-ridging at Alamata and 1–2% days later under traditional farming practice at a different location; Melkassa which had a less steep slope. Floral initiation under ridging could therefore have been influenced by availability of soil moisture content at planting which delayed seedling emergence or at the end of the growing season which delayed maturity.

4.3.6 Stover yield

The results did not show any significant ($p>0.05$) difference on sorghum dry stover yield due to ridging either in the year 2019 or 2020 (table 7; appendix XIII and XIV). There was however a consistent increase in stover yield in the order NR<OR<TR in both the year 2019 and 2020 (table 7). Stover yield increased by 21% and 30% due to tie ridging over no ridges in the year 2019 and 2020 respectively. Intercrops of sorghum with beans exhibited a significant ($p\leq 0.05$) decrease on sorghum stover yield (table 7; appendix X111 and XIV Stover yield decreased by 31% and 26% due to Sorghum *KAT B1* intercropping and 25% and 35% due to sorghum *KAT X56* intercropping in the year 2019 and 2020 respectively.

Table 7: Influence of ridging and cropping system on stover yield

Factors	Treatments	Sorghum stover yield (tha^{-1})	
		2019	2020
Ridging (R)	No ridging	2.7^a	2.3^a
	Open ridging	2.7^a	2.8^a
	Tied ridging	3.4^a	3.0^a
Cropping system (CS)	Sole Sorghum	3.6^b	3.4^b
	Sorghum/ *KAT B1*	2.5^a	2.5^a
	Sorghum/ *KAT X56*	2.7^a	2.2^a
LSD $_{0.05}$ (R)		ns	ns
LSD $_{0.05}$ (CS)		0.5	0.4
LSD $_{0.05}$ (R*CS)		ns	ns
CV%		10.9	11.2

Means in a column bearing different letter (s) for each assessed treatment in a specific category of factors differ significantly ($p\leq 0.05$) and ns is not significant.

Increase in stover yield under ridging could have been due to adequate soil-plant water supply, while decline in stover yield under sorghum bean intercropping could have been due to low crop soil water supply. Moreover, low stover yields under intercrops relative to sole crop could have been due to suppressed crop physiology hence low growth and biomass accumulation (Chimonyo *et al.*, 2016). Higher stover yield was obtained under tie ridging and sole sorghum which also recorded the highest moisture content (%) (table 1 & 7). Regression analysis showed moisture content (%) to significantly ($p \leq 0.05$) influence sorghum dry stover yield (Appendix XXVI). Increase in soil moisture content (%) led to an increase in stover yield (R^2=0.39) (figure 9). Higher stover yield under tie ridging could therefore be due to increased moisture retention thus enhancing crop's response to soil growth resources (Miriti *et al.*, 2012).

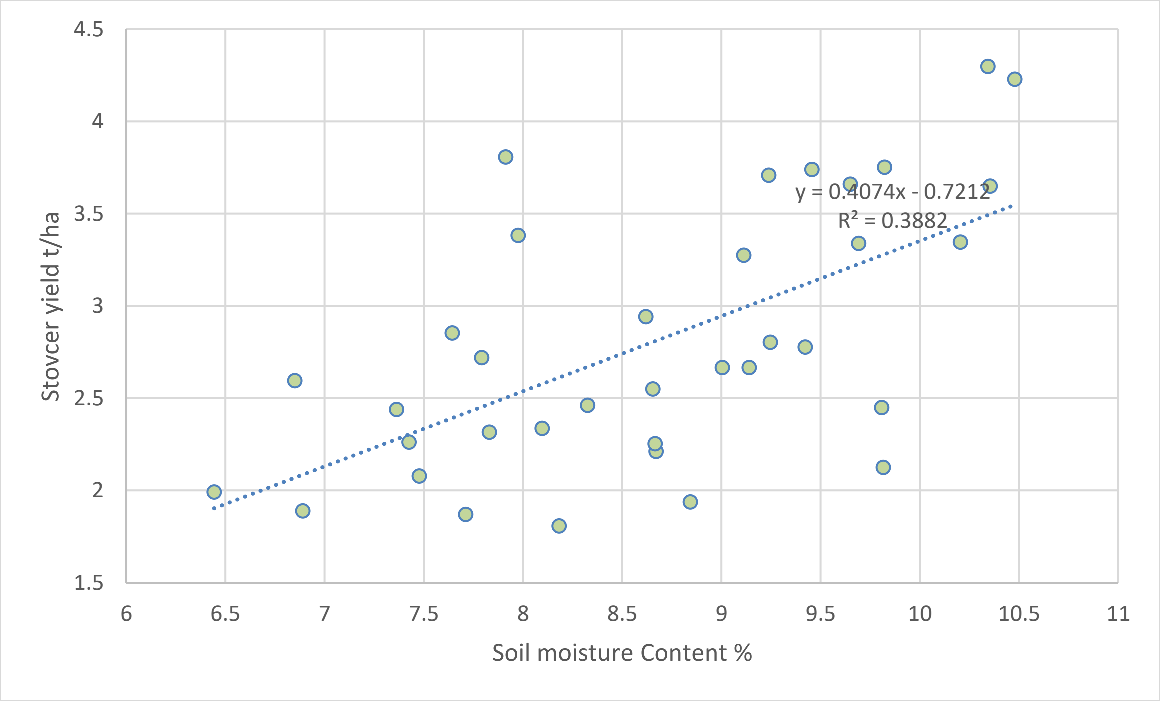

Figure 9: Correlation graph between soil moisture content and sorghum dry stover yield

Higher leaf area, number of tillers, plant height could also have contributed to improvement in sorghum stover yield; this because correlation results showed increase in these growth parameters to have positive effect on sorghum stover yield (appendix XXI). In-adequate plant water supply under no ridges may have decreased rate of cell expansion affecting the cells size and low sorghum vegetative growth (Mutiso *et al.,* 2018). Besides, limited water supply under no ridges could have led to other productivity constraints including delocalization of soil nutrients, their uptake and transfer to and within the plants (Kilambya and Witwer 2013), this because plants take up nutrients in ionic form (Mwende *et al.*, 2019).

Decline in sorghum stover yield under intercrops of sorghum and beans could be due to reduced crop spacing triggering competition for soil resources affecting crop growth (Miriti *et al.,* 2012; Mwende *et al,* 2019). The results support the finding of Igbal *et al*., (2019) who reported component crops in intercrops suffer yield losses owing to competition for finite divisible pool of growth resources and in particular soil moisture and nutrients. Uwizeyimana *et al.,* (2018) also found out that increasing crop population increase competition for available soil resources which negatively affect plant height, grain yield and overall biomass production. Sole sorghum under the standard planting density had superior vegetative growth and this was associated with minimal competition for water (Miriti *et al,* 2012). Low competition for soil moisture could have contributed to higher plant cells turgidity resulting to higher meristematic activity of sorghum and thus more foliage development, higher photosynthetic rate and improved plant growth (Mwende *et al.,* 2019; Zhang *et al.,* 2019).

4.3.7 Grain yield (tha^{-1})

Ridging was found to significantly ($p \leq 0.05$) influence sorghum grain yield (tha^{-1}) in the year 2019 (Table 8; appendix XV). In the year 2020, although means on sorghum grain yield did not show any significant ($p \leq 0.05$) difference (appendix XVI), there was a progressive increase on sorghum grain yield in either the year 2019 or 2020 in the order NR<OR<TR (Table 8). Grain yield increased by 29% and 33% under tie ridging over no ridges in 2019 and 2020 respectively. Grain yield under no ridges and open ridges were at par (NR=OR) in the year 2019, but increased by 28% in the year 2020 ($P>0.05$) (table 8). Intercropping exhibited significant ($p \leq 0.05$) decrease in sorghum grain yield (Table 8; appendix XV and XVI). Sorghum mono performed better than sorghum planted together with beans. Sorghum grain yield declined by 34% and 34% under intercrops of sorghum-*KAT B1* and 31% and 41% under sorghum-*KAT X56* intercropping in the year 2019 and 2020 respectively (Table 8).

Table 8: Influence of ridging and cropping system on sorghum grain yield

Factors	Treatments	Sorghum Grain yield (tha^{-1})	
		2019	2020
Ridging (R)	No ridging	2.0a	1.8a
	Open ridging	2.0a	2.3a
	Tied ridging	2.8b	2.4a
Cropping system (CS)	Sole Sorghum	2.9b	2.9b
	Sorghum/*KAT B1*	1.9a	1.9a
	Sorghum/*KAT X56*	2.0a	1.7a
LSD $_{0.05}$ (R)		0.7	ns
LSD $_{0.05}$ (CS)		0.34	0.41
LSD $_{0.05}$ (R*CS)		ns	ns
CV%		10.8	13.7

Means in a column bearing different letter (s) for each assessed treatment in a specific category of factors differ significantly ($p \leq 0.05$) and ns is not significant.

Regression results showed positive correlation (R^2=4) between moisture content (%) and grain yield (figure 10). Increase in soil moisture content (%) caused a significant increase in sorghum grain yield (table 8).

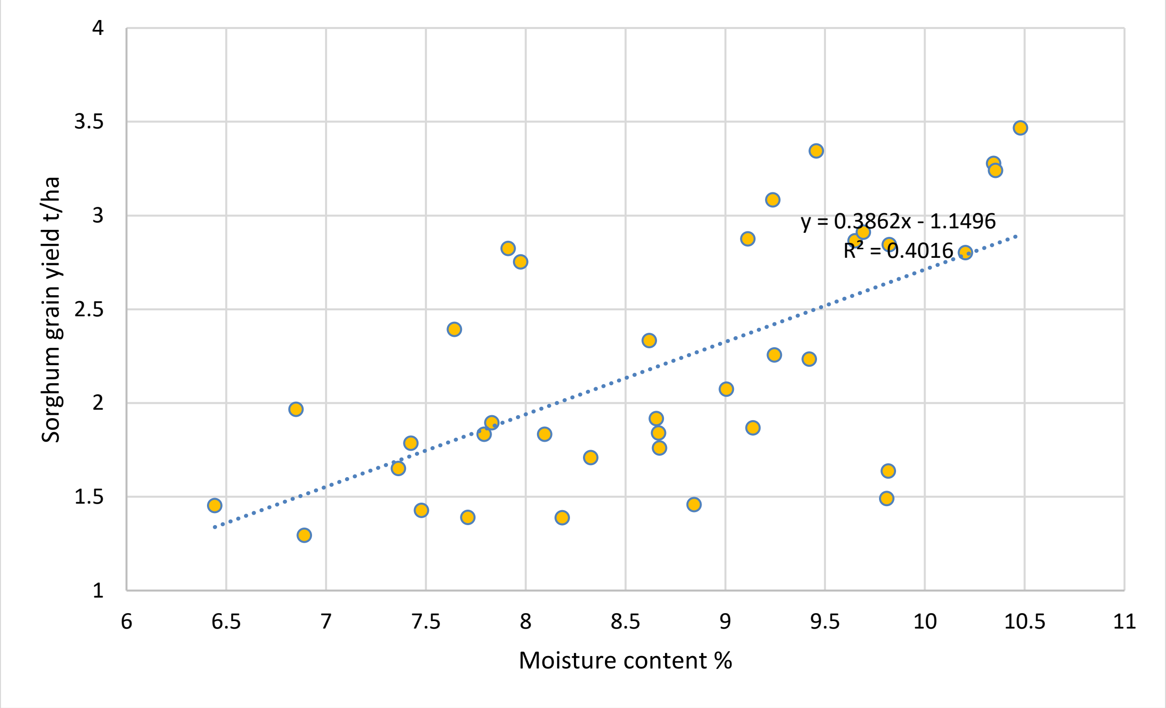

Figure 10: Correlation graph between moisture content (%) and sorghum grain yield (tha^{-1})

Increase in sorghum stover yield was found to positively correlate (R^2=0.93) with sorghum grain yield (figure 11, appendix XXI). Other parameters which exhibited a strong correlation with grain yield were plant height (R^2=0.66), leaf area (R^2=0.47), and number of productive tillers (R^2=0.94) (appendix XXI).

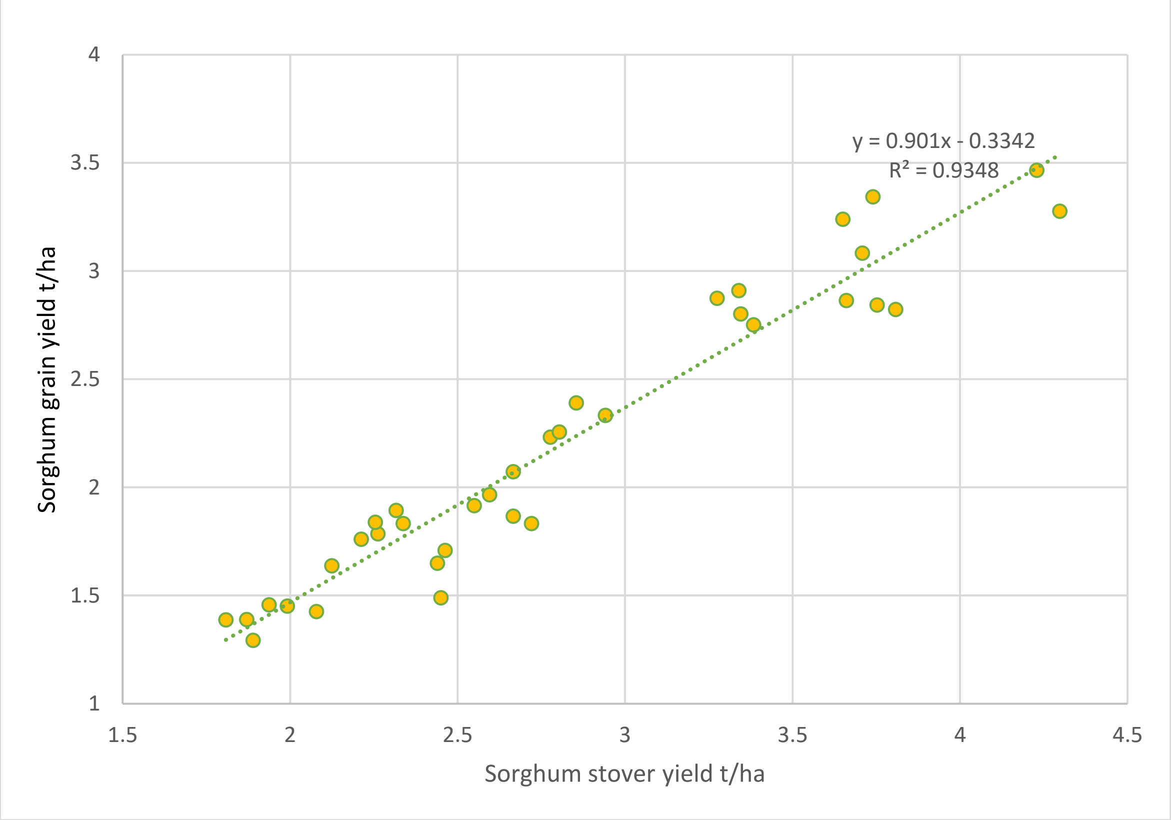

Figure 11: Correlation between sorghum stover yield and grain yield (tha^{-1})

Increase in grain yield with other growth parameter could have been due to their sensitivity to soil moisture content (%). Sorghum stem could have contributed to higher grain yield because its serves as a reservoir for labile non-structural carbohydrates which are mobilized as sugars and translocated to the filling grains against longer term effects of persistent post flowering water-stress (Mwende *et al.*, 2019). Higher plant leaf area increases crop light interception and stomatal conductance enhancing CO_2 assimilation (Assefa *et al.*, 2010; He *et al.*, 2020). Zhang *et al.*, (2019) reported sorghum leaf light saturation point and light compensation point to decrease under water stress, and this was found to adversely affect photosynthetic rate resulting to low plant biological and economic yield. Enyi, (1973) found reported sorghum leaf area indices to account for 24 percent of the variation in sorghum grain yield. Light capture and transpiration are key for crop production, and therefore low grain yield per plant and low yield per unit area under no ridges could have been due to the negative effect of water shortage on the yield components (Uwizeyimana *et al.,* 2018). Jabereldar *et al.,* (2017) found sorghum under water stress to decrease the number of grains per panicle which was due to plant stress at floral initiation stage, affecting pollination and thus abortion of floret, the authors found sorghum seed weight to decrease under water stress due to decrease in sink of photosynthate during seed filling stage. These results are in line with those of Gano *et al.*, 2021, the authors found sorghum grain yield to be reduced by 22-28% under water stress. Assefa *et al.,* 2010 reported water stress at vegetative stage and reproductive stage separately to reduce sorghum grain yield by 36% and 55% respectively.

Ridging was effective in soil moisture retention which in effect enhanced sorghum grain, the study finding agrees with those of Mesfin *et al*, 2009, who found sorghum grain yield to increase by 6–45%, Tekle and Wedajo (2015) who reported a 55.72% increase in sorghum grain yield and Chimdessa *et al.,* 2017 who reported a 28% increase in maize grain yield under tie ridging relative to flat bed. On the other hand, sorghum-bean intercropping (additive system) competed with sorghum for soil moisture content which in effect affected overall sorghum grain yield. This study is in line with those of Arshad *et al.,* (2020) who reported a decrease (-12%) in sorghum grain yield under intercrop of mung bean due to competition for N instead of supplementation of N by the associated legume.

Ayele, 2020 also found sole maize to yield better than when intercropped with either cowpea or lablab, due to lack of competition for nutrient and moisture. Arshad *et al.,* (2020) in contrast found sorghum grain yield to increase (+2.5%) when intercropped with soybean relative to sole crop. Soybean did not suppress the growth of sorghum and grain yield. This could mean the type of legume used in intercrops determine moisture content and crop grain yield. Intercropping (additive system) was not effective in moisture retention and in improving sorghum grain yield.

4.3.8 Harvest Index

Harvest index did not show any significant ($p \leq 0.05$) difference due to ridging or intercropping (table 9, appendix XVII and XVIII). Harvest index was however shown to be higher under ridged plot to no ridges and on sorghum mono to where sorghum was intercropped with either *KAT B1* or *KAT X56* (table 9).

Table 9:Influence of ridging and cropping system on harvest index

Factors	Treatments	Harvest Index	
		2019	2020
Ridging (R)	No ridging	0.42a	0.43a
	Open ridging	0.41a	0.44a
	Tied ridging	0.44a	0.44a
Cropping system (CS)	Sole Sorghum	0.44a	0.45a
	Sorghum/*KAT B1*	0.43a	0.42a
	Sorghum/*KAT X56*	0.41a	0.43a
$LSD_{0.05}$ (R)		ns	ns
$LSD_{0.05}$ (CS)		ns	ns
$LSD_{0.05}$ (R*CS)		ns	ns
CV%		6.4	4.8

Means in a column bearing different letter (s) for each assessed treatment in a specific category of factors differ significantly ($p \leq 0.05$) and ns is not significant.

Regression results showed soil moisture content to significantly ($p \leq 0.05$) increase sorghum harvest index (table 9). According to Karanja *et al.*, (2014) higher harvest index denotes higher the plant dry matter conversion efficiency. Using tie ridging therefore enhanced economic crop yield as the highest ratio of grain yield to above ground biomass was obtained. Zhang *et al.*, (2019) reported sorghum under water stress to escape water stress through regulation of photosynthetic parameters such as stomatal conductance, transpiration rate and water use efficiency which adversely affected photosynthesis decreasing harvest index.

4.3.9 Sorghum equivalent yield (SEY)

Conversion of legume grain yield into sorghum grain yield and summation with the sorghum yield per unit area, was used to estimate land productivity in terms of sorghum equivalent yield (SEY). Ridging did not show significant ($p > 0.05$) effect on sorghum equivalent yield (SEY), however the means on SEY were found to increase in the order NR<OR<TR in both 2019 and 2020 (Table 10, appendix XIX and XX). Ridging therefore caused an increase in overall land productivity. Intercropping exhibited significant ($p \leq 0.05$) increase on SEY (Table 10; appendix XIX and XX). SEY increased by 45% and 34% due to sorghum *KAT B1* intercropping and 41% and 24% due to sorghum *KAT X56* intercropping in the year 2019 and 2020 respectively (Table 10).

Table 10: Influence of ridging and cropping system on sorghum equivalent yield

Factors	Treatments	Sorghum Equivalent yield t/ha	
		2019	2020
Ridging (R)	No ridging	3.4^a	3.0^a
	Open ridging	3.3^a	3.6^b
	Tied ridging	4.4^a	3.8^b
Cropping system (CS)	Sole Sorghum	2.9^a	2.9^a
	Sorghum/*KAT B1*	4.2^b	3.9^b
	Sorghum/*KAT X56*	4.1^b	3.6^b
$LSD_{0.05}$ (R)		ns	0.49
$LSD_{0.05}$ (CS)		0.45	0.49
$LSD_{0.05}$ (R*CS)		ns	ns
CV%		8.6	10

Means in a column bearing different letter (s) for each assessed treatment in a specific category of factors differ significantly ($p \leq 0.05$) and ns is not significant.

Increase in SEY under sorghum bean intercropping could be due to higher water use efficiency per unit area. Chimonyo *et al.,* 2016 found intercropping of sorghum with either cowpea or bottle gourd to improve water use efficiency relative to sorghum sole crop. Higher production could also have been triggered by enhanced resource capture facilitated by the positive effect of component crops and increased soil microbial activity enhancing soil resources conversion and effectiveness (Iqbal *et al*., 2019). In a similar study Ghanbari *et al.,* (2010) found maize cowpea intercropping to enhance productivity resulting to a yield advantage of 2-63 percent over their sole crops. Ayele, (2020) reported that intercropping maize with cowpea or lablab increases land productivity (LER>1) indicating the benefits of intercropping. Intercropping is an ultimate management practise for ASALs in reducing soil-water loss through evapo-transpiration and surface runoff and in optimising utilization of soil moisture and growth resources. Intercropping thus produce higher financial benefit to sole crop by optimising utilization of land and labour resources for higher crop yield (Assefa *et al.*, 2016). Results on sorghum equivalent yield could therefore mean that soil moisture was more fully exploited in sorghum-bean intercropping to sole sorghum. We can conclude that the component beans varieties in the intercrops reduced water loss and improved it use. The beans could have operated as live mulch sustaining soil water content, enhancing it utilization and thus high SEY.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Overview

The major conclusions from the study are stated. The recommendations contain insights obtained from the research.

5.2 Conclusion

The conclusions emanating from the finding of this study have been presented as follows:

i. Ridging facilitated water harvesting and withholding which in effect increased water infiltration and thus increase in percentage soil moisture content. Intercropping on the other hand, resulted to higher plant population which increased competition for plant growth resources and thus over extraction and in effect decrease in percentage soil moisture content. The effect of bean variety on moisture content (%) was not significant. There was no significant interaction between ridging and intercropping.

ii. At germination seed planted on ridges suffered moisture stress as the hills drained water into the furrows, and thus resulting to low seedling germination vigor. On establishment however, the crop exhibited higher growth on ridges which was due to adequate water supply. Sorghum plant height, leaf area, number of tillers, stover and grain yield, harvest index and land productivity increased due to ridging to no ridges. Intercropping increased plant population per unit area, which smothered and competed sorghum for soil moisture. Sorghum plant height, leaf area, number of tillers, stover and grain yield and harvest index decreased due to intercropping. The effect of bean variety on sorghum agronomic yield was not significant. There was no significant interaction between the treatments.

5.3 Recommendations

Based on experiences grained through first hand field knowledge, analysed data, and literature review the following are the key recommendations;

i. Ridging can be adopted in arid and semi-arid lands to enhance soil moisture content. Farmers should consider crop spacing when cultivating sorghum under bean intercropping as the legume can compete with the cereal on available soil moisture content.

ii. Ridging did not affect intercropping and vice versa. This study would recommend for higher sorghum yield per plant; sorghum mono under tie ridging should be practiced at the same spacing of (75*20) cm, or revise the crop spacing for sorghum beans intercrop.

5.4 Suggestion for further research

i. More research need to be carried out to determine the effect of preparing ridges before and after planting on sorghum productivity.

ii. Ridging and intercropping were showed to complement each other, intercropping also increased overall land productivity; therefore, further research would be crucial to determine at what intercrop spacing can we achieve optimal sorghum yield per unit area.

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APPENDICES

Percentage moisture content

Appendix I: 2019, Moisture content (%)

Variate: moisture_content_by_gravimetric (2019)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Blocks stratum	1	5.0172	5.0172	11.96	
Blocks.Sub_Block stratum					
Ridging	2	10.8910	5.4455	12.98	0.072
Residual	2	0.8389	0.4194	1.36	
Blocks.Sub_Block. *Units* stratum					
Intercropping	2	3.1446	1.5723	5.10	0.051
Ridging.Intercropping	4	1.4857	0.3714	1.20	0.399
Residual	6	1.8500	0.3083		

Total 17 23.2274

Appendix II: 2020, Moisture content (%)

Variate: moisture_content_by_gravimetric (2020)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Blocks stratum	1	0.0015	0.0015	0.00	
Blocks.Sub_Block stratum					
Ridging	2	12.6422	6.3211	12.35	0.075
Residual	2	1.0233	0.5116	2.91	
Blocks.Sub_Block. *Units* stratum					
Intercropping	2	2.5297	1.2649	7.20	0.025
Ridging.Intercropping	4	0.4258	0.1065	0.61	0.673
Residual	6	1.0545	0.1758		

Total 17 17.6771

Sorghum seedling vigor

Appendix III: 2019, Seedling vigor

Variate: Seedling_vigor_1_5 (2019)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Blocks stratum	1	0.8889	0.8889	16.00	
Blocks. Sub Block stratum					
Ridging	2	3.0000	1.5000	27.00	0.036
Residual	2	0.1111	0.0556	0.33	
Blocks.Sub_Block. *Units* stratum					
Intercropping	2	0.3333	0.1667	1.00	0.422
Ridging. Intercropping	4	0.6667	0.1667	1.00	0.475
Residual	6	1.0000	0.1667		
Total	17	6.0000			

Appendix IV: 2020, Seedling vigor

Variate: Seedling_vigor_1_5 (2020)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Blocks stratum	1	0.05556	0.05556	0.05	
Blocks.Sub_Block stratum					
Ridging	2	1.44444	0.72222	0.68	0.594
Residual	2	2.11111	1.05556	19.00	
Blocks.Sub_Block. *Units* stratum					
Intercropping	2	0.11111	0.05556	1.00	0.422
Ridging.Intercropping	4	0.22222	0.05556	1.00	0.475
Residual	6	0.33333	0.05556		
Total	17	4.27778			

Sorghum plant height (cm)

Appendix V: 2019, Plant height (cm)

Variate: Plant_height_cm (2019)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Blocks stratum	1	264.500	264.500	58.78	
Blocks.Sub_Block stratum					
Ridging	2	156.333	78.167	17.37	0.05
Residual	2	9.000	4.500	1.80	
Blocks.Sub_Block. *Units* stratum					
Intercropping	2	79.000	39.500	15.80	0.004
Ridging.Intercropping	4	10.667	2.667	1.07	0.448
Residual	6	15.000	2.500		
Total	17	534.500			

Appendix VI: 2020, Plant height (cm)

Variate: Plant_height_cm (2020)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Blocks stratum	1	2.000	2.000	1.71	
Blocks.Sub_Block stratum					
Ridging	2	46.333	23.167	19.86	0.048
Residual	2	2.333	1.167	0.20	
Blocks.Sub_Block. *Units* stratum					
Intercropping	2	17.333	8.667	1.46	0.305
Ridging.Intercropping	4	2.333	0.583	0.10	0.979
Residual	6	35.667	5.944		
Total	17	106.000			

Leaf area

Appendix VII: 2019, leaf area (cm^2)

```
Variate: leaf_area_cm2 (2019)

Source of variation              d.f.       s.s.       m.s.     v.r.   F pr.

Blocks stratum                      1     887.26     887.26     1.28

Blocks.Sub_Block stratum
Ridging                             2     353.85     176.92     0.25   0.797
Residual                            2    1389.36     694.68    10.01

Blocks.Sub_Block. *Units* stratum
Intercropping                       2    2351.27    1175.63    16.95   0.003
Ridging.Intercropping               4    1078.11     269.53     3.89   0.068
Residual                            6     416.21      69.37

Total    17      6476.06
```

Appendix VIII: 2020, leaf area (cm^2)

```
Variate: leaf_area_cm2 (2020)

Source of variation              d.f.       s.s.       m.s.     v.r.   F pr.

Blocks stratum                      1     3686.2     3686.2     1.52

Blocks.Sub_Block stratum
Ridging                             2     1583.2      791.6     0.33   0.755
Residual                            2     4866.0     2433.0    18.98

Blocks.Sub_Block. *Units* stratum
Intercropping                       2     1623.9      811.9     6.33   0.033
Ridging.Intercropping               4     2875.5      718.9     5.61   0.032
Residual                            6      769.2      128.2

Total    17      15404.0
```

Sorghum no of productive tillers

Appendix IX: 2019, no of productive tillers

Variate: No_of_productive_tillers_ha_1 (2019)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Blocks stratum	1	6.028E+06	6.028E+06	0.89	
Blocks.Sub_Block stratum					
Ridging	2	6.771E+08	3.385E+08	50.14	0.020
Residual	2	1.350E+07	6.752E+06	0.21	
Blocks.Sub_Block. *Units* stratum					
Intercropping	2	1.694E+09	8.471E+08	26.61	0.001
Ridging.Intercropping	4	1.808E+08	4.521E+07	1.42	0.333
Residual	6	1.910E+08	3.183E+07		
Total	17	2.763E+09			

Appendix X: 2020, no of productive tillers

Variate: No_of_productive_tillers_ha_1 (2020)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Blocks stratum	1	6.969E+07	6.969E+07	7.81	
Blocks.Sub_Block stratum					
Ridging	2	7.846E+08	3.923E+08	43.97	0.022
Residual	2	1.784E+07	8.922E+06	0.38	
Blocks.Sub_Block. *Units* stratum					
Intercropping	2	1.988E+09	9.942E+08	42.51	<.001
Ridging.Intercropping	4	4.147E+07	1.037E+07	0.44	0.775
Residual	6	1.403E+08	2.339E+07		
Total	17	3.042E+09			

Sorghum number of days to 50% flowering

Appendix XI: 2019, day to 50% flowering

Variate: Days_to_50%_flowering (2019)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Blocks stratum	1	2.0000	2.0000	12.00	
Blocks.Sub_Block stratum					
Ridging	2	2.1111	1.0556	6.33	0.136
Residual	2	0.3333	0.1667	0.27	
Blocks.Sub_Block. *Units* stratum					
Intercropping	2	0.7778	0.3889	0.64	0.562
Ridging.Intercropping	4	4.8889	1.2222	2.00	0.214
Residual	6	3.6667	0.6111		
Total	17	13.7778			

Appendix XII: 2020, day to 50% flowering

Variate: Days_to_50%_flowering (2020)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Blocks stratum	1	1.3889	1.3889	1.92	
Blocks.Sub_Block stratum					
Ridging	2	0.7778	0.3889	0.54	0.650
Residual	2	1.4444	0.7222	1.63	
Blocks.Sub_Block. *Units* stratum					
Intercropping	2	0.1111	0.0556	0.13	0.885
Ridging.Intercropping	4	1.8889	0.4722	1.06	0.450
Residual	6	2.6667	0.4444		
Total	17	8.2778			

Sorghum stover yield (tha^{-1})

Appendix XIII: 2019, Stover yield (tha^{-1})

Variate: Dry_stover_yield_t_ha (2019)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Blocks stratum	1	0.3932	0.3932	1.45	
Blocks.Sub_Block stratum					
Ridging	2	2.1951	1.0975	4.04	0.198
Residual	2	0.5431	0.2715	2.66	
Blocks.Sub_Block. *Units* stratum					
Intercropping	2	4.3554	2.1777	21.31	0.002
Ridging.Intercropping	4	0.1439	0.0360	0.35	0.834
Residual	6	0.6132	0.1022		
Total	17	8.2437			

Appendix XIV: 2020, Stover yield (tha^{-1})

Variate: Dry_stover_yield_t_ha (2020)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Blocks stratum	1	0.93864	0.93864	11.94	
Blocks.Sub_Block stratum					
Ridging	2	1.34552	0.67276	8.56	0.105
Residual	2	0.15727	0.07864	0.87	
Blocks.Sub_Block. *Units* stratum					
Intercropping	2	5.23701	2.61850	28.81	<.001
Ridging.Intercropping	4	0.46005	0.11501	1.27	0.379
Residual	6	0.54524	0.09087		
Total	17	8.68373			

Sorghum grain yield (tha^{-1})

Appendix XV: Grain yield (tha-1)

Variate: Grain_yield_t_ha (2019)

```
Source of variation             d.f.        s.s.        m.s.     v.r.   F pr.

Blocks stratum                     1     0.24451     0.24451     3.50

Blocks.Sub_Block stratum
Ridging                            2     2.44150     1.22075    17.49    0.05
Residual                           2     0.13960     0.06980     1.17

Blocks.Sub_Block. *Units* stratum
Intercropping                      2     3.89990     1.94995    32.80   <.001
Ridging.Intercropping              4     0.19319     0.04830     0.81   0.561
Residual                           6     0.35668     0.05945

Total    17        7.27538
```

Appendix XVI: Grain yield (tha^{-1})

Variate: Grain_yield_t_ha (2020)

```
Source of variation             d.f.        s.s.        m.s.     v.r.   F pr.

Blocks stratum                     1     0.47464     0.47464    11.74

Blocks.Sub_Block stratum
Ridging                            2     1.20607     0.60303    14.91   0.063
Residual                           2     0.08087     0.04044     0.47

Blocks.Sub_Block. *Units* stratum
Intercropping                      2     5.15520     2.57760    30.10   <.001
Ridging.Intercropping              4     0.35636     0.08909     1.04   0.459
Residual                           6     0.51384     0.08564

Total                             17     7.78698
```

Harvest index

Appendix XVII: Harvest index

Variate: harvest_index (2019)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Blocks stratum	1	0.0000085	0.0000085	0.06	
Blocks.Sub_Block stratum					
Ridging	2	0.0024395	0.0012198	8.02	0.111
Residual	2	0.0003043	0.0001522	0.27	
Blocks.Sub_Block. *Units* stratum					
Intercropping	2	0.0027393	0.0013697	2.47	0.165
Ridging.Intercropping	4	0.0013801	0.0003450	0.62	0.664
Residual	6	0.0033320	0.0005553		
Total	17	0.0102037			

Appendix XVIII: Harvest index

Variate: harvest_index (2020

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Blocks stratum	1	0.0000680	0.0000680	2.76	
Blocks.Sub_Block stratum					
Ridging	2	0.0004877	0.0002438	9.89	0.092
Residual	2	0.0000493	0.0000247	0.11	
Blocks.Sub_Block. *Units* stratum					
Intercropping	2	0.0025229	0.0012614	5.46	0.045
Ridging.Intercropping	4	0.0002393	0.0000598	0.26	0.894
Residual	6	0.0013854	0.0002309		
Total	17	0.0047525			

Sorghum Equivalent Yield

Appendix XIX: Sorghum Equivalent Yield

Variate: Sorghum_Equivalent_Yield_t_ha (2019)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Blocks stratum	1	0.32000	0.32000	0.48	
Blocks.Sub_Block stratum					
Ridging	2	4.07444	2.03722	3.08	0.245
Residual	2	1.32333	0.66167	7.13	
Blocks.Sub_Block. *Units* stratum					
Intercropping	2	5.70111	2.85056	30.72	<.001
Ridging.Intercropping	4	0.46222	0.11556	1.25	0.385
Residual	6	0.55667	0.09278		
Total	17	12.43778			

Appendix XX: Sorghum Equivalent Yield

Variate: Sorghum_Equivalent_Yield t_ha (2020)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Blocks stratum	1	1.0091	1.0091	25.85	
Blocks.Sub_Block stratum					
Ridging	2	1.8884	0.9442	24.19	0.040
Residual	2	0.0781	0.0390	0.32	
Blocks.Sub_Block. *Units* stratum					
Intercropping	2	3.5884	1.7942	14.65	0.005
Ridging.Intercropping	4	0.4213	0.1053	0.86	0.538
Residual	6	0.7350	0.1225		
Total	17	7.7201			

Appendix XXI: Correlations between moisture content and grain yield and component yield parameters

		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1	Moisture content (%)	-							
2	Days to 50% flowering	0.15	-						
3	Plant height (cm)	0.70	-0.23	-					
4	Leaf area (cm^2)	0.11	-0.07	0.16	-				
5	Productive tillers (M^{-2})	0.65	0.08	0.58	0.46	-			
6	Dry stover yield (tha^{-1})	0.62	-0.04	0.68	0.49	0.90	-		
7	Grain yield (tha^{-1})	0.63	-0.01	0.66	0.47	0.94	0.97	-	
8	Harvest index	0.38	0.07	0.33	0.23	0.66	0.45	0.66	-

Appendix XXII: Regression results between moisture content (%) and plant height (cm)

Coefficients	Estimate	Standard Error	t-value	p-value
Intercept	98.68	4.57	21.59	<.001
Moisture content by gravimetric	3.007	0.523	5.75	<.001

Appendix XXIII: Regression results between moisture content (%) and leaf area (cm2)

Coefficients	Estimate	Standard Error	t-value	p-value
Intercept	160.7	34.5	4.66	<.001
Moisture content by gravimetric	2.56	3.94	0.65	0.521

Appendix XXIV: Regression results between moisture content (%) and No. of productive tillers (m2)

Coefficients	Estimate	Standard Error	t-value	p-value
Intercept	-3.43	1.39	-2.48	0.018
Moisture content by gravimetric	0.781	0.159	4.93	<.001

Appendix XXV: Regression results between moisture content (%) and days to 50% flowering

Coefficients	Estimate	Standard Error	t-value	p-value
Intercept	50.25	1.10	45.53	<.001
Moisture content by gravimetric	0.116	0.126	0.91	0.367

Appendix XXVI: Regression results between moisture content (%) and stover yield (tha^{-1})

Coefficients	Estimate	Standard Error	t-value	p-value
Intercept	-0.721	0.766	-0.94	0.353
Moisture content by gravimetric	0.4074	0.0877	4.64	<.001

Appendix XXVII: Regression results between moisture content (%) and Grain yield

Coefficients	Estimate	Standard Error	t-value	p-value
Intercept	-1.150	0.706	-1.63	0.113
Moisture content by gravimetric	0.3862	0.0808	4.78	<.001

(tha^{-1})

Appendix XXVIII: Regression results between moisture content (%) and harvest index

Coefficients	Estimate	Standard Error	t-value	p-value
Intercept	0.3721	0.0271	13.72	<.001
Moisture content by gravimetric	0.00735	0.00310	2.37	0.024

Appendix XXIX: Summary of ANOVA Tables pgs. (71-80)

Parameter	Treatment	2019,	2020,	Reference page
% Soil moisture content	Intercropping	*	*	70
	Ridging	ns	ns	70
	Ridging*Intercropping	ns	ns	70
Seedling vigor	Intercropping	ns	ns	71
	Ridging	*	ns	71
	Ridging*Intercropping	ns	ns	71
Plant height	Intercropping	***	ns	72
	Ridging	*	*	72
	Ridging*Intercropping	ns	ns	72
Leaf area	Intercropping	***	*	73
	Ridging	ns	ns	73
	Ridging*Intercropping	ns	*	73
No of productive tillers	Intercropping	***	***	74
	Ridging	*	*	74
	Ridging*Intercropping	ns	ns	74
Days to 50% flowering	Intercropping	ns	ns	75
	Ridging	ns	ns	75
	Ridging*Intercropping	ns	ns	75
Stover yield	Intercropping	***	***	76
	Ridging	ns	ns	76
	Ridging*Intercropping	ns	ns	76
Grain yield	Intercropping	***	***	77
	Ridging	*	ns	77
	Ridging*Intercropping	ns	ns	77
Harvest index	Intercropping	ns	*	78
	Ridging	ns	ns	78
	Ridging*Intercropping	ns	ns	78
Sorghum Equivalent Yield	Intercropping	*	*	79
	Ridging	ns	*	79
	Ridging*Intercropping	ns	ns	79

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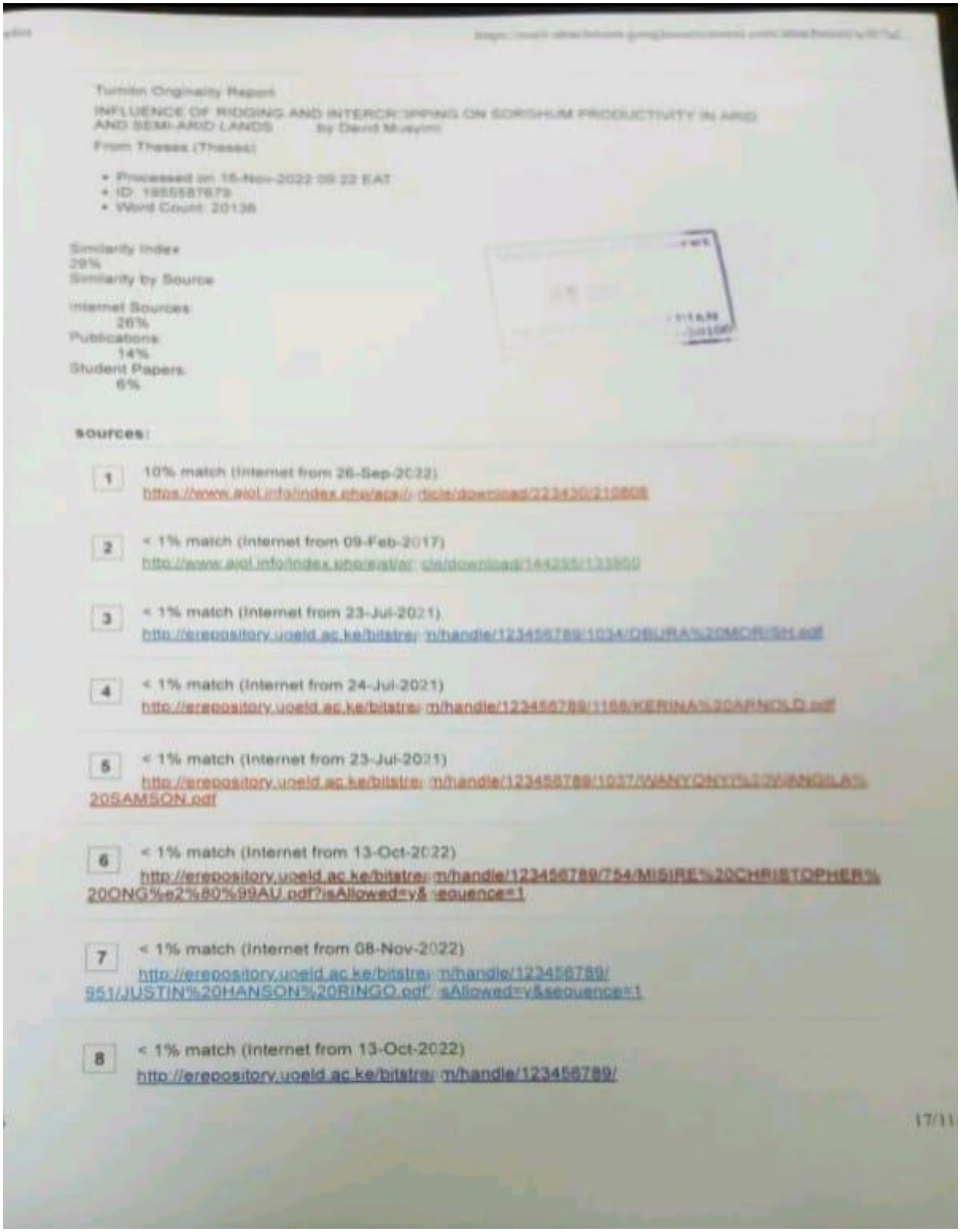

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